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Genetic diversity of sugar beet under heat stress and deficit irrigation

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Abstract

In the light of climate changes and global warming, as well as the rapid expansion in sugar beet (*Beta vulgaris* L.) cultivation in Egypt, the development of sugar beet varieties with improved tolerance to high temperature and deficit irrigation is of great importance. The objective of this study was to evaluate sugar beet genotypes under high temperatures and deficit irrigation conditions for further identification and selection of heat and drought tolerant genotypes. In the current study, a panel of 18 sugar beet breeding lines produced at the USDA–ARS–NWISRL, Kimberly, ID, and the commercial sugar beet cultivar Kawimera were evaluated for yield and quality under high temperature. Six promising lines in terms of yield and quality were further evaluated under both high temperature and deficit irrigation for two growing seasons.

All lines performed differently under deficit irrigation, indicating a high degree of genetic variability in the evaluated lines. Additionally, yield traits showed negative effect due to deficit irrigation. A significant positive correlation was observed between stress tolerance index (STI), and average root and sugar yields under stressed and non-stressed conditions. A linear relationship between STI and average root and sugar yields indicates that STI is a reliable stress index to select high yielding genotypes under both optimum- and deficit-irrigation conditions. USKPS25 and USC944-6-68 breeding lines are most likely adapted to deficit irrigation and high temperature and suitable to be utilized in the proposed sugar beet breeding programs in Egypt.

1 | INTRODUCTION

The beet sugar industry in the tropical and subtropical regions, which are mostly developing countries (including Egypt), is growing as an important component of sugar production (Abo-Elwafa, Abdel-Rahim, Abou-Salama, & Teama, 2006; Balakrishnan & Selvakumar, 2009). Recently, extensive efforts have been made to cultivate and adapt sugar beet in the tropical and subtropical countries in order to replace or supplement the sugar production from sugarcane. Sugar beet production dominates the industry outside these countries. One reason is that sugar beet has a lower irrigation requirement. The second reason is that sugar beet has a shorter growing season (5–6 mo). The third

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Abbreviations: Pol, sucrose content; QZ, quality index; RS, sugar recovery; RSY, recoverable sugar yield; RY, root yield; SL, sugar loss; SSI, stress susceptibility index; STI, stress tolerance index; SY, sugar yield; Ys, yield under deficit irrigation; YSI, yield stability index; Yp, optimum-irrigated yield.

reason is that sugar beet could be a possible solution as a tolerant crop of soil alkalinity or for newly reclaimed soils, which are common in tropical and subtropical areas (Abo-Elwafa et al., 2006; Mawusi, 2004; Nasr & Abd El-Razek, 2008).

Cultivation of sugar beet in developing countries could be profitable for farmers in two ways: (a) by diversifying their incomes by enabling them to grow an additional cash crop, and (b) by supplying sugar factories with raw material in addition to the sugar cane that will extend the factories' supply for up to 10 mo of the year (Balakrishnan & Selvakumar, 2009; Mandere, Persson, Anderberg, & Pilesjo, 2010). Recently, tropical sugar beet varieties which are better adapted to cultivation in the tropical and subtropical regions have been launched by sugar beet breeding companies (Syngenta), and could be successfully grown under these conditions in India, Kenya, and Sudan with a reasonable sugar yield (Abdelgader, Eltahir, Abbas, & Abdelrahim, 2013; Balakrishnan & Selvakumar, 2009; Mandere et al., 2010; Mohammad, Ahmed, & Marchelo-d'Ragga, 2015; Singh, Sidana, & Kummar, 2018).

Deficit irrigation has adverse effects on agricultural production. Irrigation deficiency during the growing season is a critical issue that has a substantial effect on many plant growth- and development-related physiological processes. In the light of climate change and global warming, the development of drought tolerant cultivars is the most efficient and cost-effective strategy for fighting drought stress in low-input cropping systems (IPCC 2007; Simova-Stoilova, Vassileva, & Feller, 2016; Abou-Elwafa & Shehzad, 2018).

Significant efforts have been made to minimize the effects of drought stress on sugar beet yield and quality. The occurrence of drought stress during early growth stages adversely affect sugar beet root growth and development. Furthermore, the occurrence of drought stress later in the growing season causes a reduction in leaf area and the number of leaves, and consequently decreases the photosynthetic efficiency. Besides, drought stress may increase the concentrations Na, K, and α-amino N, which negatively affect sugar extraction from roots (Putnik-Delić, Maksimović, Nagl, & Lalić, 2018). The identification of morphological and/or physiological traits associated with drought tolerance and high yield potential is a challenge when selecting sugar beet genotypes with improved tolerance to deficit irrigation.

Genetic variation for drought tolerance is a crucial prerequisite for the development of stress-tolerant varieties. However, studies on the yield performance of commercial sugar beet variations under drought conditions have not revealed any significant genotypic variations, indicating the narrow genetic base of commercial varieties (Moosavi,

Core Ideas

- Evaluation of 18 sugar beet breeding lines identified six high-yielding lines under high temperature conditions.
- Stress tolerance index (STI) revealed significant positive correlation with root and sugar yields.
- STI is a reliable stress index to select high yielding lines under optimum and stressed irrigation.
- Two breeding lines adapted to deficit irrigation and high temperature were identified.
- These two lines are suitable for utilization in sugar beet breeding programs for such stresses.

Ramazani, Hemayati, & Gholizade, 2017; Sen & Alikamanoglu, 2012). Furthermore, selecting the appropriate plant idiotype for specific agroecological conditions is a great challenge in sugar beet breeding programs. However, introgression of exotic wild germplasm into sugar beet breeding lines requires additional time and cost to get rid of weedy characteristics while maintaining desired agronomic traits. Therefore, conducting such experiments are of immense importance in determining research direction and in designing strategies for breeding programs (Moosavi et al., 2017; Ober & Luterbacher, 2002; Ober et al., 2005; Sen & Alikamanoglu, 2012; Shaw, Thomas, & Cooke, 2002).

The current study aims to (a) evaluate sugar beet genotypes for heat stress tolerance under deficit irrigation conditions, (b) identification and selection of heat- and drought-tolerant genotypes to initiate a national program for sugar beet germplasm enhancement in Egypt, and (c) introduce the gated-pipe system as a powerful irrigation system in sugar beet cultivation in Egypt.

2 | MATERIALS AND METHODS

2.1 | Plant materials

A set of 17 sugar beet breeding lines designated USC944-6-64, USC944-6-68, USC944-6-77, USC944-19-12, USKEMS-19-15, USKEMS-19-17, USKEMS-19-19, USK39-1-61, USK39-1-20, USKEMS-08, USKEMS-09, USKEMS-11, USKEMS-1, USKEMS-12, USC944-6-63, USKEMS-43, USC944-19-08, produced at the USDA–ARS–NWISRL, Kimberly Sugar beet Research Project, ID (Supplemental Table 1) in addition to the commercial sugar beet cultivar Kawimera were evaluated for yield and quality under high temperature and deficit irrigation conditions.

2.2 | Field experiments and deficit irrigation treatments

All field experiments were carried out at Assiut University Experimental Farm (27°03′ N, 31°01′ 70 m asl). In the first growing season (2016–2017), plants were evaluated under the high temperature conditions prevailing in southern Egypt. Plants were sown on 15 Sept. 2016 and harvested on 2–3 Apr. 2017. Seeds from each of the 18 genotypes were hand sown at 15- to 20-cm spaces in a 10.50-m² plot consisting of five rows of 3-m length, with a distance of 70 cm between rows.

In the second growing season (2017–2018), the best six performing genotypes (USC944-6-68, USKEMS-08, USKEMS-09, USKEMS-12, USKEMS-19-17, USKEMS-19-19), in addition to breeding line USKPS25 and the commercial cultivar Kawimera, were evaluated for yield and quality under deficit irrigation and high temperature conditions. Planting and experimental units were the same as in the previous growing season. Plants were sown on 17 Sept. 2018 and harvested on 1 Apr. 2018.

In the third growing season (2018–2019), the same eight genotypes of the 2017–2018 season were re-evaluated for the same yield and quality traits under deficit irrigation conditions using gated-pipe irrigation system as an improved system for irrigation. Each experimental unit consists of six 70-cm spaced rows of 2.5 m in length with an area of 10.50 m². Sowing was performed at 10-cm spaces between plants.

Irrigation was applied based on measuring the soil field capacity using the undisturbed method essentially described by Ali (2010). Optimum irrigation was applied when the soil moisture reached 40% of the field capacity, meanwhile the deficit irrigation experiments were irrigated when the soil moisture reached about 26% of the soil field capacity (65% of the optimum-irrigated experiments).

2.3 | Phenotypic evaluation

At harvest, root yield was determined using roots from the three guarded rows of each plot, and a sample of ∼5 kg of roots were collected for quality analysis at the Egyptian Sugar and Integrated Industries Company (ESIIC) in Abu Qurqas sugar factory lab. Pol% (sucrose content), Na%, K%, α-amino N, and quality index (QZ) were measured. Theoretical sugar recovery % (RS%) and sugar loss % (SL%) were calculated according to Reinefield, Merich, Baumgarten, Winner, and Besis (1974) as follow:

$$\text{Sugar recovery}\% = \text{Pol} - 0.29 - 0.343 \, (\text{K} + \text{Na})$$

$$-0.094 \, (\alpha - \text{amino N})$$

$$\text{Sugar loss}\% = 0.343 \, (\text{K} + \text{Na}) + 0.094 \, (\alpha - \text{amino N}) + 0.29$$

Recoverable sugar yield (RSY) and sugar losses yield (SLY) in tons per acre were calculated.

Stress tolerance indices were calculated using the following formulas according to Fernandez (1992), Hossain et al. (1990), Fischer & Maurer (1978), and Bouslama & Schapaugh (1984):

$$\text{Stress tolerance index (STI)} = \frac{y_p + y_s}{\bar{y}_p^2}$$

$$\text{Stress tolerance (TOL)} = y_p - y_s$$

$$\text{Stress susceptibility index (SSI)} = \frac{1 - \left(y_p/y_s\right)}{1 - \left(\bar{y}_s/\bar{y}_p\right)}$$

$$\text{Yield stability index (YSI)} = \frac{y_s}{y_p}$$

where y_p is average of a genotype under optimum irrigation conditions, y_s is mean of the same genotype under deficit irrigation conditions, and $\bar{y}_s$ and $\bar{y}_p$ are the average yields of all genotypes in deficit irrigation and optimum-irrigated environments, respectively.

2.4 | Experimental design and statistical analysis

In the first growing season, the experiment was laid out in a six-replicates randomized complete block design (RCBD). In the second and third growing seasons, a four-replicates RCBD arranged in a split-plot design was implemented in designing the experiments. Irrigation treatments were assigned to the main plots and sugar beet genotypes to the sub-plots. The Proc Mixed of SAS package version 9.2 was implemented to perform analysis of variance (ANOVA), Fisher's least significant difference (LSD), linear regression and Pearson correlation coefficients (R) among measured traits and stress tolerance indices.

3 | RESULTS

3.1 | Phenotypic evaluation

All measured and calculated phenotypic traits showed significant differences among evaluated genotypes (Supplemental Table 1). Analysis of variance also exhibited highly significant differences between optimum irrigated and deficit irrigation treatments in all studied phenotypic traits, except Na and K concentrations,

under both irrigation systems (Supplemental Table 2). Except for impurity traits, the ANOVA revealed highly significant genotype × environment interaction. Root and recoverable sugar yields, impurities concentrations, and sugar losses yield were significantly decreased in response to deficit irrigation (Tables 1, 2; Figure 1). Meanwhile, Pol%, quality index, and theoretical sugar recovery percentage (RS%) were increased under deficit irrigation conditions compared to the optimum-irrigated treatment (Tables 1, 2).

Pearson correlation coefficients (R) among the studied traits under both the optimum- and the deficit-irrigation conditions were calculated (Table 3). Root yield exhibited highly significant positive correlations with recoverable sugar yield (RSY) and sugar losses yield (SLY). Sucrose content showed highly significant positive correlations with theoretical sugar recovery % and the quality index. As expected, highly significant positive correlations between impurity traits (Na%, K%, and α-amino N) and sugar loss (SL) were observed. Meanwhile, the correlations between impurity traits and SL% with quality index were highly significantly negative. Results showed that correlation between theoretical sugar recovery % (RS) and quality index is highly significantly positive (Supplemental Table 2).

3.2 | Effect of deficit irrigation and genotypes on root yield

Root yield exhibited highly significant differences between genotypes, environments, and the interaction as well (Table 2). In general, root yield in the third growing season was significantly higher than the first growing season under either optimum- or deficit-irrigation conditions. Root yield was significantly reduced in response to deficit irrigation by 24.54 and 6.73% in the second and third growing seasons, respectively (Tables 1, 2). Although, the commercial cultivar Kawimera produced the highest root yield under either optimum- or deficit-irrigation conditions in both growing seasons. The breeding line USKPS25 significantly surpassed the other five breeding lines in the second season under both irrigation levels and produced a root yield that did not differ significantly from Kawimera (Tables 1, 2).

3.3 | Effect of deficit irrigation and genotypes on quality parameters (Pol% and QZ)

Sucrose content and QZ were highly significantly affected by genotypes, irrigation levels, and their interaction. Sucrose content was higher in the third growing season

under optimum- and deficit-irrigation conditions. Sucrose content and QZ were significantly increased in response to deficit irrigation by 0.25 and 1.5%, and 0.44 and 1.5% in the second and third growing seasons, respectively (Table 1). In the second season, genotypes USKPS25 and Kawimera produced the highest Pol% and QZ under optimum-irrigation conditions, whereas the superiority in Pol% and QZ was scored for USKPS25 under deficit-irrigation conditions. In the third growing season, both USKPS25 and Kawimera yielded the highest values of Pol% and QZ under either optimum- or deficit-irrigation conditions (Table 2).

3.4 | Effect of deficit irrigation and genotypes on impurities (Na%, K%, and α-amino N)

Deficit irrigation led to a significant reduction in the roots content of α-amino-N in both growing seasons (Supplemental Table 2). Sodium content, K%, and α-amino N differed significantly among genotypes. Genotypes USKPS25 and Kawimera produced the lowest values of Na%, K%, and α-amino N in the second growing season under both optimum- and deficit-irrigation conditions (Table 1). However, in the third growing season, only the commercial cultivar Kawimera produced the lowest values of impurity traits under both optimum- and deficit-irrigation conditions (Table 2).

3.5 | Effect of deficit irrigation and genotypes on sugar recovery

Sugar recovery (RS%) was significantly increased in response to deficit irrigation under both growing seasons as tested by ANOVA, however, RS% did not differ significantly between growing seasons (Supplemental Table 2). The highest values of RS% were produced by the genotypes USKPS25 and Kawimera (17.80 and 17.87%, and 18.65 and 17.74% under both optimum-irrigated and deficit irrigation conditions, in the second growing season, respectively, and 16.55 and 16.44%, and 17.93 and 18.24% under optimum-irrigated and deficit irrigation conditions, in the third growing season, respectively (Tables 1, 2).

3.6 | Effect of deficit irrigation and genotypes on recoverable sugar yield

Recoverable sugar yield (RSY) exhibited highly significant differences between genotypes, environments, and the interaction as well (Supplemental Table 2). Deficit irrigation treatment has significantly reduced RSY in both

TABLE 1 Yield and quality traits of eight sugar beet genotypes under optimum irrigation and deficit irrigation conditions in the second growing seasons (2017–2018)

		Pol[a]	K	Na	α-amino N	QZ	RS	S	RY	RSY	LSY
					%					1,000 kg ha⁻¹	
Optimum irrigation	USC944-6-68	17.91 ± 0.48	4.33 ± 0.94	1.86 ± 0.44	3.76 ± 1.19	84.55 ± 2.16	16.42 ± 0.78	2.16 ± 0.39	70.78 ± 2.54	11.58 ± 0.24	1.55 ± 0.16
	USKI9-17	16.71 ± 0.82	4.07 ± 0.75	1.08 ± 0.17	3.55 ± 0.91	85.60 ± 2.53	15.55 ± 1.04	1.79 ± 0.33	75.00 ± 2.58	11.68 ± 0.51	1.33 ± 0.09
	USKI9-19	16.77 ± 1.31	4.24 ± 0.50	1.17 ± 0.20	3.13 ± 1.04	85.33 ± 2.70	15.48 ± 1.36	1.84 ± 0.29	55.30 ± 5.27	8.45 ± 0.58	1.05 ± 0.16
	USKEM08	18.23 ± 0.23	3.61 ± 0.23	1.00 ± 0.20	4.27 ± 1.53	87.53±1.05	17.33 ± 0.40	1.67 ± 0.18	64.08 ± 2.93	11.10 ± 0.56	1.08 ± 0.07
	USKEM09	17.55 ± 1.07	4.24 ± 1.29	1.14 ± 0.55	3.19 ± 1.71	85.88 ± 5.51	16.28 ± 1.56	1.83 ± 0.77	50.00 ± 3.34	8.13 ± 0.64	0.90 ± 0.16
	USKEMS12	18.62 ± 1.09	4.86 ± 0.96	1.49 ± 0.68	4.07 ± 0.84	84.95 ± 3.84	17.60 ± 1.63	2.25 ± 0.54	36.58 ± 2.06	6.40 ± 0.29	0.83 ± 0.12
	USKPS25	19.16 ± 0.62	3.87 ± 0.88	1.45 ± 0.33	1.95 ± 0.26	88.03 ± 1.56	17.80 ± 0.78	1.70 ± 0.26	72.20 ± 1.55	12.85 ± 0.31	1.23 ± 0.07
	Kawimera	19.00 ± 0.72	3.59 ± 0.22	1.22 ± 0.16	2.53 ± 0.67	88.55 ± 0.47	17.87 ± 0.72	1.58 ± 0.19	95.78 ± 5.64	17.10 ± 0.99	1.53 ± 0.12
Deficit irrigation	USC944-6-68	18.02 ± 0.55	3.95 ± 0.70	1.54 ± 0.36	2.13 ± 0.17	86.83 ± 2.01	16.61 ± 0.78	1.77 ± 0.32	55.00 ± 2.97	9.15 ± 0.54	0.98 ± 0.10
	USKI9-17	17.14 ± 0.64	3.82 ± 0.32	1.04 ± 0.22	2.08 ± 0.56	87.40 ± 1.15	15.95 ± 0.61	1.55 ± 0.15	44.38 ± 4.00	7.05 ± 0.58	0.68 ± 0.05
	USKI9-19	17.27 ± 0.58	3.85 ± 0.22	1.20 ± 0.25	2.55 ± 1.11	86.85 ± 1.21	16.05 ± 0.65	1.66 ± 0.17	39.70 ± 1.65	6.38 ± 0.33	0.65 ± 0.05
	USKEM08	18.66 ± 0.43	3.50 ± 0.26	1.04 ± 0.08	2.36 ± 0.70	87.93 ± 0.97	17.61 ± 0.51	1.47 ± 0.13	45.00 ± 2.53	7.90 ± 0.41	0.68 ± 0.06
	USKEM09	17.39 ± 0.55	4.08 ± 0.22	1.37 ± 0.25	2.03 ± 0.62	86.43 ± 1.39	15.99 ± 0.59	1.75 ± 0.17	45.78 ± 2.19	7.30 ± 0.26	0.80 ± 0.07
	USKEMS12	18.98 ± 0.60	3.78 ± 0.26	1.49 ± 0.27	2.97 ± 0.84	87.68 ± 0.94	18.03 ± 0.61	1.78 ± 0.11	27.83 ± 0.63	5.03 ± 0.14	0.50 ± 0.02
	USKPS25	19.80 ± 0.47	3.79 ± 0.17	0.94 ± 0.17	2.05 ± 0.42	89.95 ± 0.61	18.65 ± 0.56	1.50 ± 0.08	60.78 ± 2.14	11.35 ± 0.48	0.93 ± 0.04
	Kawimera	18.90 ± 1.53	3.78 ± 0.29	0.92 ± 0.06	1.85 ± 0.43	88.95 ± 1.30	17.74 ± 1.52	1.47 ± 0.10	73.75 ± 3.94	13.18 ± 1.06	1.08 ± 0.03
	LSD$_{0.05}$	0.71	0.52	0.28	0.89	1.850	0.82	0.27	6.90	1.26	0.19

[a] Pol, sucrose content; QZ, quality index; RS, recoverable sugar; SL, Sugar losses; RY, root yield; RSY, recoverable sugar yield; SLY, loss sugar yield.

TABLE 2 Yield and quality traits of eight sugar beet genotypes under optimum irrigation and deficit irrigation conditions in the second growing seasons (2018–2019)

		Pol[a]	K	Na	α-amino N	QZ	RS	SL	RY	RSY	LSY
					%				1,000 kg ha^{-1}		
Optimum irrigation	USC944-6-68	18.63 ± 1.06	4.50 ± 0.85	1.57 ± 0.74	3.37 ± 0.96	85.40 ± 3.62	15.94 ± 1.54	2.69 ± 0.51	83.40 ± 1.68	13.33 ± 0.69	2.23 ± 0.14
	USK19-17	18.24 ± 0.29	4.75 ± 0.77	1.45 ± 0.27	3.44 ± 0.58	85.50 ± 0.85	15.50 ± 0.32	2.74 ± 0.36	66.58 ± 2.13	10.33 ± 0.41	1.83 ± 0.08
	USKI19-19	17.69 ± 0.35	4.53 ± 0.82	1.18 ± 0.29	3.75 ± 0.44	84.53 ± 1.38	14.98 ± 0.61	2.70 ± 0.37	62.23 ± 1.99	9.35 ± 0.44	1.68 ± 0.05
	USKEM08	18.35 ± 1.37	4.39 ± 0.48	1.31 ± 0.10	2.97 ± 1.28	86.13 ± 1.39	15.83 ± 1.41	2.52 ± 0.11	61.63 ± 3.36	9.68 ± 0.20	1.55 ± 0.09
	USKEM09	18.89 ± 1.80	4.48 ± 0.54	1.37 ± 0.24	2.28 ± 1.20	86.78 ± 0.60	17.88 ± 1.70	2.51 ± 0.11	55.75 ± 2.02	9.93 ± 0.33	1.40 ± 0.04
	USKEMS12	18.39 ± 1.24	4.29 ± 0.63	1.44 ± 0.14	3.51 ± 0.60	85.43 ± 1.79	15.80 ± 1.39	2.58 ± 0.24	62.53 ± 2.77	9.93 ± 0.69	1.60 ± 0.08
	USKPS25	19.65 ± 0.33	4.24 ± 0.22	2.21 ± 0.88	2.67 ± 0.70	87.85 ± 1.40	16.55 ± 0.39	3.10 ± 0.31	92.88 ± 3.32	15.38 ± 0.64	2.90 ± 0.15
	Kawimera	19.82 ± 0.25	4.20 ± 0.49	1.19 ± 0.26	2.50 ± 0.74	87.13 ± 0.40	16.44 ± 0.17	2.37 ± 0.12	99.73 ± 2.84	16.40 ± 0.51	2.38 ± 0.08
Deficit irrigation	USC944-6-68	19.75 ± 0.96	4.33 ± 0.47	1.78 ± 0.40	2.43 ± 1.02	86.75 ± 1.33	17.14 ± 1.00	2.61 ± 0.20	82.65 ± 2.39	14.20 ± 0.71	2.15 ± 0.08
	USK19-17	19.19 ± 1.14	4.28 ± 0.58	1.19 ± 0.07	3.51 ± 1.01	87.18 ± 1.35	16.70 ± 1.25	2.49 ± 0.17	61.13 ± 2.79	10.25 ± 0.67	1.53 ± 0.04
	USKI19-19	18.33 ± 0.99	4.09 ± 0.31	1.33 ± 0.40	2.56 ± 0.79	86.95 ± 0.84	15.94 ± 0.89	2.39 ± 0.19	61.23 ± 3.43	9.73 ± 0.46	1.45 ± 0.04
	USKEM08	17.55 ± 0.28	4.26 ± 0.10	1.34 ± 0.32	3.11 ± 0.93	85.75 ± 0.90	15.05 ± 0.38	2.50 ± 0.13	57.38 ± 1.99	8.63 ± 0.31	1.43 ± 0.07
	USKEM09	17.60 ± 0.25	4.35 ± 0.45	1.16 ± 0.35	2.93 ± 1.27	86.68 ± 1.20	15.15 ± 0.39	2.45 ± 0.24	54.60 ± 1.46	8.28 ± 0.24	1.33 ± 0.05
	USKEMS12	19.77 ± 1.10	4.55 ± 0.65	1.25 ± 0.19	1.77 ± 0.50	88.23 ± 0.96	17.62 ± 1.04	2.45 ± 0.21	53.88 ± 3.29	9.88 ± 0.66	1.33 ± 0.11
	USKPS25	19.98 ± 1.31	4.18 ± 0.36	1.17 ± 0.05	2.44 ± 0.51	88.78 ± 0.98	17.93 ± 1.32	2.35 ± 0.10	85.23 ± 3.83	15.00 ± 0.90	2.00 ± 0.11
	Kawimera	20.47 ± 0.54	3.77 ± 0.11	1.24 ± 0.19	2.36 ± 0.34	89.00 ± 0.50	18.24 ± 0.53	2.23 ± 0.06	89.28 ± 3.43	16.28 ± 0.64	1.98 ± 0.07
LSD$_{0.05}$		0.95	0.44	0.36	0.79	1.31	1.00	0.22	6.51	1.29	0.21

[a] Pol, sucrose content; QZ, quality index; RS, recoverable sugar; SL, Sugar losses; RY, root yield; RSY, recoverable sugar yield; SLY, loss sugar yield.
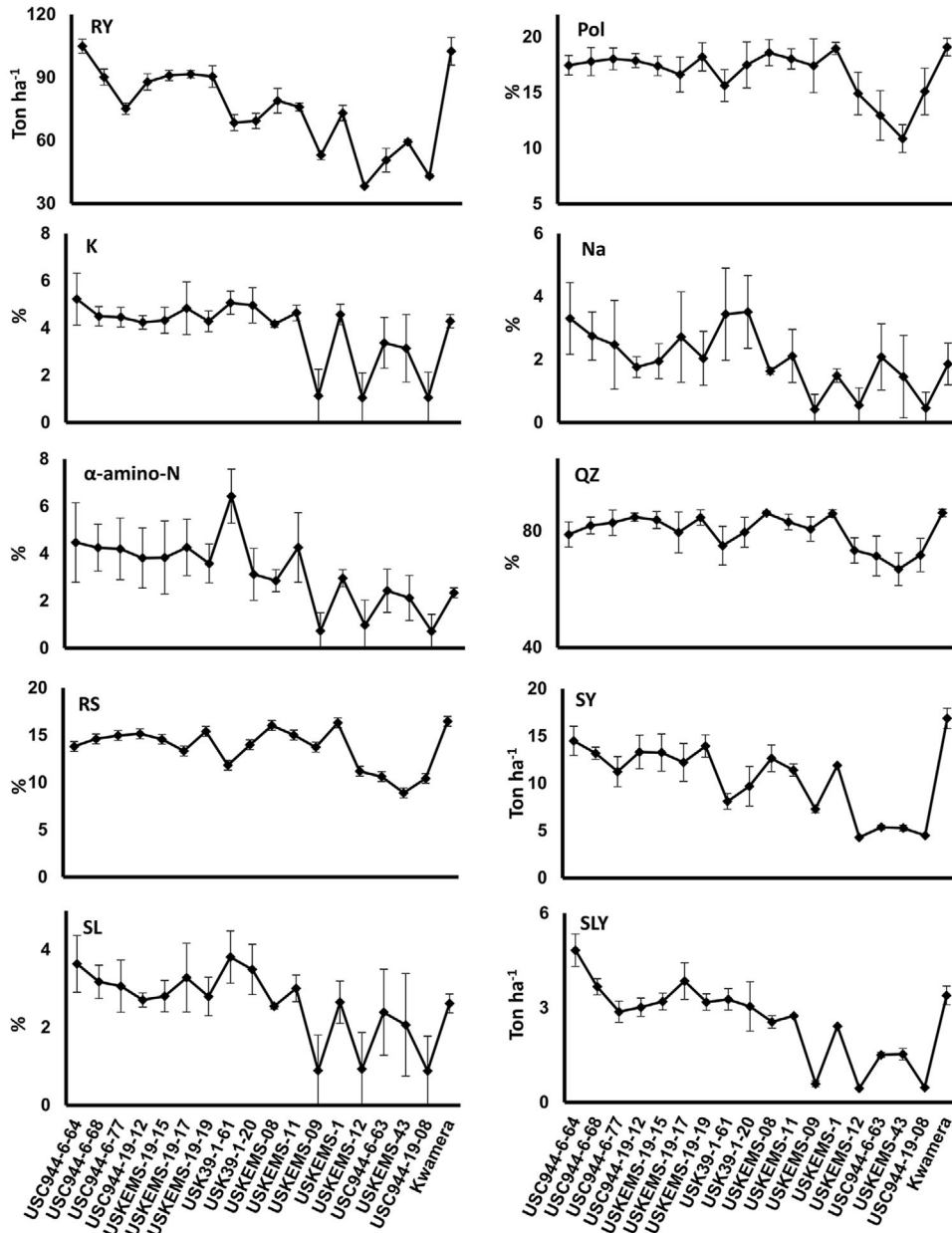
FIGURE 1 Evaluation of 18 sugar beet breeding lines and a commercial cultivar (Kawimera) for yield performance and quality traits under high temperatures. RY, root yield; Pol, sucrose content; QZ, quality index; RS, recoverable sugar; SL, sugar losses; RSY, recoverable sugar yield; SLY, loss sugar yield

growing seasons. Genotypes USKPS25 and Kawimera produced the highest RSY in both growing seasons under both optimum- and deficit-irrigation conditions (Tables 1, 2).

3.7 | Effect of deficit irrigation and genotypes on sugar loss

Sugar loss yield were significantly reduced under deficit irrigation conditions in both growing seasons (Supplemental Table 2). Genotypes USKPS25 and Kawimera produced the lowest SL% in both growing seasons under both

optimum- and deficit-irrigation conditions, however, both genotypes produced the highest sugar loss yields because of their high root yields (Tables 1, 2). Sugar loss (%) and sugar loss yield differed significantly between growing seasons (Supplemental Table 2).

3.8 | Root and sugar yields correlation to stress tolerance indices

Stress tolerance indices were calculated based on root and sugar yields of genotypes over the two growing seasons (Table 4). Results showed that the greater the stress

TABLE 3 Pearson correlation coefficient (R) calculated between studied traits under deficit irrigation conditions over the two growing seasons 2017–2018 and 2018–2019

	RY[a]	Pol	K	Na	α-amino-N	QZ	RS	SL	RSY
Pol	.183								
K	−.104	−.183							
Na	.133	−.023	.460*						
α-amino-N	−.089	−.445*	.328*	.103					
QZ	.105	.650*	−.732**	−.558**	−.673**				
RS	.171	.983**	−.335*	−.170	−.465*	.756**			
RSY	.973**	.395	−.181	.072	−.196	.281	.389*		
SL	−.029	−.257	.874**	.735**	.558**	−.879**	−.414*	−.134	
LSY	.893**	.092	.274	.471*	.099	−.252	.007	.829**	.396*

*Significant at the .05 probability level;
**Significant at the .01 probability level.
[a] RY, root yield; Pol, sucrose content; QZ, quality index; RS, recoverable sugar; SL, Sugar losses; RY, root yield; RSY, recoverable sugar yield; SLY, loss sugar yield.

TABLE 4 Drought stress indices for root and recoverable sugar yields of eight sugar beet genotypes over the two growing seasons

	Root yield stress indices						Recoverable sugar yield stress indices					
	RYp[a]	RYs	STI	TOL	SSI	YSI	SYp	SYs	STI	TOL	SSI	YSI
USC944-6-68	30.84	27.53	1.11	3.31	1.11	0.88	30.84	27.53	1.11	3.31	1.11	0.88
USK19-17	28.31	21.10	0.78	7.22	3.06	0.75	28.31	21.10	0.78	7.22	3.06	0.75
USK19-19	23.51	20.18	0.62	3.33	1.48	0.85	23.51	20.18	0.62	3.33	1.48	0.85
USKEM08	25.14	20.48	0.67	4.66	2.38	0.82	25.14	20.48	0.67	4.66	2.38	0.82
USKEM09	21.15	20.08	0.56	1.07	0.69	0.95	21.15	20.08	0.56	1.07	0.69	0.95
USKEMS12	19.82	16.34	0.44	3.48	3.22	0.81	19.82	16.34	0.44	3.48	3.22	0.81
USKPS25	33.01	29.20	1.26	3.81	1.99	0.88	33.01	29.20	1.26	3.81	1.99	0.88
Kawimera	39.10	32.60	1.67	6.50	2.65	0.83	39.10	32.60	1.67	6.50	2.65	0.83

[a] RYp, root under optimum irrigation; RYs, root under deficit irrigation; STI, stress tolerance index; TOL, stress tolerance; SSI, stress susceptibility index; YSI, yield stability index; SYp, sugar under optimum irrigation; Sys, sugar under deficit irrigation.

tolerance (TOL) value, the greater the reduction in root and sugar yields (RY and SY, respectively) under stress conditions, and the higher the sensitivity of a genotype to deficit irrigation (Table 4). Pearson correlation analysis between stress tolerance indexes and average values of genotypes root and sugar yields under deficit- irrigation (RYs and SYs) and optimum-irrigation (RYp and SYp) conditions exhibited significant correlations between TOL and stress susceptibility index (SSI), and yield stability index (YSI) for RY and SY (Tables 5, 6). The positive significant correlations between TOL and optimum-irrigated yields (Yp) and the negative correlations between TOL and yields under deficit irrigation conditions (Ys; Tables 5, 6) suggest that using TOL as a selection index will result in yield reduction under optimum-irrigated conditions. The results revealed that there was a positive significant correlation among Yp and stress tolerance index (STI), and Ys and STI for root sugar yields, suggesting that STI is a better predictor of Yp and Ys than TOL, SSI, and YSI. The general linear model regression of root and sugar

yields under deficit irrigation conditions on STI revealed a positive correlation between these criteria with a similar coefficient of determination (R^2 = .97 and .98, respectively; Figure 2).

4 | DISCUSSION

The present study was carried out to evaluate the performance and yielding ability of sugar beet genotypes for irrigation deficiency under heat stress conditions in Upper Egypt. In the light of steady population growth, diminishing sugarcane cultivated area, and irrigation shortage, increasing sugar beet cultivated area is the only possible solution to overcome the gap between sugar production and consumption in Egypt (Abou-Elwafa, 2011). This necessitates the establishment of a national sugar beet breeding program to select for high yielding genotypes that are tolerant to deficit irrigation and high temperatures. Furthermore, drought stress is frequently

TABLE 5 Pearson correlation coefficient (R) between drought stress indices and average root yield over the two growing seasons

		RYp[a]	RYs	STI	TOL	SSI
Season 2	RYs	.897**				
Season 3		.977**				
Season 2	STI	.953**	.968**			
Season 3		.996**	.990**			
Season 2	TOL	.659*	−.234	.436*		
Season 3		.531*	−.014	.460*		
Season 2	SSI	.213	.259	−.035	.865**	
Season 3		.225	.337	.140	.930**	
Season 2	YSI	−.217	.230	.030	−.865**	−.999**
Season 3		−.187	.023	−.101	−.913**	−.998**

*Significant at the .05 probability level;
**Significant at the .01 probability level.
[a]RYp, root under optimum irrigation; RYs, root under deficit irrigation; STI, stress tolerance index; TOL, stress tolerance; SSI, stress susceptibility index; YSI, yield stability index.

TABLE 6 Pearson correlation coefficient (R) between drought stress indices and average recoverable sugar yield over the two growing seasons

		SYp[a]	Sys	STI	TOL	SSI
Season 2	SYs	.924**				
Season 3		.970**				
Season 2	STI	.965**	.975**			
Season 3		.995**	.987**			
Season 2	TOL	.629*	−.284	.438**		
Season 3		.457*	−.285	−.345		
Season 2	SSI	.132	−.254	−.089	.845**	
Season 3		−.294	−.516	−.382	.992**	
Season 2	YSI	−.152	.234	.068	−.855**	−.999**
Season 3		.295	.517	.382	−.992**	−.999**

*Significant at the .05 probability level;
**Significant at the .01 probability level.
[a]SYp, sugar under optimum irrigation; Sys, sugar under deficit irrigation; STI, stress tolerance index; TOL, stress tolerance; SSI, stress susceptibility index; YSI, yield stability index.

FIGURE 2 Relationship between deficit irrigation average root and sugar yields (ton ha^{-1}) and stress tolerance index (STI)

associated with heat stress in field conditions, which makes the development of sugar beet lines responding to combined drought and heat stress necessary.

In that context, a panel of 18 sugar beet breeding lines produced at the USDA–ARS–NWISRL, in Kimberly, ID, in addition to the commercial sugar beet cultivar Kawimera, one of the most widely cultivated sugar beet cultivars in Upper Egypt, were preliminarily evaluated for performance and yielding ability under high temperature conditions in the first growing season. Out of those 18 breeding lines, six lines exhibited superiority in yield and quality traits under high temperatures in addition to the promising line USKPS25 and the commercial cultivar
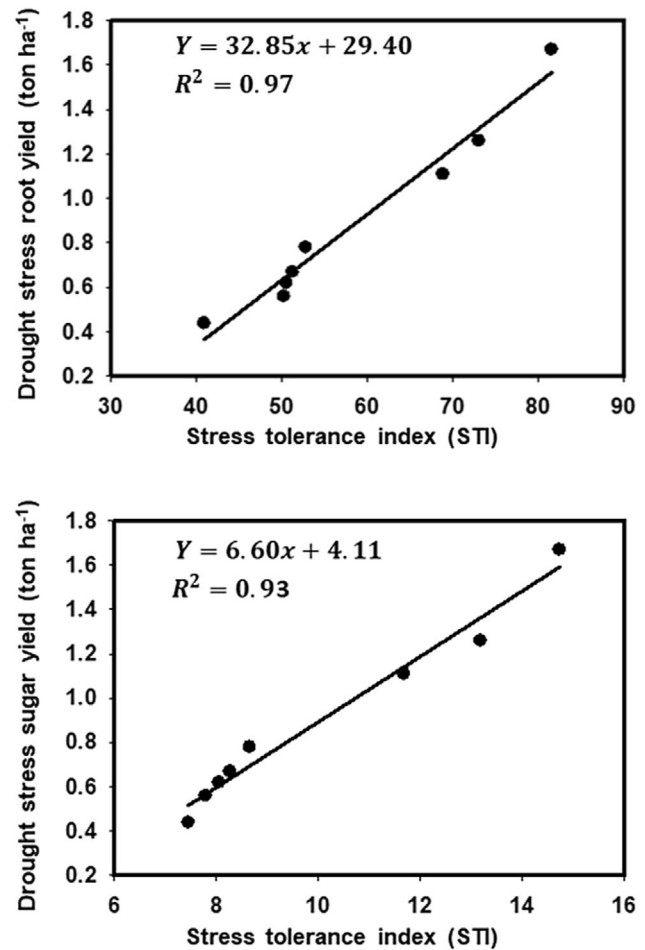
Kawimera which were evaluated for irrigation deficiency for two successive growing seasons. The irrigation deficiency treatment was irrigated when the soil moisture reached about 26% of the soil field capacity, which was equivalent to 65% of the field capacity at optimum irrigation (40%).

Evaluated traits reacted differently to deficit irrigation, signifying the adverse effect of deficit irrigation stress on sugar beet. All evaluated genotypes performed differently under deficit irrigation stress conditions indicating genetic variability in the sugar beet panel of breeding lines with respect to drought stress tolerance. The high yield performance of all evaluated genotypes observed in the third growing season under both optimum- and deficit-irrigation conditions could be in due to (a) sowing at high planting density in that growing season compared to the two previous seasons (10 vs. 15- to 20-cm spaces between plants), and (b) the enhanced accumulation of dry matter in roots caused by increasing temperature and high solar radiation during this growing season (Figure 3; Kenter, Hoffmann, & Märländer, 2006). The
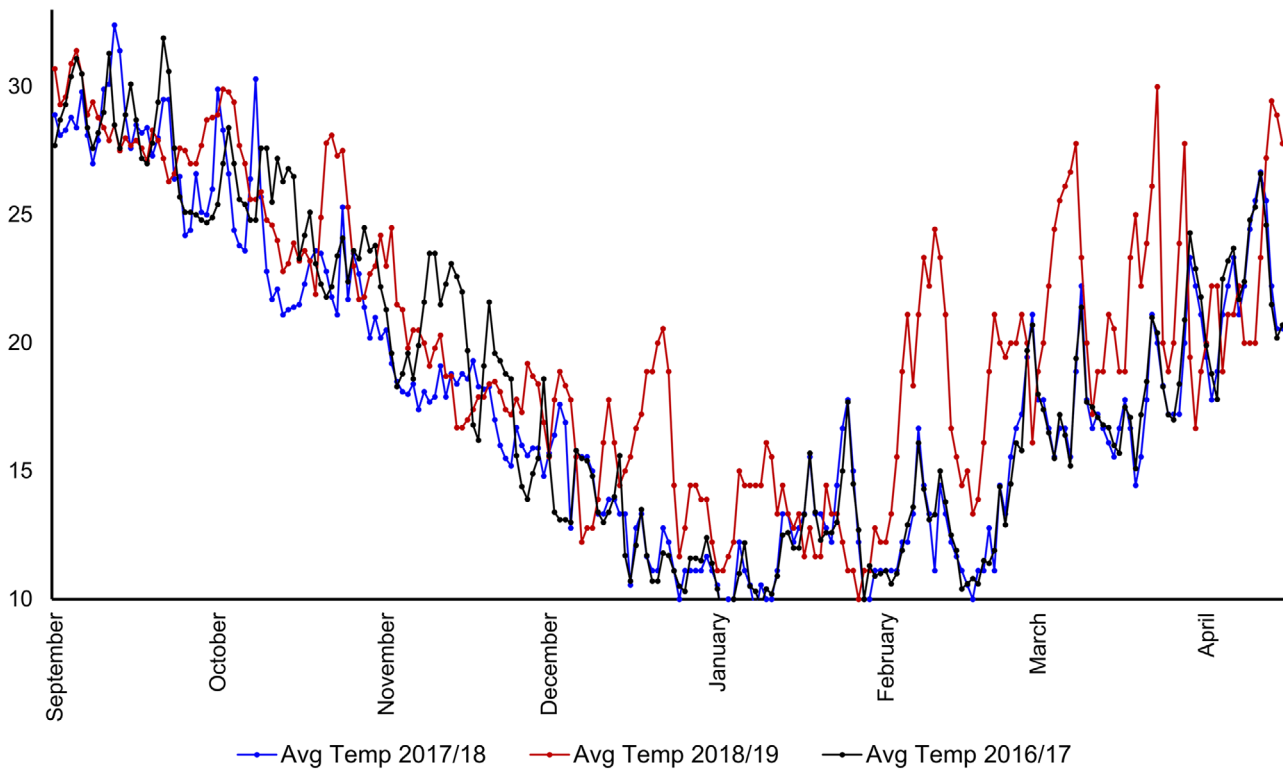
FIGURE 3 Average day and night temperatures in the field from 1 September to 15 April during the 2016–2017, 2017–2018, and 2018–2019 growing seasons

results show considerable genetic variations in quality traits; however, the effect of environmental conditions is obvious especially for Na, K, and α-amino-N contents, which have been reported (Bosemark, 1993). Unlike the significant reductions in α-amino-N content, deficit irrigation has only small, inconsistent effects on Na and K concentrations. This is probably due to the various counteracting effects of deficit irrigation on ion uptake (Last, Draycott, Messem, & Webb, 2009; Winter, 1990).

Four drought stress indices—TOL, STI, SSI, and YSI—were used to identify high yielding genotypes under stressed and non-stressed environments. Since correlations between stress tolerance indices for all studied traits are similar, only the correlations for root and recoverable sugar yields were presented and discussed. The STI was the only stress index that has positive correlations with average root and recoverable sugar yields under both optimum irrigated and deficit irrigation conditions. The significant positive correlations found between STI, and average yields under stressed conditions (Ys) and average yields under non-stressed conditions (Yp) in the two growing seasons indicate that STI is the best stress index that can be used to predict for average productivity compared to other stress indices (SSI, TOL, and YSI). Therefore, the selection of genotypes of high yielding performance based on SSI, TOL, or YSI stress indices may not result in vari-

eties that are productive in unlike environments. Besides, the linear relationship between STI and average root and recoverable sugar yields (Figure 2), indicating that STI could be implemented in identifying high yielding genotypes under both optimum irrigated and deficit irrigation conditions. However, when other stress indices (TOL, SSI, and YSI) were plotted against average sugar yield (Supplemental Figure 1), no linear relationship was observed in all cases, implying that neither TOL, nor SSI and YSI could be implemented to identify high yielding drought-tolerant genotypes under unlike environments. Similar results were obtained by Fernandez (1992) in mung bean (*Vigna radiata*), in sugar beet by Sadeghian, Fazl, Mohammadian, Taleghani, and Mesbah (2000), and in wheat by Talebi, Fayaz, and Naji (2009).

Deficit-irrigation-tolerance breeding program should focus on the selection of genotypes with high root and sugar yield in unlike environments. Therefore, because of their high yield performance under optimum-irrigated and drought-stressed conditions and their high STI values, USKPS25 and USC944-6-68 breeding lines (scored the highest root and sugar yields after the commercial cultivar) seem to be more adapted to deficit irrigation and high temperature conditions. This emphasizes the advantage of implementing STI as a criterion to select high yielding performance and stress-tolerant genotypes. Therefore,

it is intended to implement these particular breeding lines USKPS25 and USC944-6-68 in any sugar beet breeding or crossing activities.

In conclusion, a preliminary evaluation of 18 sugar beet breeding lines produced at the USDA–ARS–NWISRL in Kimberly, ID identified six high yielding lines under high temperature conditions. Evaluation of those six lines in addition to a promising breeding line for deficit-irrigation stress tolerance revealed the superiority of two lines, that is, USKPS25 and USC944-6-68, in yield and quality under optimum- and deficit-irrigation conditions. Besides, the two lines exhibited high STI values, thus seem to be better adapted to deficit irrigation and high temperature conditions and should therefore be implemented in any sugar beet breeding programs.

CONFLICTS OF INTEREST
The authors report no conflicts of interest.

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