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Integrated Application of K and Zn as an Avenue to Promote Sugar Beet Yield, Industrial Sugar Quality, and K-Use Efficiency in a Salty Semi-Arid Agro-Ecosystem

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Abstract: Salinity combined with a deficiency of potassium (K) and zinc (Zn) negatively affect sugar beet yield and quality. A two-year (2017/18–2018/19) field trial was undertaken to investigate the mediating role of soil-applied K [120 (K_{120}) and 180 (K_{180}) kg ha^{-1}] and foliar-applied Zn [0 (Zn_0), 150 (Zn_{150}), and 300 (Zn_{300}) ppm] in alleviating salt-stress (8.60 dS m^{-1}) based on sugar beet morpho-physiological responses, sugar yield and quality, and K-use efficiency in the BTS 301 and Kawemira cultivars. Application of $K_{180} \times Zn_{300}$ was more effective and resulted in 23.39 and 37.78% higher root yield (RY) and pure sugar yield (PSY), respectively, compared to control ($K_{120} \times Zn_0$). It also enhanced sucrose, pure sugar (PS), and purity but decreased impurities (α-amino N, K, and Na), alkalinity index, and sugar loss. However, the $K_{120} \times Zn_{300}$ recorded higher K-use efficiency. PSY correlated positively (r = 0.776 **, 0.629 **, 0.602 **, 0.549 **, and 0.513 **) with RY, root fresh weight (RFW), top yield, PS, and root diameter, respectively. The stepwise and path-coefficient analysis demonstrated that RY, PS, and RFW were the most influential PSY-affected attributes. Integration of K_{180} + Zn_{300} can correct K and Zn deficiencies in the soil and mitigate salt-stress effects via improving sugar beet growth, yield and quality, and K-use efficiency.

Keywords: white sugar; nutrients management; non-sugar impurities; path-coefficient; saline soils

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1. Introduction

Sugar beet, scientifically known as *Beta vulgaris* (L.), is a strategic crop in the sugar industries and commerce terms and is typically grown in warm and Mediterranean climates, supplying 42 million MT (~30%) of pure sugar requirements worldwide [1]. In some countries, some beet cultivars are cultivated not only for the pure sugar industry and animal fodder but also for biofuels (i.e., bioethanol and biomethane) production as a renewable energy source [2]. Sugar beet's requirements of water and various fertilizers are 30–40% lower than that of sugarcane, which makes it the ideal sugar crop for cultivation in diverse environments, especially the dry areas suffering from water scarcity in the world [3]. In Egypt, sugar beet and sugar cane contribute about 70% of the domestic needs of pure sugar, while the remaining part (30%) is imported from other countries. Yearly, sugar beet contributes nearly 59% of total sugar production (2.3 million MT) compared to 41% of sugar cane [4]. Globally, crop production is under direct threat through diverse abiotic stressors, including soil salinity and consecutive droughts that may occur under future climate change scenarios [5]. Soil salinity is described by the presence of excess salts in soil solutions. Globally, there is a large area of agricultural land equal to more than 800 million hectares (i.e., more than 6%) that suffers from salinity, particularly in arid and semi-arid environments, including Egypt [6]. Additionally, salinity resulting from saline

irrigation water has adversely affected nearly 20% of the world's cultivable lands [7], and these areas are expected to reach 50% by 2050 [8]. Egypt is considered an arid region and possesses about 900,000 hectares (about 25%) of irrigated agricultural land that suffers from the occurrence of salinization [9]. High soil salinity causes adverse effects on different plant responses in terms of morpho-physiology and biochemistry, leading to a severe reduction in crop productivities [10,11]. Soil solutions containing Na^+ and Cl^- ions due to high salinity cause osmotic stress, ionic imbalance, nutrient uptake antagonism (especially Na^+ with K^+), and damage to cellular membranes and some organelles by producing reactive oxygen species (ROS) [12–14]. Salinity also disrupts the synthesis of proteins, metabolic enzymes, particularly nitrate reductase [15], and other important cellular macromolecules, thus, it severely impairs photosynthesis and plant growth, resulting in a loss of about 20–50% of crop yields [11]. In arid and semi-arid environments, these negative consequences are exacerbated by drought conditions due to limited fresh irrigation water and high evapotranspiration rates [6]. Sugar beet salt resistance reaches $EC_e = 7$ dS m^{-1} as a critical maximum without a decrease in its economic yield [16,17], which depends on the stage of plant growth and/or the state of salt tolerance of the cultivated genotype [18]. Although high Na^+ ion concentrations have detrimental effects on the growth and survival of some plants [13–15], a low Na^+ concentration may be required for normal sugar beet growth and may replace K^+ in some nonspecific metabolic activities under K^+ deficiency [19,20].

Different strategies (i.e., chemical, physical, and biological) have been adapted to crop plants to beat the soil salinity-induced stress. Among these, exogenously applied potassium (K^+) has been used and is still used by researchers to confer salt stress tolerance in plants [21,22]. Disruption of Na^+/K^+ homeostasis may negatively affect the growth and productivity of higher plants such as sugar beet in conditions of high salinity due to the K^+/Na^+ interaction and is often associated with K^+ deficiency [23,24]. K^+ roles in plants are multifaceted and include water relations, stomatal movement, ionic homeostasis, osmoregulation, cellular membrane polarization, metabolic enzyme activities, protein and carbohydrate metabolism, and many metabolic activities [12,16,22,25]. K^+ also plays a significant role in the biochemical transfer of photosynthates from leaves to taproots, which leads to the promotion of pure sugar production in sugar beet [26]. When saline soils do not contain enough K^+ in addition to high pH and low organic matter, high Na^+ levels impede K^+ uptake through plant roots and induce membrane depolarization to evade K^+ pathways out [27], leading to K^+ starvation in plants. Appropriate K^+ applications under abiotic stress can improve N uptake by activating nitrate reductase and positively affect the uptake and transport of plant nutrients, increasing their concentrations in different plant organs [12,27,28].

Zinc (Zn) is considered a prime micronutrient in crop plants' nutrition, including sugar beet [29]. It acts as a necessary nutrient for plenty of physio-biochemical functions such as biosynthesis and/or a catalyst for several metabolic enzymes, particularly RuBisCO during photosynthesis [30,31]. It also contributes to the regulation of growth (through tryptophan, IAA, and gibberellin biosynthesis), energy production, carbohydrate metabolism, protein synthesis, and sugar storage [32]. Besides, it also adjusts stomatal conductance, maintains root cell membrane integrity, and assists with ionic equilibria in the Phyto-system to avoid osmotic stress induced by stressful conditions, including salinity [33]. Sugar beets are markedly affected by the deficiency of Zn, with a relatively large response to Zn [34]. Still, other researchers reported that soil or foliar applications of Zn significantly increase plant growth, productivity, and sugar quality indices in sugar beets [35,36]. As reported by Finck [37], Zn available at a rate of 10 ppm in the soil is a sufficient level for healthy growth in the sugar beet crop. Additionally, soils are considered Zn-deficient when they contain less than 0.5 mg available Zn kg^{-1} [38]. Thus, the absence or presence of Zn in quantities less or more than the critical level available prohibits plant growth and development, reduces sugar translocation, and decreases taproot and sugar yields [16,39]. Nowadays, Zn deficiency has become a great concern in originally Zn-deficient soils, which have higher salinity or pH level, have free calcium carbonate, and lower organic matter along with

soils that have received excessive quantities of phosphorus [40]. Exogenously applied Zn to crop plants imparts improved tolerance to soil salinity stress by hindering Na^+ and/or Cl^- uptake, and translocation across the plant's root cells [33,41]. In some cases, sugar productivity and technological qualities can decline without showing signs of "latent deficiency" on sugar beets when cultivated in salty soils suffering from Zn deficiency [42]. However, excessive use of Zn can be phytotoxic [43], and sugar beet plants may exhibit signs similar to those observed when exposed to Cd^{2+} or Pb^{2+} [16]. Lucas and Knezek [44] stated that Zn is a much-needed micronutrient for sugar beet, which is classified as a semi-Zn-sensitive crop. Therefore, the use of Zn as a foliar feed for sugar beets grown under the stress of soil salinity has not received adequate attention from researchers in recent years. Relatively little is known about the positive roles of K in integration with Zn, applied to soil and plant leaves, respectively, in mitigating the adverse effects of soil salinity in sugar beets.

Therefore, this study aimed to overpass the knowledge gap in current research by knowing the mediating role of K and Zn in mitigating soil salinity by improving growth, sugar yield, yield quality, and K-use efficiency of two commercial cultivars of sugar beet under a salty semi-arid agro-ecosystem. Our study hypothesized that the integrative application of K + Zn would outperform K or Zn individual application and positively affect the performance of salt-stressed sugar beet plants.

2. Materials and Methods

2.1. Description of the Experimental Site and the Properties of the Tested Soil

Two consecutive field trials were conducted during two winter growing seasons (2017/18 and 2018/19). The trials were implemented using an agricultural site (latitude: 29.17° N and longitude: 30.53° E), Fayoum University, Fayoum (an important governorate in sugar beet cultivation), Egypt. During the trial period (September–March), the experimental area was characterized by a dry and semi-arid climate with an average precipitation of 0.27 mm d^{-1} and a mean standard class "A" pan evaporation of 3.14 mm d^{-1} across both seasons. Additionally, the mean daily and night temperatures were 25.45 and 11.98 °C, respectively, mean relative humidity was 51.02%, and wind speed was 2.70 m s^{-1} across both seasons (Table 1). Based on the aridity scale reported in [45], the experimental area is climatically categorized as a semi-arid. With a soil depth of 0.6 m, samples were collected from the experimental site prior to the start of the experiments and at harvest to determine the physicochemical properties chosen [46,47]. The pre-experimental soil analysis (Table 2) indicated that the experimental soil is categorized as saline [48] with an EC_e of 8.60 dS m^{-1}. Besides, it is classified as a sandy loam (74.43% sand, 11.20% silt, and 11.37% clay), with a pH of 7.86, dry bulk density (1.53 g m^{-3}), and retains available water by 10.01%. The experimental soil is also categorized as sandy, mixed, and hyperthermic-typic torriorthents [49]. The EC of the irrigation water used in our study was 1.63 dS m^{-1}.

Table 1. Averages of some meteorological indices per month during experiment period at El-Fayoum province, Egypt (data pooled over both growing seasons).

Month	Air Temperatures (°C)		RH (%)	Wind Speed (m s^{-1})	Precipitation (mm d^{-1})	E_P (mm d^{-1})
	Day	Night				
September	35.40	20.45	42.70	3.55	0.00	5.50
October	30.65	17.05	46.90	3.10	0.10	4.50
November	25.05	12.55	56.65	2.35	1.30	2.30
December	20.45	9.10	63.35	2.25	0.14	1.51
January	18.65	5.80	56.40	2.55	0.19	1.50
February	21.75	8.50	49.85	2.25	0.13	2.70
March	26.20	10.40	41.30	2.85	0.07	4.00

RH is an average of maximum and minimum of air relative humidity and E_P is the measured evaporation from standard Class-A pan evaporimeter.

Table 2. Some properties of irrigation water and tested soil (0.0–60 cm depth) before planting and at harvest (data pooled over both growing seasons).

Characteristic	Unite	Soil (Before Sowing)	Soil (At Harvest)	Irrigation Water
Particle size analysis:				
Sand	(%)	77.43	77.37	—
Silt		11.20	11.23	—
Clay		11.37	11.40	—
Soil textural class	—-	Sandy loam	Sandy loam	—
Dry bulk density	($g\ cm^{-3}$)	1.53	1.55	—
Hydraulic conductivity	($cm^3\ h^{-1}$)	1.97	1.98	—
Soil moisture content at:				
Field capacity	(%)	22.26	22.34	—
Wilting point		12.25	12.28	—
Available water		10.01	10.05	—
pH *		7.86	7.94	7.46
EC_e **	($dS\ m^{-1}$)	8.60	8.65	1.63
$CaCO_3$	(%)	7.89	7.87	—
Organic matter		0.95	0.94	—
Soluble cations **:				
Ca^{2+}	$mmol_c\ L^{-1}$	21.82	21.98	2.80
Mg^{2+}		15.74	15.67	2.00
Na^{+}		67.60	67.71	8.10
K^{+}		5.59	5.62	0.22
Soluble anions **:				
CO_3^{2-}	$mmol_c\ L^{-1}$	Nil	Nil	Nil
HCO_3^{-}		9.41	9.38	2.00
Cl^{-}		78.29	78.40	10.20
SO_4^{2-}		23.05	23.15	0.92
Available nutrients:				
Nitrogen (N)	$mg\ kg^{-1}$ soil	0.041	0.040	—
Phosphorus (P)		3.54	3.61	—
Potassium (K)		39.12	39.27	—
Zinc (Zn)		1.55	1.52	—
Manganese (Mn)		4.90	4.84	—
Iron (Fe)		0.70	0.67	—
Boron (B)		0.32	0.30	—

* Suspension of soil:H_2O 1:1 (w/v) and ** soil paste extract 1:2.5 soil:H_2O (w/v) for soil characteristics.

2.2. Experimental Setup and Sugar Beet Husbandry

The trials were accomplished in a split-split plot relying on randomized complete blocks with three replicates. The main plot was assigned to two multigerm cultivars of sugar beet (i.e., BTS 301 and Kawemira). While, two K rates [120 (K_{120}) as the recommended rate and 180 Kg of K_2O ha^{-1} (K_{180})] and three Zn rates [0; tap water (Zn_0) as a control, 150 (Zn_{150}), and 300 ppm (Zn_{300})] were randomly designated for the sub and sub-sub plots, respectively. An area of 12.0 m^2 was specified for each sub-sub plot, which included five ridges (rows) of 4.0 m in length and 0.6 m spaced from each other. Each applied rate of K (K_2SO_4; 48% K_2O) was split into two identical doses, one-half was applied basally at planting and the other half directly top-dressed after thinning. Zn in a chelate form of Zn-EDTA (15% Zn) was used and sprayed, to run-off, two times 25 d intervals beginning from 50 days after planting (DAP). These two dates were at phenological (BBCH 31/32; leaves cover 10–20% and BBCH 33/34; 30–40% of the ground) stages on the BBCH scale. To ensure effective penetration of Zn into sugar beet leaf tissues, a few drops of Tween-20 (0.1% solution, v/v) as a surfactant were mixed with the spraying solutions. Selected healthy, uniform seeds of two high-yielding commercial multigerm sugar beet cultivars (i.e., BTS 301 and Kawemira, Germany) were secured from the Agricultural Research Center (Institute of Sugar Crops Research), Egypt. They were selected due to the extensive range of their use in the cultivation of sugar beet regions in Egypt. Prior to sowing, the seed

surface was sterilized for 10 min with 1% (*v*/*v*) NaClO. The seeds were then rinsed directly with distilled water to wash off any adhesive NaClO and air-dried to reach the original dampness content. The seeds were planted at a rate of 3–5 balls per hill (20 cm apart) on September 9 and 11 in both seasons, respectively. The method of dry planting was used on one side of all ridges. Sugar beet seedlings were thinned to 8.33 plants m^{-2} by leaving one healthy plant per hill at 40 DAP. Based on the recommendations of the Egyptian ARC, all other agricultural practices of sugar beet cultivation were accomplished [50].

2.3. Sampling

For all morpho-physiological traits, three plant samples were collected, randomly, from each of the sub-sub plots at 100 DAP. At 200 DAP (harvest date), five individual guarded beet plants were collected, randomly, from each of the sub-sub plots for all yields and their components. The plants were immediately transported to the laboratory where the beetroots were washed to remove sticky particles from the soil, and then carefully separated into the roots and tops.

2.4. Morpho-Physiological Responses

Total chlorophyll concentration (i.e., SPAD index) was measured for four youngest fully widened leaves per plant by using a chlorophyll meter (SPAD-502, INC., Tokyo, Japan) and the average of the three beet plants that were randomly sampled was recorded. Leaf area index (LAI) was determined [51]:

$$\text{LAI} = [\text{Leaf area plant}^{-1}\ (\text{cm}^2)/\text{Ground area plant}^{-1}\ (\text{cm}^2)] \quad (1)$$

Using a meter scale, the length and diameter of the root were estimated in cm, besides, the fresh weight of the root was estimated in kg for each plant using a digital balance.

2.5. Industrial Sugar Quality

The industrial sugar quality including sucrose percentage was estimated based on the method itemized in [52]. The pure sugar (PS%) in the juice of beets was computed with the following formula [53]:

$$\text{PS\%} = \text{Sucrose (\%)} - [0.343\ (\text{K} + \text{Na}) + 0.094\ \alpha\text{-amino N} + 0.29] \quad (2)$$

$$\text{Also, loss sugar (LS\%)} = \text{Sucrose (\%)} - \text{PS (\%)} \quad (3)$$

$$\text{Purity (\%)} = [\text{PS (\%)}/\text{sucrose (\%)}] \times 100 \quad (4)$$

The soluble non-sugar contents (i.e., Na, K, and α-amino N) were estimated (in mmol kg^{-1} of root juice) utilizing a digital automatic sugar polarimeter (model AP-300, ATAGO CO., LTD, Minato-Ku, Tokyo, Japan).

$$\text{Alkalinity index} = (\text{K} + \text{Na})/\alpha\text{-amino N} \quad (5)$$

2.6. Sugar Beet Productivity and Potassium-Use Efficiencies (R-KUE and S-KUE)

From all sub-sub plots, all plants on all ridges were gathered, washed for cleaning. They were topped and weighed, plus the five previously weighed plants, all were transformed to appreciate yields (t ha^{-1}) of roots (RY) and tops (TY). By adding RY with TY, the biological yield (BY; t ha^{-1}) was calculated. The yield (t ha^{-1}) of gross sugar (GSY) was computed by multiplying sucrose (%) by RY, besides, yield (t ha^{-1}) of pure sugar (PSY) was computed by multiplying RY by PS%. K-use efficiencies based on RY (R-KUE; kg root kg k^{-1}) and sugar yield (S-KUE; kg sugar kg k^{-1}) were calculated by dividing the RY and PSY, respectively, by the applied K rate.

2.7. Data Processing and Statistical Analysis

Descriptive statistical analysis was performed to compute the mean ± standard error (SE) for each variable. Combined analysis was performed for the data of the two studied seasons by Bartlett's chi-square test after verifying the homogeneity of experimental error variance. All the collected data were analyzed, statistically, relying on multifactor analysis of variance (ANOVA) according to the split-split plot in a randomized complete block design by using GenStat 12 (12th Ed., VSN Intl. Ltd., Hemel Hempstead, UK). Duncan's test at $\alpha \leq 0.05$ and 0.01 was applied to compare all means. The analysis technique of stepwise regression was applied to recognize the extent of relationships among the studied parameters. Pearson's correlation analysis was done to know the degree of correlation among the sugar beet parameters and path analysis [54] to assess the direct and indirect effects of nine selected PSY-related attributes in their response variable (PSY). All figures were plotted using Microsoft Excel 2016 software program.

3. Results

3.1. Morpho-Physiological Responses

Data in Table 3, averaged over both SI and SII, offered a considerable difference ($p \leq 0.001$) between the two tested sugar beet cultivars in RL, RD, RFW, LAI, and SPAD index. The BTS 301 cultivar significantly outperformed the Kawemira cultivar by 14.6%, 25.0%, 37.4%, 38.2%, and 20.1%, respectively, for the parameters mentioned above. The data in Table 3 offered a considerable difference ($p \leq 0.001$) between the two K rates in morpho-physiological responses, by increasing the K rate from K_{120} to K_{180}, where the averages of plant RL, RD, RFW, LAI, and SPAD index were increased by 7.4%, 16.7%, 30.4%, 22.2%, and 7.4%, respectively, averaged over SI and SII. Sugar beet morpho-physiological responses were progressively increased by increasing the rates of Zn applied as foliar sprays (Table 3). The foliar sprayed-Zn_{300} rate was accompanied by increases in RL by 5.5%, RD by 8.9%, RFW by 17.8%, LAI by 13.2%, and SPAD index by 4.6% compared to control (Zn_0).

Table 3. Morphology (root length (RL), root diameter (RD), root fresh weight (RFW), leaf area index (LAI)) and SPAD index of two sugar beet cultivars (e.g., Kawemira (Cv1) and BTS 301 (Cv2)) affected by soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

Treatment		RL	RD	RFW	LAI	SPAD Index
		(cm)		(kg Plant^{-1})		
Season (S)	SI	26.6 ± 0.3 a	11.9 ± 0.3 a	1.18 ± 0.06 a	3.8 ± 0.13 a	49.7 ± 0.9 a
	SII	29.2 ± 0.5 a	11.6 ± 0.4 a	1.18 ± 0.04 a	4.2 ± 0.17 a	48.9 ± 0.9 a
Cultivar (Cv)	Cv1	26.0 ± 0.2 b	10.4 ± 0.2 b	0.99 ± 0.04 b	3.4 ± 0.07 b	44.8 ± 0.4 b
	Cv2	29.8 ± 0.4 a	13.0 ± 0.2 a	1.36 ± 0.04 a	4.7 ± 0.13 a	53.8 ± 0.4 a
Potassium (K)	K_{120}	26.9 ± 0.4 b	10.8 ± 0.3 b	1.02 ± 0.04 b	3.6 ± 0.11 b	47.6 ± 0.8 b
	K_{180}	28.9 ± 0.4 a	12.6 ± 0.3 a	1.33 ± 0.04 a	4.4 ± 0.16 a	51.1 ± 0.8 a
Zinc (Zn)	Zn_0	27.1 ± 0.6 c	11.2 ± 0.4 c	1.07 ± 0.06 c	3.8 ± 0.17 c	48.2 ± 1.1 c
	Zn_{150}	27.9 ± 0.6 b	11.7 ± 0.4 b	1.20 ± 0.06 b	4.0 ± 0.18 b	49.3 ± 1.0 b
	Zn_{300}	28.6 ± 0.6 a	12.2 ± 0.4 a	1.26 ± 0.06 a	4.3 ± 0.20 a	50.4 ± 1.0 a
p-value	S	0.083 ^{ns}	0.729 ^{ns}	0.983 ^{ns}	0.314 ^{ns}	0.501 ^{ns}
	Cv	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
	K	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
	Zn	<0.001 **	<0.001 **	<0.001 **	<0.001 **	<0.001 **
C.V (%)		1.00	0.90	0.60	3.40	0.90

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

For the two-way interactions of the three studied factors, sugar beet morpho-physiological responses regarding RFW and LAI were significantly affected by the cultivars × K, the BTS 301 × K_{180} interaction resulted in the greatest values (1.51 kg plant^{-1}) and (5.2) compared to the lowest values (0.83 kg plant^{-1}) and (3.1) with Kawemira × K_{120} for these parameters, respectively (Table S1). Additionally, the cultivars × Zn significantly affected the sugar beet morpho-physiological responses in terms of RL and LAI, the BTS 301 × Zn_{300} resulted in the maximum RL (30.6 cm) and LAI (5.0). The interaction application of K × Zn significantly affected the sugar beet morpho-physiological responses concerning RL, RD, RFW, LAI, and SPAD index. The K_{180} × Zn_{300} produced the highest values (29.5 cm, 13.0 cm, 1.45 kg plant^{-1}, 4.8, and 51.9, respectively) of these attributes. For the three-way interaction of the three factors, data in Table S1 showed a significant difference in RFW when the cultivars × K × Zn interactions were considered as averages across both seasons. The BTS 301 × K_{180} × Zn_{300} resulted in the highest RFW.

3.2. Industrial Sugar Quality

Significant differences ($p \leq 0.001$) were observed between the two cultivars regarding industrial sugar quality (i.e., sucrose, PS, purity, Na, K, α-amino N, alkalinity index, and LS) as averages across both seasons (Tables 4 and 5). Even though, the sugar of the BTS 301 cultivar gave the lowest impurities, e.g., Na (13.6 mmol kg^{-1}), K (23.2 mmol kg^{-1}), and α-amino N (10.4 mmol kg^{-1}) besides LS (1.65%), and the highest sucrose (21.6%), PS (19.9%), purity (92.3%), and alkalinity index (4.12). Contrary, the Kawemira cultivar produced sugar that possessed high values of Na (24.7 mmol kg^{-1}), K (33.9 mmol kg^{-1}), α-amino N (14.4 mmol kg^{-1}), and LS (2.43%) and lowest alkalinity index (3.61).

Table 4. Sucrose, pure sugar (PS), loss sugar (LS), and purity of two sugar beet cultivars (e.g., Kawemira (Cv1) and BTS 301 (Cv2)) affected by soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

Treatment		Sucrose	PS	LS	Purity
		(%)			
Season (S)	SI	20.2 ± 0.1 b	17.9 ± 0.2 b	2.35 ± 0.08 a	88.3 ± 0.5 b
	SII	21.3 ± 0.2 a	19.6 ± 0.3 a	1.74 ± 0.07 b	91.7 ± 0.4 a
Cultivar (Cv)	Cv1	20.0 ± 0.1 b	17.5 ± 0.2 b	2.43 ± 0.07 a	87.7 ± 0.4 b
	Cv2	21.6 ± 0.2 a	19.9 ± 0.2 a	1.65 ± 0.05 b	92.3 ± 0.3 a
Potassium (K)	K_{120}	20.3 ± 0.2 b	18.1 ± 0.2 b	2.19 ± 0.09 a	89.0 ± 0.5 b
	K_{180}	21.3 ± 0.2 a	19.4 ± 0.3 a	1.90 ± 0.08 b	91.0 ± 0.5 a
Zinc (Zn)	Zn_0	20.5 ± 0.3 c	18.3 ± 0.4 c	2.12 ± 0.11 a	89.5 ± 0.7 c
	Zn_{150}	20.8 ± 0.3 b	18.7 ± 0.4 b	2.05 ± 0.11 b	90.0 ± 0.6 b
	Zn_{300}	21.0 ± 0.3 a	19.1 ± 0.4 a	1.96 ± 0.11 c	90.5 ± 0.6 a
p-value	S	0.049 *	0.046 *	0.049 *	0.046 *
	Cv	0.007 **	0.001 **	<0.001 **	<0.001 **
	K	<0.001 **	<0.001 **	<0.001 **	<0.001 **
	Zn	<0.001 **	<0.001 **	<0.001 **	<0.001 **
C.V (%)		0.40	0.60	2.20	0.30

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to a nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

Table 5. Sodium (Na), potassium (K), α-amino N, and alkalinity index of two sugar beet cultivars (e.g., Kawemira (Cv1) and BTS 301 (Cv2)) affected by soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

Treatment		Na	K	α-Amino N	Alkalinity Index
		(mmol kg^{-1})			
Season (S)	SI	21.2 ± 0.1 a	35.6 ± 0.1 a	11.9 ± 0.04 a	4.78 ± 0.1 a
	SII	17.1 ± 0.1 a	21.6 ± 0.1 b	13.0 ± 0.04 a	2.94 ± 0.1 b
Cultivar (Cv)	Cv1	24.7 ± 0.1 a	33.9 ± 0.1 a	14.4 ± 0.02 a	3.61 ± 0.2 b
	Cv2	13.6 ± 0.1 b	23.2 ± 0.1 b	10.4 ± 0.03 b	4.12 ± 0.2 a
Potassium (K)	K_{120}	20.7 ± 0.1 a	31.1 ± 0.2 a	13.4 ± 0.03 a	3.85 ± 0.2 a
	K_{180}	17.6 ± 0.1 b	26.1 ± 0.1 b	11.5 ± 0.05 b	3.88 ± 0.2 a
Zinc (Zn)	Zn_0	19.8 ± 0.1 a	30.0 ± 0.2 a	12.8 ± 0.05 a	3.92 ± 0.2 a
	Zn_{150}	19.3 ± 0.1 b	28.7 ± 0.2 b	12.4 ± 0.05 b	3.88 ± 0.2 b
	Zn_{300}	18.3 ± 0.1 c	27.0 ± 0.2 c	12.1 ± 0.05 c	3.79 ± 0.2 b
p-value	S	0.123 ^{ns}	0.028 *	0.425 ^{ns}	0.014 **
	Cv	<0.001 **	<0.001 **	<0.001 **	0.011 **
	K	<0.001 **	<0.001 **	<0.001 **	0.815 ^{ns}
	Zn	<0.001 **	<0.001 **	<0.001 **	<0.001 **
C.V (%)		0.90	4.70	1.20	2.6

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to a nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

Averaged over both SI and SII, results in Tables 4 and 5 illustrated that industrial sugar quality was significantly ($p \leq 0.001$) improved as the K rate increased from K_{120} to K_{180}. K_{180} was more effective, increasing sucrose by 4.93%, PS by 7.18%, and purity by 2.25%, while decreasing the impurities (i.e., Na by 14.97%, K by 16.07%, and α-amino N by 14.18%) and LS by 13.24% compared with those of the K_{120} rate. On the contrary, application of K_{120} had higher Na (20.7 mmol kg^{-1}), K (31.1 mmol kg^{-1}), α-amino N (13.4 mmol kg^{-1}), and LS (2.19%), as well as lower sucrose (20.3%), PS (18.1%), and purity (89%). Under saline soil (8.60 dS m^{-1}) conditions, the concentrations of sucrose, PS, and purity showed significant increases, while the non-sugar contents (i.e., Na, K, and α-amino N), alkalinity index, and LS were reduced when the Zn rate was increased from 0 up to 300 ppm (Tables 4 and 5).

It was observed that foliar spray with Zn_{300} caused significant increases in sucrose by 2.44%, PS by 4.37%, and purity by 1.12% compared with control (Zn_0), while produced the lowest non-sugar contents such as Na (18.3 mmol kg^{-1}), K (27.0 mmol kg^{-1}), α-amino N (12.1 mmol kg^{-1}), alkalinity index (3.79), and LS (1.96%). On the other side, the control (Zn_0) had the highest content of Na, K, α-amino N, alkalinity index, and LS, while the lowest content of sucrose, PS, and purity were obtained under salinity stress of our study. Data in Tables S2 and S3 showed that the interaction application of cultivars × K considerably ($p \leq 0.05$) improved the industrial sugar quality in terms of Na, α-amino N, purity, and alkalinity index. The highest values of Na (26.9 mmol kg^{-1}) and α-amino N (14.8 mmol kg^{-1}) were observed when the sugar beet plants were treated with Kawemira × K_{120}, while the BTS 301 × K_{180} and BTS 301 × K_{120} produced the highest purity (93.0%) and alkalinity index (4.35), respectively. Additionally, Na and α-amino N were considerably influenced by the two-way interaction of cultivars × Zn (Table S3). The Kawemira × Zn_0 gave the highest impurities for Na (25.4 mmol kg^{-1}) and α-amino N (14.7 mmol kg^{-1}). Further, Na content of sugar beet root was significantly ($p \leq 0.001$) affected by the K × Zn interaction rates (Table S3). The K_{120} × Zn_0 produced the highest Na (21.3 mmol kg^{-1}), while the K_{180} × Zn_{300} gave the highest sucrose (21.5%). Significant differences ($p \leq 0.001$) were found in Na content due to the interaction application of

cultivars × K × Zn (Table S3), and the sugar beet BTS 3.01 cultivar supplemented by K_{180} and Zn_{300} collected the lowest Na content.

3.3. Sugar Beet Productivity

The data presented in Tables 6 and 7, Tables S4 and S5 and Figure 1 display the influences of the individual and interaction treatments on sugar beet productivity over the 2017/18 and 2018/19 seasons. The cultivars showed significant variation in RY, TY, and BY (Table 6). The BTS 301 cultivar was the best, surpassing the Kawemira cultivar by 12.8%, 29.6%, and 16.9% for the above traits, respectively. Tables 6 and 7 also showed that with fertilization of sugar beet plants with K_{180}, all their final yields in terms of RY, TY, BY, GSY, and PSY significantly ($p \leq 0.01$) increased by 14.31%, 17.46%, 15.12%, 20.0%, and 22.45%, respectively, compared to K_{120}. Results in Tables 6 and 7 illustrated that yields in terms of RY, TY, BY, GSY, and PSY significantly ($p \leq 0.001$) increased as the Zn rate increased from 0 up to 300 ppm. The Zn_{300} rate caused significant increases in RY by 6.56%, TY by 11.92%, BY 8.07%, GSY by 9.57%, and PSY by 10.68% compared with control (Zn_0). Additionally, data in Figure 1 showed that RY, TY, BY, GSY, and PSY were significantly ($p \leq 0.001$) affected by the K × Zn interaction rates. Application of K_{180} + Zn_{300} was more effective, resulted in 23.39%, 35.29%, 26.35%, 33.33%, 37.78% higher for RY, TY, BY, GSY, PSY, respectively, than those of the K_{120} × Zn_0 interaction. The other bi and trilateral interactions of the three investigated factors had no considerable effects on the studied sugar beet productivity in our study (Tables S4 and S5).

Table 6. Productivity (root yield (RY), top yield (RY), biological yield (BY), and gross sugar yield (GSY)) of two sugar beet cultivars (e.g., Kawemira (Cv1) and BTS 301 (Cv2)) affected by soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

Treatment		RY	TY	BY	GSY
		(t ha^{-1})			
Season (S)	SI	61.9 ± 1.3 a	20.0 ± 0.5 a	81.7 ± 1.8 a	12.5 ± 0.31 a
	SII	54.9 ± 0.9 a	21.1 ± 0.8 a	76.0 ± 1.6 a	11.7 ± 0.18 a
Cultivar (Cv)	Cv1	54.9 ± 1.1 b	17.9 ± 0.4 b	72.8 ± 1.5 b	11.8 ± 0.24 a
	Cv2	61.9 ± 1.1 a	23.2 ± 0.6 a	85.1 ± 1.4 a	12.4 ± 0.27 a
Potassium (K)	K_{120}	54.5 ± 0.9 b	18.9 ± 0.6 b	73.4 ± 1.4 b	11.0 ± 0.16 b
	K_{180}	62.3 ± 1.3 a	22.2 ± 0.6 a	84.5 ± 1.6 a	13.2 ± 0.21 a
Zinc (Zn)	Zn_0	56.4 ± 1.6 c	19.3 ± 0.9 c	75.6 ± 2.4 c	11.5 ± 0.34 c
	Zn_{150}	58.7 ± 1.5 b	20.8 ± 0.7 b	79.5 ± 2.0 b	12.2 ± 0.29 b
	Zn_{300}	60.1 ± 1.5 a	21.6 ± 0.8 a	81.7 ± 2.1 a	12.6 ± 0.29 a
p-value	S	0.076 ^{ns}	0.310 ^{ns}	0.157 ^{ns}	0.222 ^{ns}
	Cv	0.013 *	0.001 **	0.004 **	0.162 ^{ns}
	K	<0.001 **	<0.001 **	<0.001 **	<0.001 **
	Zn	<0.001 **	<0.001 **	<0.001 **	<0.001 **
C.V (%)		0.60	0.90	0.40	0.70

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to a nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

Table 7. Pure sugar yield (PSY), potassium use efficiency (based on root yield (R-KUE), and pure sugar yield (S-KUE)) of two sugar beet cultivars (e.g., Kawemira (Cv1) and BTS 301 (Cv2)) affected by soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

Treatment		PSY (t ha^{-1})	R-KUE (kg Roots kg k^{-1})	S-KUE (kg Sugar kg k^{-1})
Season (S)	SI	11.1 ± 0.30 a	0.42 ± 0.009 a	0.075 ± 0.001 a
	SII	10.7 ± 0.18 a	0.38 ± 0.013 a	0.074 ± 0.002 a
Cultivar (Cv)	Cv1	10.9 ± 0.23 a	0.38 ± 0.010 b	0.074 ± 0.002 a
	Cv2	10.9 ± 0.26 a	0.42 ± 0.012 a	0.074 ± 0.002 a
Potassium (K)	K_{120}	9.8 ± 0.15 b	0.45 ± 0.007 a	0.082 ± 0.001 a
	K_{180}	12.0 ± 0.17 a	0.35 ± 0.007 b	0.067 ± 0.001 b
Zinc (Zn)	Zn_0	10.3 ± 0.32 c	0.38 ± 0.012 c	0.070 ± 0.002 c
	Zn_{150}	11.0 ± 0.27 b	0.40 ± 0.014 b	0.075 ± 0.002 b
	Zn_{300}	11.4 ± 0.27 a	0.41 ± 0.016 a	0.078 ± 0.002 a
p-value	S	0.568 ^{ns}	0.096 ^{ns}	0.764 ^{ns}
	Cv	0.872 ^{ns}	0.012 *	0.824 ^{ns}
	K	<0.001 **	<0.001 **	<0.001 **
	Zn	<0.001 **	<0.001 **	<0.001 **
C.V (%)		0.90	0.60	1.00

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to a nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

3.4. Potassium-Use Efficiencies (R-KUE and S-KUE)

The data presented in Tables 7 and 8, and Table S5 display the influences of the individual and interaction treatments on K-use efficiencies (i.e., R-KUE and S-KUE) over the 2017/18 and 2018/19 seasons. The cultivars showed significant variation in R-KUE (Table 7). The BTS 301 cultivar was the better, surpassing the Kawemira cultivar by 10.5%. Table 7 also showed that fertilization of sugar beet plants with K_{180} significantly ($p \leq 0.01$) exhibited the lowest R-KUE (0.35 kg roots kg k^{-1}) and S-KUE (0.067 kg sugar kg k^{-1}). Results in Table 7 illustrated that R-KUE and S-KUE significantly ($p \leq 0.001$) increased as the Zn rate increased from 0 up to 300 ppm. The Zn_{300} rate caused significant increases in R-KUE by 7.89% and S-KUE by 11.45% compared with control (Zn_0). R-KUE was considerably ($p \leq 0.001$) influenced by the interaction application of cultivars × K rates (Table S5). The interaction application of BTS 301 × K_{120} resulted in the significant highest R-KUE (0.48 kg roots kg k^{-1}), however, the lowest R-KUE (0.33 kg roots kg k^{-1}) was achieved when the Kawemira × K_{180} interaction was applied. Additionally, data in Table 8 showed that R-KUE and S-KUE were significantly ($p \leq 0.001$) affected by the K × Zn interaction rates. Application of K_{120} interaction with Zn_{300} resulted in the best R-KUE (0.48 kg roots kg k^{-1}) and S-KUE (0.087 kg sugar kg k^{-1}). The other bi and trilateral interactions of the three investigated factors had no considerable effects on K-use efficiencies in our study (Table S5).

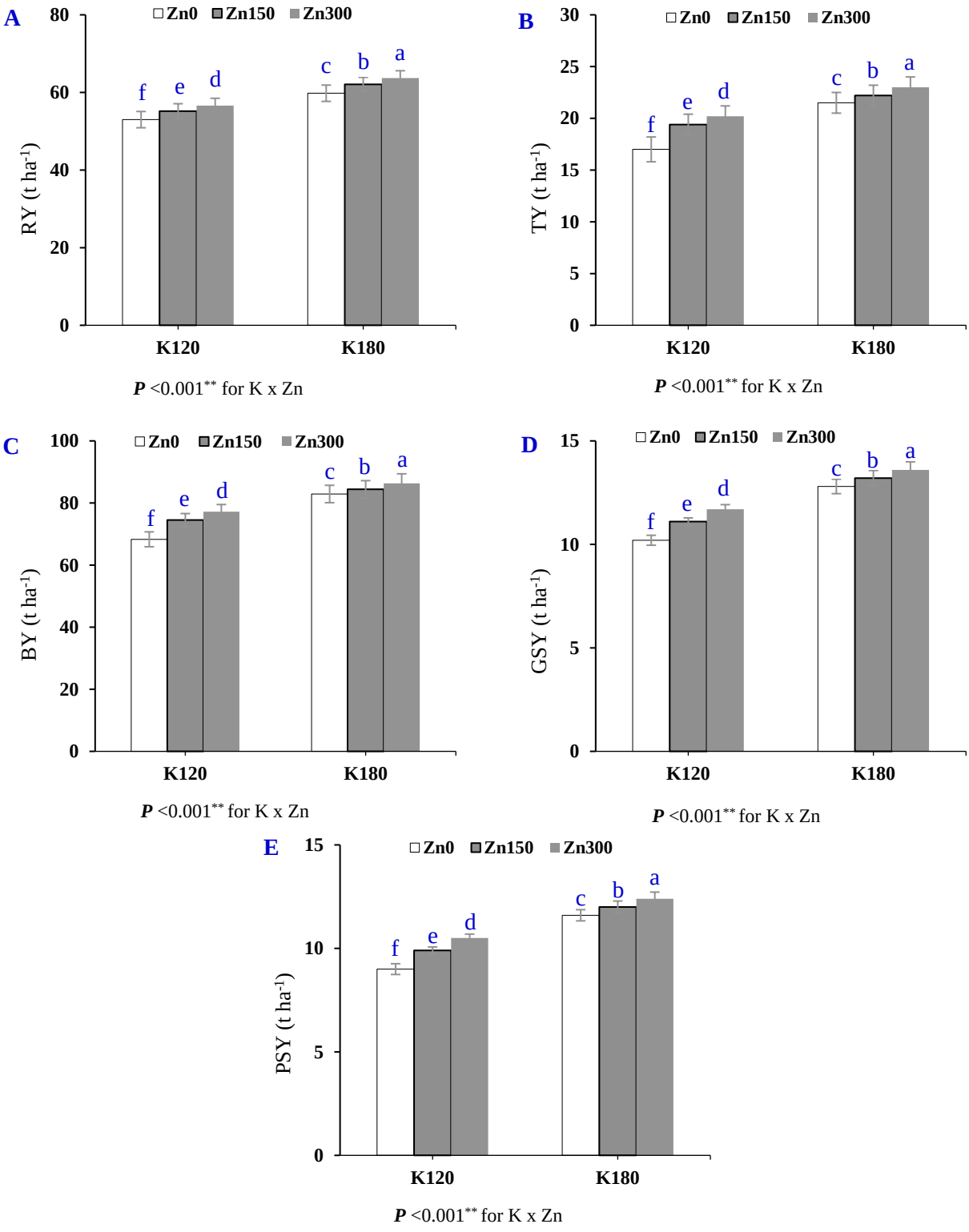


Figure 1. Interactive effect of two K rates (K = 120 (K_{120}) and 180 (K_{180}) kg ha^{-1}) and three foliar-applied Zn (0 (Zn_0), 150 (Zn_{150}) and 300 (Zn_{300}) ppm) on root yield (RY; **A**), top yield (TY; **B**), biological yield (BY; **C**), gross sugar yield (GSY; **D**), and pure sugar yield (PSY; **E**) of sugar beet grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions. Bars sharing the same letter in each chart are not significantly ($p \leq 0.05$) different according to Duncan's test. ** refer to significant difference at $p \leq 0.01$.

Table 8. Potassium use efficiency (based on root yield (R-KUE) and pure sugar yield (S-KUE)) of sugar beet affected by the interaction of soil fertilization with two potassium levels (e.g., 120 (K_{120}) and 180 kg ha^{-1} (K_{180})) and foliar application with three zinc levels (e.g., 0 (Zn_0), 150 (Zn_{150}), and 300 ppm (Zn_{300})) when grown under saline soil (EC_e = 8.60 dS m^{-1}) conditions over both sugar beet cultivars (data pooled over both seasons).

Treatment		R-KUE (kg Roots kg k^{-1})	S-KUE (kg Sugar kg k^{-1})
K_{120}	Zn_0	0.43 ± 0.011 c	0.075 ± 0.002 b
	Zn_{150}	0.46 ± 0.011 b	0.082 ± 0.001 b
	Zn_{300}	0.48 ± 0.013 a	0.087 ± 0.002 a
K_{180}	Zn_0	0.34 ± 0.012 e	0.064 ± 0.002 d
	Zn_{150}	0.35 ± 0.012 d	0.067 ± 0.002 c
	Zn_{300}	0.35 ± 0.013 d	0.069 ± 0.002 c
p-value	K × Z	<0.001 **	<0.001 **
	Cv × K × Zn	0.277 ^{ns}	0.122 ^{ns}

*, ** refer to the significant difference at $p \leq 0.05$ and $p \leq 0.01$, respectively; "ns" refers to a nonsignificant difference. Means sharing the same letter in each column are not significantly different according to Duncan's multiple range test.

3.5. Correlation, Regression, and Path-Coefficient Analyses

Pearson's correlation coefficients in Table 9 between PSY and each of RL, RD, RFW, LAI, SPAD index, PS, LS, RY, and TY were computed to highlight the efficacious sugar beet traits of interest. Highest significant ($p \leq 0.01$) positive correlations (r = 0.776 **, r = 0.629 **, r = 0.602 **, r = 0.549 ** and r = 0.513 **) markedly were obtained between PSY and each of RY, RFW, TY, PS, and RD, respectively. Furthermore, the highest significant positive correlation (r = 0.926 **) was also observed between RY and RFW. Outputs of stepwise regression analysis in Table 10 clarify that there exist five sugar beet parameters (i.e., RY, PS, RL, RFW, and RD), three studied factors, and both seasons had a highly significant contribution to differences in PSY. Additionally, PSY and (RY, PS%, and RFW) by the data of cultivars ×K × Zn interactions averaged across both studied seasons are explained as highly significant ($p \leq 0.01$) positive linear (Figure 2) models. These functional relationships exhibit that the PSY was enhanced with increasing RY (R^2 = 0.571 **), PS (R^2 = 0.289 **), and RFW (R^2 = 0.421 **). These linear dependencies showed that 57.1%, 28.9%, and 42.1% of the variations in PSY could be interpreted by variations in RY, PS, and RFW, respectively, and could be equalized as follows:

$$PSY = 0.1617\ RY + 1.4545\ (R^2 = 0.5712\ **) \quad (6)$$

$$PSY = 0.4566\ PS\% + 2.3501\ (R^2 = 0.2888\ **) \quad (7)$$

$$PSY = 3.0112\ RFW + 7.3544\ (R^2 = 0.4212\ **) \quad (8)$$

Table 9. A matrix of linear correlation coefficients and their significance levels between pure sugar yield (t ha^{-1}) and other important attributes under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

	C	1	2	3	4	5	6	7	8	9	10
1	RL	1	0.967 **	0.935 **	0.872 **	0.970 **	−0.420 *	0.579 **	0.869 **	0.903 **	0.457 **
2	RD		1	0.961 **	0.896 **	0.959 **	−0.367 *	0.504 **	0.894 **	0.929 **	0.513 **
3	RFW			1	0.922 **	0.890 **	−0.234 ^{ns}	0.394 *	0.926 **	0.939 **	0.629 **
4	LAI				1	0.832 **	−0.333 *	0.500 **	0.840 **	0.931 **	0.492 **
5	SPADindex					1	−0.575 **	0.675 **	0.808 **	0.868 **	0.309 ^{ns}
6	PS						1	−0.939 **	−0.099 ^{ns}	−0.300 ^{ns}	0.549 **
7	LS							1	0.273 ^{ns}	0.486 **	−0.366 *
8	RY								1	0.946 **	0.776 **
9	TY									1	0.602 **
10	PSY										1

* $p \leq 0.05$, ** $p \leq 0.01$, and ns—not significant. Root length (RL), root diameter (RD), root fresh weight (RFW), leaf area index (LAI), pure sugar (PS), loss sugar (LS), root yield (RY), top yield (TY), and pure sugar yield (PSY).

Table 10. Correlation coefficient (*r*), coefficient of determination (R^2), and standard error of the estimates (SEE) for predicting pure sugar yield (PSY; t ha^{-1}) under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

r	R^2	SEE	Significance	Fitted Equation
0.999	0.998	0.043	***	PSY = −9.413 + 0.19 RY + 0.54 PS% − 0.028 RL + 0.488 RFW − 0.059 RD

*** $p \leq 0.001$. Root length (RL), root diameter (RD), root fresh weight (RFW), pure sugar concentration (PS%), root yield (RY), and pure sugar yield (PSY).

As an average across studied factors and seasons, the direct and indirect effects of nine selected PSY-related attributes in PSY (dependent variable) are shown in Table 11. The results of path coefficient analysis under saline soil (8.60 dS m^{-1}) conditions in our study showed that PS, RFW, and RY in sugar beet had the highest positive direct effects with 0.62, 0.12, and 0.09 path coefficients, respectively, on PSY. While LS had a slight positive direct effect on PSY with a path coefficient of 0.03. On the other hand, RL, RD, LAI, SPAD index, and TY had a negative direct effect of −0.08, −0.05, −0.01, −0.01, and −0.06, respectively, on PSY. RY had the greatest indirect positive effects on PSY through TY by 0.85, RFW by 0.83, and RD by 0.80. These attributes (i.e., TY, RFW, and RD) also had significant and positive correlations with PSY by correlation coefficients of r = 0.60, r = 0.63, and r = 0.51, respectively (Table 11).

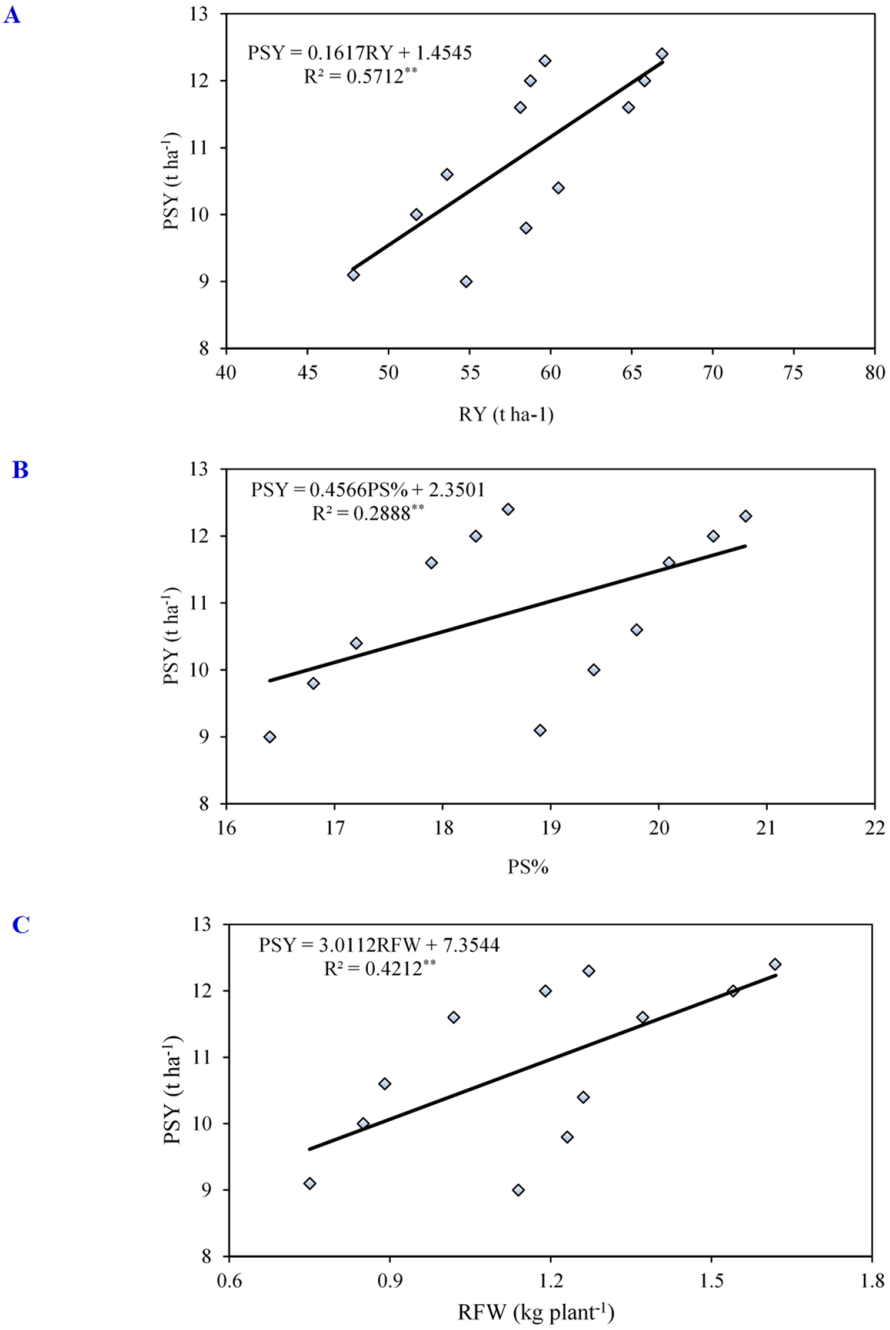


Figure 2. Functional relation between the pure sugar yield (PSY) and root yield (RY; **A**) and pure sugar concentration (PS%; **B**) and root fresh weight (RFW; **C**) by data of V × K × Zn interaction (data pooled over both seasons) under saline soil (EC_e = 8.60 dS m^{-1}) conditions. ** refer to significant difference at $p \leq 0.01$.

Table 11. Direct (underlined diagonals) and indirect effects of pure sugar yield (PSY) components and their correlations with PSY under saline soil (EC_e = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

	Character	1	2	3	4	5	6	7	8	9	Total *r*
1	RL	**−0.08**	−0.05	0.12	−0.01	−0.01	−0.26	0.02	0.78	−0.05	0.46 **
2	RD	−0.07	**−0.05**	0.12	−0.01	−0.01	−0.23	0.02	0.80	−0.05	0.51 **
3	RFW	−0.07	−0.05	**0.12**	−0.01	−0.01	−0.14	0.01	0.83	−0.05	0.63 **
4	LAI	−0.07	−0.04	0.11	**−0.01**	−0.01	−0.21	0.02	0.75	−0.05	0.49 **
5	SPAD index	0.07	−0.05	0.11	−0.01	**−0.01**	−0.36	0.02	0.73	−0.05	0.31 ns
6	PS	0.03	0.02	−0.03	0.004	0.01	**0.62**	−0.03	−0.09	0.02	0.55 **
7	LS	−0.04	−0.02	0.05	−0.01	−0.01	−0.85	**0.03**	0.25	−0.03	−0.37 *
8	RY	−0.07	−0.04	0.12	−0.01	−0.01	−0.06	0.01	**0.09**	−0.05	0.78 **
9	TY	−0.07	−0.04	0.12	−0.01	−0.01	−0.19	0.01	0.85	**−0.06**	0.60 **

* $p \leq 0.05$, ** $p \leq 0.01$, and ns; not significant. Root length (RL), root diameter (RD), root fresh weight (RFW), leaf area index (LAI), pure sugar (PS), loss sugar (LS), root yield (RY), top yield (TY) and pure sugar yield (PSY).

4. Discussion

Among the abiotic stresses, agricultural soils suffer from low fertility (N- and K^+-deficient saline soil), lack of water, and a high level of salinity (EC_e = 8.60 dS m^{-1}), which were found in the soil under study (Tables 1 and 2). These adverse conditions influence the quantitative and qualitative response of plants by altering their growth, physiology, metabolic activities, and yield quality [55,56]. Therefore, it is imperative to select plant cultivars that can withstand such harsh environmental conditions. Two cultivars of sugar beet, BTS 301 and Kawemira, were selected as cultivars widespread in the region to be tested for stress tolerance (Tables 1 and 2). Our results indicated that the performance of the BTS 301 cultivar in terms of growth, productivity, industrial sugar quality, R-KUE, and S-KUE (Tables 3–8, Tables S1–S5, and Figure 2) was significantly higher than the Kawemira cultivar under the adverse conditions of the tested soil (Tables 1 and 2). These results indicate that the BTS 301 cultivar appears to be more tolerant, as it exhibited more morphological–physiological responses, yield, and yield quality than the Kawemira cultivar. However, no studies were found to compare these two cultivars in terms of tolerance to environmental stresses. The significant outperformance of the BTS 301 cultivar compared to the Kawemira cultivar in favor of morpho-physiology, yield components, and yield quality traits may be due to inherent variances depending on their genetic makeup.

Application of K enhances the response to K-applied soil due to the high availability of K^+ resulting from the high retention of K^+ ions on soil particle surfaces [56]. K^+ has been reported to protect plants from salt-driven harms due to its direct defensive role in cellular osmoprotection and indirect role in antioxidation [22,31]. Soil fertilization with K singly or in interactions (Table 3 and Table S1) significantly improved sugar beet morpho-physiological responses and chlorophyll concentration (SPAD index), particularly with K_{180}. Increased salt tolerance has been reported in several crops, including sugar beet, with increased availability of K^+ in plant tissues [10,12,21,22,56]. Under saline conditions, K^+ assists the availability of water and phytonutrients [57] to sugar beet plants by deepening the roots into the soil to balance the uptake of nutrients, resulting in higher root dimensions, RFW, and thus yields [12]. Due to the lack of K^+ in the growth medium, Faust and Schubert [58] observed that sugar beetroot growth was much lower than that of leaves. However, an adequate supply of K^+, under salinity, increases the active chlorophyll concentration (SPAD index; Table 3), assimilation of N [28], and photosynthetic carbon in plant leaves. Therefore, the light reaction (PSI and PSII) routes increase [59], reflecting increased sugar beet growth and productivity. K^+-mediated improvements of sugar beet growth (e.g., RL, RD, RFW, and LAI) under saline soil conditions (8.60 dS m^{-1}) can also be ascribed to K's ability to alter cell turgor pressure and/or cell enlargement by enhancing cell-wall extensibility [60,61]. Besides, as per the acidic-growth theory, the plasma membrane H^+-ATPase performs a crucial role in plant growth with the application of K^+ to stressed plants [62]. The activity of H^+-ATPase acidifies the apoplast by pumping cellular

protons, activating pH-dependent metabolic enzymes that mediate cell-walls laxation and its extensibility, and thereby growth stimulation [58,63]. Wakeel et al. [20] reported inhibition of H^+-ATPase under K^+ deficiency in sugar beet. On the other hand, the production of pure sugar depends greatly on sucrose concentration in the sugar extracted from beets. Additionally, the presence of Na, K, and α-amino N in high quantities in beet juice has an undesirable molassegenic effect and reduces the sugar extracted from the beet pulp and thus reduces the PSY [53,64]. These impurities bind an equal or greater quantity of sucrose to molasses, causing a lot of sucrose to be wasted and weakening its crystallinity during sugar extraction from beets [65]. Each 1.0 kg of these impurities retains about 1.5 kg of sucrose to the molasses stage [64]. A reduction of 1.0 g kg^{-1} (i.e., 0.1%) of sucrose wasted into molasses would have resulted in an average annual return of extra tonnes of beet sugar produced annually with little or no excess in extraction costs in beet production areas globally, including Egypt.

Our results revealed that K application, particularly K_{180}, singly or in interactions (Tables 4 and 5 and Tables S2 and S3), improved the quality of industrial sugar by increasing sucrose, PS, and purity and reducing non-sugar impurities (i.e., Na, K, and α-amino N) and LS in salt-stressed sugar beet plants. Sugar quality has also been reported with the addition of K to the soil under the stress of salinity or drought [10,12,56,57,66]. These positive results can be attributed to the positive role of K^+ in the accumulation of photo-assimilated products, including sucrose and its translocation from leaves of sugar beet (source organs) to vacuoles of the parenchyma cells (sink tissues) in the roots, thus increasing the PS content [67]. K^+ is also a cation that is more effective in balancing the uptake of phytonutrients required to activate carbohydrate synthesis and maintain a natural balance between the synthesis of nonstructural carbohydrates and soluble proteins [68,69]. Under salinity stress, low Na content in beet juice with adequate K^+ supply (K_{180}) might be due to competitive interference of K^+ for uptake sites in low and high-affinity transport systems on the plasma membrane [70]. Therefore, the decrease in electrochemical gradients of negative Na uptake, and consequently, the higher the ratio of K^+:Na^+ [71]. Another possible explanation for reducing the K^+ and Na^+ contents and thus the alkalinity index in the root juice of stressed sugar beet plants may be an attempt to maintain high levels of these cations in the plant's shoots to counteract salinity.

Sugar beet is among the few crops capable of using Na^+ (a dominant ion in salinity) along with K^+ in osmotic adaptation and stimulation of plant cell expansion [72,73]. Wakeel et al. [20] reported an accumulation of more than 90% of the total Na^+ content in sugar beets in shoot cell vacuoles, and residues remain in storage root cells when K^+ replaces Na^+ in a nutrition experiment. Moreover, the decrease in the level of the α-amino N anion in sugar beet juice is usually associated with a similar decrease in the K^+ and Na^+ cations, which maintains the balance of cations and anions in the plant tissues under the stress of salinity [12,16,74]. It is possible in this study that the K^+ and α-amino N content was decreased in sugar beetroot as it is considered among the predominant osmoprotective substances during vegetative growth under salinity conditions. Once the sugars start to be stored, these compatible solutes decrease in the storable root tissues due to their replacement by storing sugars as osmoprotectants (reviewed in [75] on sugar beet). The high α-amino N content in sugar beet juice induces the formation of enzymatic colorants (e.g., melanins) and nonenzymatic colorants (e.g., melanoidins) [76], which require more time, energy, and costs in the syrup clarification step during sugar extraction. The accepted industrial limits for non-sugar impurities of Na, K, and α-amino N are 13.3, 35.9–51.3, and 21.4 mmol kg^{-1} sugar beetroots during the processing of crystallized sucrose [53,68]. Our results reported acceptable limits for impurities in the beetroots (Tables 4 and 5). The K_{180} applied singly or in interactions, was the best (Table 7 and Table S5, Figure 1) for PSY (RY multiplied by PS%) and this could be attributed to enhancements in both RY and PS contents that directly contribute to this final main attribute. However, this treatment resulted in the lowest levels of R-KUE (0.35 kg roots kg k^{-1}) and S-KUE (0.067 kg sugar kg k^{-1}) (Table 7). These reduced levels of R-KUE and S-KUE with K_{180} (compared to

K_{120}) are logical and could be ascribed to the higher amount of applied K fertilizer and the corresponding rises in RY and PSY, respectively.

Foliar Zn_{300}, applied singly or in interactions (Table 3 and Table S1), substantially increased all sugar beet morpho-physiological responses and the increases ranged between 4.6% and 17.8% compared to Zn_0 under the conditions of the tested saline soil. These findings are in consistent with those of [22,29,33,41,77]. Encouragement of beet growth traits caused by foliar application of Zn may be due to a low concentration of Zn in the soil (0.7 mg kg^{-1}; Table 2), in addition to a higher soil pH (7.86) that fixes Zn against root uptake. The Zn^{2+} predominates at soil pH below 7.7, as well as $ZnOH^+$ at pH 7.7–9.1, while the form $Zn(OH)_2$ predominates at pH above 9.1, which means that Zn availability decreases with higher soil pH [42]. The Zn-induced promotions in beet growth may reflect the fact that Zn appears to enhance salt tolerance through increased uptake of essential macro- and micronutrients (mainly Mg and Fe), which are mainly involved in the structure of the chlorophyll molecule [78]. Additionally, it may be implicated as a cofactor in biosynthesis and/or catalysis of photosynthetic metalloenzymes, including RuBisCO that catalyzes the first event of CO_2 fixation during photosynthesis [30]. Under salinity stress, Zn can regulate plant water relations by positively contributing to the stability and integrity of cell biomembranes and activating some ROS-scavenging enzymes to minimize damage to vital living cell components, thus increasing sugar beet growth and productivity [31,79,80]. Besides, the mediating role of Zn in the biosynthesis of growth regulators such as gibberellin and tryptophan, is a prerequisite for IAA biosynthesis [16,40].

Concerning the industrial sugar quality, foliar Zn_{300} applied singly or in combination (Tables 4 and 5, Tables S2 and S3), significantly increased sucrose, PS, and purity, while the non-sugar contents (Na, K, α-amino N, and LS) were decreased compared to control (Zn_0). Similar trends are noted in [77,81,82]. These reports show that Zn improves sugar beet sugar quality (sucrose, PS, and purity) and reduces non-sugary elements under salinity conditions. The enhancement of sucrose, PS, and purity is likely a result of Zn's role in enhancing carbohydrate metabolism by activating several Zn-dependent enzymes, particularly carbonic anhydrase (CA) and fructose 1,6 diphosphatase [83]. CA enzyme likely facilitates the diffusion of CO_2 from stomatal apertures to the carboxylation sites by RuBisCO and improves the phloem's export of carbohydrates to the storage beetroots (sinks) [80]. Besides, Zn can limit Na^+ uptake and translocation in plant tissues, which appears to be the reason for reducing the Na^+ content in sugar beet juice [84]. The inhibitory effect of Zn on the RNAse activity is accountable for the degradation of proteins to amino acids, and thus protein biosynthesis is a possible mechanism for a decrease of α-amino N in sugar beet juice [83]. All sugar beet yield components (RY, TY, BY, GSY, and PSY) and K-use efficiency (i.e., R-KUE and S-KUE) greatly improved by Zn applied singly or in interactions (Tables 6–8, Tables S4 and S5, Figure 1), however, the highest increases of these traits were obtained using Zn_{300} under saline conditions. Similar to our findings, a higher yield of sugar beet is reported under saline conditions using Zn [36,77], which plays a major role in improving sugar beet morpho-physiology, sugar quality, and final economic returns [16,29]. The highest R-KUE (0.41 kg roots kg k^{-1}) and S-KUE (0.078 kg sugar kg k^{-1}) in sugar beet plants treated with Zn_{300} resulted logically from the highest RY and PSY produced with the same treatment, respectively. Conclusively, supplying the saline soil with K_{180} in integration with salt-stressed plant leaves with Zn_{300} can be used as an effective field agronomic practice to induce salt tolerance in sugar beet and ultimately to enhance its productivity and industrial sugar standards, as well as K-use efficiency in a salty semi-arid agro-ecosystem.

The negative effects of environmental foes may exceed the natural endurance of stressed plants. In this case, the components of a stressed plant's defense system do not meet adequate defense requirements, and therefore external use of auxiliary substances such as nutrients and other beneficial strategies increases the efficiency of antioxidant defenses, and thus plants can perform efficiently under adverse conditions of environmental foes [85–89].

5. Conclusions

This research was accomplished to investigate the possible positive influences of applying the soil with K and plant leaves with Zn to induce salt tolerance by improving growth, sugar yield and quality, and K-use efficiency in two sugar beet cultivars under the undesirable conditions of a salty semi-arid agro-ecosystem. Under these adverse conditions, the BTS 301 cultivar showed higher morpho-physiological responses (i.e., RL, RD, RFW, LAI, and SPAD index), desirable industrial sugar quality, productivity (RY, TY, BY, GSY, and PSY), and R-KUE, and lower non-sugar impurities (Na, K, and α-amino N) and sugar loss across K and Zn rates compared to the Kawemira cultivar. Soil addition of K at a rate of 180 Kg ha^{-1} (K_{180}) to the tested soil, especially in integration with Zn applied to plant leaves (Zn_{300}), stimulated salt tolerance of sugar beet plants and improved all attributes mentioned above. The highest significant positive correlations of PSY were noted with RY, RFW, TY, PS, and RD as r = 0.776 **, 0.629 **, 0.602 **, 0.549 **, and 0.513 **, respectively. Stepwise and path-coefficient analysis proved that RY, PS, and RFW are the most important traits that can greatly affect PSY under salinity stress and can be employed as selection criteria for the tested cultivars. Application of K_{180} and/or Zn_{300} could help correct deficiency of soil K and/or Zn, as well as mitigate the salt stress influences on sugar beet, while their integration showed a synergistic effect and significantly improved sugar productivity, industrial sugar quality, and K-use efficiency.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11040780/s1, Table S1: Root length (RL), root diameter (RD), root fresh weight (RFW), and leaf area index (LAI), SPAD index of sugar beet as affected by the interactions of two cultivars [e.g., Kawemira (Cv1) and BTS 301 (Cv2)] grown under different fertilizer levels of potassium [e.g., 120 (K120) and 180 kg ha^{-1} (K180)] and foliar zinc [e.g., 0 (Zn0), 150 (Zn150), and 300 ppm (Zn300)] under saline soil (ECe = 8.60 dS m^{-1}) conditions (data pooled over both seasons)., Table S2. Sucrose, pure sugar (PS), loss sugar (LS), and purity of sugar beet as affected by the interactions of two sugar beet cultivars [e.g., Kawemira (Cv1) and BTS 301 (Cv2)] grown under different fertilizer levels of potassium [e.g., 120 (K120) and 180 kg ha^{-1} (K180)] and foliar zinc [e.g., 0 (Zn0), 150 (Zn150), and 300 ppm (Zn300)] under saline soil (ECe = 8.60 dS m^{-1}) conditions (data pooled over both seasons)., Table S3. Sodium (Na), potassium (K), α-amino N, and alkalinity index of sugar beet as affected by the interactions of two sugar beet cultivars [e.g., Kawemira (Cv1) and BTS 301 (Cv2)] grown under different fertilizer levels of potassium [e.g., 120 (K120) and 180 kg ha^{-1} (K180)] and foliar zinc [e.g., 0 (Zn0), 150 (Zn150), and 300 ppm (Zn300)] under saline soil (ECe = 8.60 dS m^{-1}) conditions (data pooled over both seasons)., Table S4. Root yield (RY), top yield (RY), biological yield (BY), and gross sugar yield (GSY) of sugar beet as affected by the interactions of two cultivars [e.g., Kawemira (Cv1) and BTS 301 (Cv2)] grown under different fertilizer levels of potassium [e.g., 120 (K120) and 180 kg ha^{-1} (K180)] and foliar zinc [e.g., 0 (Zn0), 150 (Zn150), and 300 ppm (Zn300)] under saline soil (ECe = 8.60 dS m^{-1}) conditions (data pooled over both seasons)., Table S5. Potassium use efficiencies based on root yield (R-KUE) and pure sugar yield (S-KUE) of sugar beet as affected by the interactions of two cultivars [e.g., Kawemira (Cv1) and BTS 301 (Cv2)] grown under different fertilizer levels of potassium [e.g., 120 (K120) and 180 kg ha^{-1} (K180)] and foliar zinc [e.g., 0 (Zn0), 150 (Zn150), and 300 ppm (Zn300)] under saline soil (ECe = 8.60 dS m^{-1}) conditions (data pooled over both seasons).

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References

1. FAOSTAT. *World Food and Agriculture-Statistical Pocketbook*; FAO: Rome, Italy, 2018; p. 254. Available online: http://www.fao.org/economic/ess/ess-publications/ess-yearbook/en/ (accessed on 15 July 2019).
2. Gumienna, M.; Szwengiel, A.; Szczepańska-Alvarez, A.; Szambelan, K.; Lasik-Kurdyś, M.; Czarnecki, Z.; Sitarski, A. The impact of sugar beet varieties and cultivation conditions on ethanol productivity. *Biomass Bioenerg.* **2016**, *85*, 228–234. [CrossRef]
3. Carr, M.K.V.; Knox, J.W. The water relations and irrigation requirements of sugar cane (*Saccharum officinarum*): A review. *Exp. Agric.* **2011**, *47*, 1–25. [CrossRef]
4. CCSC. *Central Council for Sugar Crops Annual Report*; Ministry of Agriculture and Land Reclamation: Cairo, Egypt, 2018.
5. Vaughan, M.; Block, A.; Christensen, S.A.; Allen, L.H.; Schmelz., E.A. The effects of climate change associated abiotic stresses on maize phytochemical defenses. *Phytoch. Rev.* **2018**, *17*, 37–49. [CrossRef]
6. Munns, R.; Tester, M. Mechanisms of salinity tolerance. *Annu. Rev. Plant Biol.* **2008**, *59*, 651–681. [CrossRef] [PubMed]
7. Metternicht, G.; Zinck, J. Remote sensing of soil salinity: Potentials and constraints. *Remote Sens. Environ.* **2003**, *85*, 1–20. [CrossRef]
8. Cheeseman, J. *Food Security in the Face of Salinity, Drought, Climate Change, and Population Growth. Halophytes for Food Security in Dry Lands*; Elsevier: Amsterdam, The Netherland, 2016; pp. 111–123.
9. FAOSTAT. *AQUASTAT Country Profil–Egypt*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2016.
10. Hussain, Z.; Khattak, R.A.; Irshad, M.; Mahmood, Q. Sugar beet (*Beta vulgaris* L.) response to diammonium phosphate and potassium sulphate under saline–sodic conditions. *Soil Use Manag.* **2014**, *30*, 320–327. [CrossRef]
11. El-Mageed, T.A.A.; El-Sherif, A.M.; El-Mageed, S.A.A.; Abdou, N.M. A novel compost alleviate drought stress for sugar beet production grown in Cd-contaminated saline soil. *Agric. Water Manag.* **2019**, *226*, 105831. [CrossRef]
12. Merwad, A.M.A. Efficiency of potassium fertilization and salicylic acid on yield and nutrient accumulation of sugar beet grown on saline soil. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 1184–1192. [CrossRef]
13. Abbasi, Z.; Golabadi, M.; Khayamim, S.; Pessarakli, M. The response of drought-tolerant sugar beet to salinity stress under field and controlled environmental conditions. *J. Plant Nutr.* **2018**, *41*, 2660–2672. [CrossRef]
14. Ashrafi, E.; Razmjoo, J.; Zahedi, M. Effect of salt stress on growth and ion accumulation of alfalfa (*Medicago sativa* L.) cultivars. *J. Plant Nutr.* **2018**, *41*, 818–831. [CrossRef]
15. Ghoulam, C.; Foursy, A.; Fares, K. Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. *Environ. Exp. Bot.* **2002**, *47*, 39–50. [CrossRef]
16. Marschner, P. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK; Waltham, MA, USA; San Diego, CA, USA, 2012.
17. Feizi, M.; Fallahzade, J.; Noorshargh, P. Sugar beet yield response to different levels of saline irrigation water and leaching in an arid region. *J. Plant Nutr.* **2018**, *41*, 654–663. [CrossRef]
18. Flowers, T.J. Improving crop salt tolerance. *J. Exp. Bot.* **2004**, *55*, 307–319. [CrossRef] [PubMed]
19. Wakeel, A.; Steffens, D.; Schubert, S. Substitution of K^+ by Na^+ in sugar beet nutrition on K^+-fixing soils. *J. Plant Nutr. Soil Sci.* **2010**, *173*, 127–134. [CrossRef]
20. Wakeel, A.; Sümer, A.; Hanstein, S.; Yan, F.; Schubert, S. In vitro effect of different Na^+/K^+ ratios on plasma membrane H^+-ATPase activity in maize and sugar beet shoot. *Plant Physiol. Biochem.* **2011**, *49*, 341–345. [CrossRef] [PubMed]
21. Bybordi, A. Interactive effects of silicon and potassium nitrate in improving salt tolerance of wheat. *J. Integr. Agric.* **2014**, *13*, 60345–60347.
22. Hatam, Z.; Sabet, M.S.; Malakouti, M.J.; Mokhtassi-Bidgoli, A.; Homaee, M. Zinc and potassium fertilizer recommendation for cotton seedlings under salinity stress based on gas exchange and chlorophyll fluorescence responses. *S. Afr. J. Bot.* **2020**, *130*, 155–164. [CrossRef]
23. Adams, E.; Shin, R. Transport, signaling, and homeostasis of potassium and sodium in plants. *J. Integr. Plant Biol.* **2014**, *56*, 231–249. [CrossRef]
24. Rahneshan, Z.; Nasibi, F.; Moghadam, A.A. Effects of salinity stress on some growth, physiological, biochemical parameters and nutrients in two pistachio (*Pistacia vera* L.) rootstocks. *J. Plant Interact.* **2018**, *13*, 73–82. [CrossRef]
25. Shin, R. Strategies for improving potassium use efficiency in plants. *Mol. Cells* **2014**, *37*, 575. [CrossRef]
26. Cakmak, I.; Hengeler, C.; Marschner, H. Partitioning of shoot and root dry matter and carbohydrates in bean plants suffering from phosphorus, potassium and magnesium deficiency. *J. Exp. Bot.* **1994**, *45*, 1245–1250. [CrossRef]
27. Shabala, S.; Cuin, T.A. Potassium transport and plant salt tolerance. *Physiol. Plant.* **2008**, *133*, 651–669. [CrossRef] [PubMed]

28. Zhang, L.; Gao, M.; Li, S.; Alva, A.K.; Ashraf, M. Potassium fertilization mitigates the adverse effects of drought on selected *Zea mays* cultivars. *Turk. J. Bot.* **2014**, *38*, 713–723. [CrossRef]
29. Piskin, A. Effect of Zinc applied together with compound fertilizer on yield and quality of sugar beet (*Beta vulgaris* L.). *J. Plant Nutr.* **2017**, *40*, 2521–2531. [CrossRef]
30. Brown, P.H.; Cakmak, I.; Zhang, Q. Form and function of zinc in plants. In *Zinc Soils Plants*; Robson, A.D., Ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands; Boston, MA, USA; London, UK, 1993; pp. 90–106.
31. Jan, A.U.; Hadi, F.; Nawaz, M.A.; Rahman, K. Potassium and zinc increase tolerance to salt stress in wheat (*Triticum aestivum* L.). *Plant Physiol. Biochem.* **2017**, *116*, 139–149. [CrossRef]
32. Afeez, B.; Khanif, Y.M.; Saleem, M. Role of zinc in plant nutrition—A review. *Am. J. Exp. Agric.* **2013**, *3*, 374–391.
33. Ashraf, M.Y.; Tariq, S.; Saleem, M.; Khan, M.A.; Hassan, S.W.U.; Sadef, Y. Calcium and zinc mediated growth and physio-biochemical changes in mungbean grown under saline conditions. *J. Plant Nutr.* **2020**, *43*, 512–525. [CrossRef]
34. Christenson, D.R.; Draycott, A.P. Nutrition-phosphorus, Sulphur, Potassium, Sodium, Calcium, Magnesium And Micro- Nutrients-Liming and Nutrient Deficiencies. In *Sugar Beet*; Draycott, A.P., Ed.; Bury St. Edmunds, Blackwell Publishing Ltd.: Hoboken, NJ, USA, 2006; pp. 185–219.
35. Attia, K.K.; Abdel-Motagally, F.M.F. Influence of potassium fertilization and foliar application of zinc on sugar beet plants grown on a calcareous sandy soil. *Assiut. J. Agric. Sci.* **2015**, *46*, 1–14.
36. Barłóg, P.; Nowacka, A.; Błaszyk, R. Effect of zinc band application on sugar beet yield, quality and nutrient uptake. *Plant Soil Environ.* **2016**, *62*, 30–35. [CrossRef]
37. Finck, A. *Plant Nutrition in Keywords*; Verlag Ferdinand Hirt: Wroclaw, Poland, 1969; pp. 158–159.
38. Lindsay, W.L.; Norvell, W.A. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Sci. Soc. Am. J.* **1978**, *42*, 421–428. [CrossRef]
39. Cakmak, I. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant Soil.* **2008**, *302*, 1–17. [CrossRef]
40. Barker, A.V.; Pilbeam, D.J. *Handbook of Plant Nutrition*; CRC Press: Boca Raton, FL, USA, 2015; pp. 537–564.
41. Moradi, S.; Jahanban, L. Salinity stress alleviation by Zn as soil and foliar applications in two rice cultivars. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 2517–2526. [CrossRef]
42. Alloway, B.J. *Zinc in Soils and Crop Nutrition*, 2nd ed.; International Zinc Association: Brussels, Belgium, 2008; pp. 42–46.
43. Sagardoy, R.; Vázquez, S.; Florez-Sarasa, I.D.; Albacete, A.; Ribas-Carbó, M.; Flexas, J.; Abadía, J.; Morales, F. Stomatal and mesophyll conductances to CO_2 are the main limitations to photosynthesis in sugar beet (*Beta vulgaris*) plants grown with excess zinc. *New Phytol.* **2010**, *187*, 145–158. [CrossRef] [PubMed]
44. Lucas, R.E.; Knezek, B.D. Climatic and soil conditions promoting micronutrient deficiencies in plants. In *Micronutrients in Agriculture*; Mortvedt, J.J., Giordano, P.M., Lindsay, W.L., Madison, W.I., Eds.; Soil Science society of America: Madison, WI, USA, 1972; pp. 265–288.
45. Ponce, V.; Pandey, R.; Ercan, S. Characterization of drought across climatic spectrum. *J. Hydrol. Eng.* **2000**, *5*, 222–224. [CrossRef]
46. Klute, A. *Methods of Soil Analysis: Part. 1-Physical and Mineralogical Methods*, 2nd ed.; American Society of Agronomy: Madison, WI, USA, 1986.
47. Page, A.I.; Miller, R.H.; Keeney, D.R. *Methods of Soil Analysis: Part. 2-Chemical and Microbiological Properties*, 2nd ed.; American Society of Agronomy: Madison, WI, USA, 1982.
48. Dahnke, W.C.; Whitney, D.A. Measurement of soil salinity. In *Recommended Chemical Soil Test Procedures for the North Central Region*; Dahnke, W.C., Ed.; North Central Regional Publication: Orchard, CO, USA, 1988; pp. 32–34.
49. Soil Survey Staff USDA. *Soil Taxonomy. A Basic System of Soil Classification for Making Sand Interpreting Soil Surveys*, 2nd ed.; Agriculture Handbook no. 466; USDA: Washington, WA, USA, 1999.
50. CAAE (Central Administration for Agricultural Extension). *Beta vulgaris (L.) Cultivation*; Ministry of Agriculture and Land Reclamation: Cairo, Egypt, 2017. Available online: https://ar-ar.facebook.com/caae.eg/ (accessed on 9 February 2017).
51. Watson, D.J. The physiological basis of variation in yield. *Adv. Agron.* **1952**, *4*, 101–145.
52. McGinnus, R.A. *Sugar Beet Technology*, 2nd ed.; Sugar Beet Development Foundation: Denver, CO, USA, 1971.
53. Harvey, G.W.; Dotton, J.V. Root quality and processing. In *The Sugar Beet Crop Science into Practice*; Cooke, D.A., Scott, R.K., Eds.; Chapman & Hall: London, UK, 1993; pp. 571–617.
54. Dewey, J.R.; Lu, K.H. A correlation and path coefficient analysis of yield components of crested wheat grass seed production. *Agron. J.* **1959**, *51*, 515–518. [CrossRef]
55. Yuncai, H.; Schmidhalter, U. Drought and salinity: A comparison of the effects of drought and salinity. *J. Plant Nutr. Soil Sci.* **2005**, *168*, 541–549.
56. Zaki, N.M.; Hassanein, M.S.; Ahmed, A.G.; El-Housini, E.A.; Tawfik, M.M. Foliar application of potassium to mitigate the adverse impact of salinity on some sugar beet varieties. 2: Effect on yield and quality. *Middle East J. Agric. Res.* **2014**, *3*, 448–460.
57. Mehrandish, M.; Moeini, M.M.; Armin, M. Sugar beet (*Beta vulgaris* L.) response to potassium application under full and deficit irrigation. *Eur. J. Exp. Biol.* **2013**, *2*, 2113–2119.
58. Faust, F.; Schubert, S. Protein synthesis is the most sensitive process when potassium is substituted by sodium in the nutrition of sugar beet (*Beta vulgaris*). *Plant Physiol. Biochem.* **2016**, *107*, 237–247. [CrossRef]
59. Chen, J.; Guo, Z.; Chen, H.; Yang, X.; Geng, J. Effects of different potassium fertilizer types and dosages on cotton yield, soil available potassium and leaf photosynthesis. *Arch. Agron. Soil Sci.* **2020**, *67*, 275–287. [CrossRef]

60. Rengel, Z.; Damon, P. Crops and genotypes differ in efficiency of potassium uptake and use. *Physiol. Plant.* **2008**, *133*, 624–636. [CrossRef] [PubMed]
61. Lockhart, J.A. An analysis of irreversible plant cell elongation. *J. Theor. Biol.* **1965**, *8*, 264–275. [CrossRef]
62. Bose, J.; Rodrigo-Moreno, A.; Lai, D.; Xie, Y.; Shen, W.; Shabala, S. Rapid regulation of the plasma membrane H^+-ATPase activity is essential to salinity tolerance in two halophyte species, *Atriplex lentiformis* and *Chenopodium quinoa*. *Ann. Bot.* **2015**, *115*, 481–494. [CrossRef]
63. Hager, A. Role of the plasma membrane H^+-ATPase in auxin-induced elongation growth: Historical and new aspects. *J. Plant Res.* **2003**, *116*, 483–505. [CrossRef] [PubMed]
64. Dutton, J.; Huijbregts, T. Root Quality and Processing. In *Sugar Beet*; Draycott, A.P., Ed.; Blackwell Publishing: Oxford, UK, 2006; pp. 409–442.
65. Carter, J.N. Potassium and sodium uptake effects on sucrose concentration and quality of sugar beet roots. *J. Am. Soc. Sugar Beet Technol.* **1986**, *23*, 183–202. [CrossRef]
66. Mubarak, M.U.; Zahir, M.; Ahmad, S.; Abdul, W. Sugar beet yield and industrial sugar contents improved by potassium fertilization under scarce and adequate moisture conditions. *J. Integr. Agric.* **2016**, *15*, 2620–2626. [CrossRef]
67. Wang, X.G.; Hua, Z.X.; Ji, J.C.; Hong, L.C.; Shan, C.; Di, W.; Qiu, C.Y.; Qiu, Y.H.; Yan, W.C. Effects of potassium deficiency on photosynthesis and photoprotection mechanisms in soybean (*Glycine max* (L.) Merr.). *J. Integr. Agric.* **2015**, *14*, 856–863. [CrossRef]
68. Milford, G.F.J.; Armstrong, M.J.; Jarvis, P.J.; Houghton, B.J.; Bellett-Travers, D.M.; Jones, J.; Leigh, R.A. Effect of potassium fertilizer on the yield, quality and potassium offtake of sugar beet crops grown on soils of different potassium status. *J. Agric. Sci.* **2000**, *135*, 1–10. [CrossRef]
69. Bhador, M.A.; Minoii, M.A.; Alizadeh, A.N. Effect of planting dates and NPK fertilization on growth and yield of sugar beet (*Beta vulgaris* L.). *J. Agric. Sci. Miyane Univ.* **2010**, *20*, 2683–2689.
70. Wang, M.; Zheng, Q.; Shen, Q.; Guo, S. The critical role of potassium in plant stress response. *Int. J. Mol. Sci.* **2013**, *14*, 7370–7390. [CrossRef] [PubMed]
71. Chen, Z.; Pottosin, I.I.; Cuin, T.A.; Fuglsang, A.T.; Tester, M.; Jha, D.; Zepeda-Jazo, I.; Zhou, M.; Palmgren, M.G.; Newman, I.A.; et al. Root plasma membrane transporters controlling K^+/Na^+ homeostasis in salt-stressed barley. *Plant Physiol.* **2007**, *145*, 1714–1725. [CrossRef] [PubMed]
72. Zhu, J.K. Regulation of ion homeostasis under salt stress. *Curr. Opin. Plant Biol.* **2003**, *6*, 441–445. [CrossRef]
73. Jafarzadeh, A.A.; Aliasgharza, N. Salinity and salt composition effects on seed germination and root length of four sugar beet cultivars. *Biol. Bratisl.* **2007**, *62*, 562–564. [CrossRef]
74. Ćirić, M.Z. The effect of genotype x environment interaction on root yield and quality of sugar beet. *Fac Agric. Univ. Belgrade.* **2017**, *9*, 1041.
75. Beringer, H.; Koch, K.; Lindhauer, M.G. Sucrose accumulation and osmotic potentials in sugar beet at increasing levels of potassium nutrition. *J. Sci. Food Agric.* **1986**, *37*, 211–218. [CrossRef]
76. Schlumbach, K.; Scharfe, M.; Flöter, E. Color transfer into sucrose crystallized from blended beet and cane syrups. *Sugar Ind.* **2016**, *141*, 97–104. [CrossRef]
77. Moustafa, M.S. Influence of sowing dates and foliar spraying of iron and zinc on sugar beet productivity in salt affected soil. *J. Plant Prod.* **2019**, *10*, 569–573. [CrossRef]
78. Fischer, E.S. Moderate magnesium deficiency affected chlorophyll content of bean plat. *Photosynthetica* **1997**, *33*, 385–390.
79. Cakmak, I. Possible roles of zinc in protecting plant cells from damage by reactive oxygen species. *New Phytol.* **2000**, *146*, 185–205. [CrossRef]
80. Henriques, F.S. Loss of blade photosynthetic area and of chloroplasts' photochemical capacity account for reduced CO_2 assimilation rates in zinc-deficient sugar beet leaves. *J. Plant Physiol.* **2001**, *158*, 915–919. [CrossRef]
81. Neamatollahi, E.; Khademosharieh, M.M.; Darban, A.S.; Jahansuz, M.R. Application of different amounts of $ZnSO_4$ in five varieties of sugar beet. *Adv. Environ. Biol.* **2013**, *7*, 1113–1116.
82. Abo-Steet, S.; El-Edfawy, Y.; Niazy, M. Mutual effect among compost and foliar spraying with zinc and boron on sugar beet (*Beta vulgaris* L.) grown on saline sandy loam soil. *J. Soil Sci. Agric. Eng.* **2015**, *6*, 1091–1105. [CrossRef]
83. Broadley, M.; Brown, P.; Çakmak, I.; Rengel, Z.; Zhao, F. Function of nutrients: Micronutrients. In *Marschner's Mineral Nutrition of Higher Plants*; Marschner, P., Ed.; Academic Press: London, UK, 2012; pp. 191–248.
84. Weisany, W.; Sohrabi, Y.; Heidari, G.; Siosemardeh, A.; Badakhshan, H. Effects of zinc application on growth, absorption and distribution of mineral nutrients under salinity stress in soybean (*Glycine max* L.). *J. Plant Nutr.* **2014**, *37*, 2255–2269. [CrossRef]
85. ElSayed, A.I.; Boulila, M.; Rafudeen, M.S.; Sengupta, S.; Rady, M.M. Melatonin regulatory mechanisms and phylogenetic analyses implying new sequences of melatonin biosynthesis related genes extracted from peanut under salinity stress. *Plants* **2020**, *9*, 854. [CrossRef]
86. Seleiman, M.F.; Semida, W.M.; Rady, M.M.; Mohamed, G.F.; Hemida, K.A.; Alhammad, B.A.; Hassan, M.M.; Shami, A. Sequenced Antioxidants Application Rectifies Ion Imbalance and Strengthens Antioxidant Systems in Salt-stressed Cucumber. *Plants* **2020**, *9*, 1783. [CrossRef]
87. Taha, R.S.; Seleiman, M.F.; Alotaibi, M.; Alhammad, B.A.; Rady, M.M.; Mahdi, A.H.A. Exogenous potassium treatments elevate salt tolerance and performances of *Glycine max* by boosting antioxidant defense system under actual saline field conditions. *Agronomy* **2020**, *10*, 1741. [CrossRef]

88. Desoky, E.S.; Mansour, E.; Ali, M.M.A.; Yasin, M.A.T.; Abdul-Hamid, M.I.E.; Rady, M.M.; Ali, E.F. Exogenously used 24-epibrassinolide promotes drought tolerance in maize hybrids by improving plant and water productivity in an arid environment. *Plants* **2021**, *10*, 354. [CrossRef] [PubMed]
89. Semida, W.M.; Abdelkhalik, A.; Mohamed, G.F.; Abd El-Mageed, T.A.; Abd El-Mageed, S.A.; Rady, M.M.; Ali, E.F. Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (*Solanum melongena* L.). *Plants* **2021**, *10*, 421. [CrossRef]