Physio-biochemical and Agronomic Changes of Two Sugar Beet Cultivars Grown in Saline Soil as Influenced by Potassium Fertilizer

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Abstract

In salt-affected soils, more than one approach should be adopted for minimizing the salinity impacts and enhancing the land productivity. The most effective practices in crop management under saline soil are choosing the plant type and variety and exploiting the best nutrient tactics. Under two soil salinity levels (3.54 and 9.28 dS m⁻¹), representing low and high salinity, respectively), two sugar beet cultivars (Romulus and Francesca) were fertilized with three potassium (K) rates (48, 96, and 144 kg K ha⁻¹), in addition to the check treatment (0 kg K ha⁻¹). During two seasons of 2018/2019 and 2019/2020, treatments were distributed in a split-split plot design based on a randomized complete block arrangement with three replicates. Several physio-biochemical and agronomic traits, as well as leaf mineral contents and juice quality, were assessed. Briefly, findings illustrated that K at a rate of 144 kg ha⁻¹ enhanced cell membrane stability, relative water content, and performance index by 1.17, 1.01, and 2.73 times, respectively, in high salinity soil, compared to low salinity × no K addition. Under high salinity, the addition of 48 and 144 kg K ha⁻¹ recorded the highest values of total phenolic content and total antioxidant activity, respectively. In high salinity soil, K supplying (144 kg ha⁻¹) caused the maximum improvements in gross and white sugar content with a decrease of 42.0% in sodium content and an increase of 35.9% in root yield ha⁻¹. Romulus cultivar fertilized with 144 kg K ha⁻¹ had the maximum relative water content, Fv/Fm, and performance index. Francesca cultivar with 144 kg K ha⁻¹ was the potent combination for increasing total soluble sugars, total phenolic content, total flavonoid content, and total antioxidant activity. Romulus cultivar fertilized with 144 kg K ha⁻¹ was the best practice for improving all agronomic traits of sugar beet. It could be concluded that a high potassium rate, i.e., 144 kg K ha⁻¹, reduced the injury ionic impacts of saline soils along with improving the genetic makeup of sugar beet cultivars, expressed in sugar yield and quality. However, all other attempts for reclamation of the saline soil should be adopted for increasing the potentiality of K fertilizer and enhancing gene expressions of different sugar beet varieties.

Keywords Beta vulgaris · Biochemical indices · Genetic diversity · Plant nutrition · Salinity tolerance · Sugar impurities

1 Introduction

Sucrose, a disaccharide sugar, is one of the main plant-derived foods in the human diet worldwide. Sugar beet (Beta vulgaris L.) is being still one of the major sources for sucrose extraction. Yearly, the total world cultivated acreage of ~4.44 Mt produces ~253 Mt of sugar beet roots that provides ~30% of the gross world’s requirements of white sugar (FAO 2022). Approximately 2.3 million tons (~59%) of consumed sucrose in Egypt is produced from beet and ~41% being from cane (CCSC 2018). Due to global climate change, sugar beet production in arid and semiarid climates, including Egypt, has frequently faced adverse environmental challenges such as dryness, heat, nutrient
deficiency and soil salinization (Abd El-Mageed et al. 2019; Saudy et al. 2020, 2022; Mekdad et al. 2021b; El-Bially et al. 2022a; El-Metwally et al. 2022).

Salinized lands area is about 7% of the total irrigated croplands in the world and the salinization annually causes bringing 1.5 million hectares out of production (Munns and Tester 2008; Semida et al. 2014). Egypt has about 0.9 million hectares (~25%) of the total irrigated cultivable croplands suffering from salinization problems (FAO 2016).

Sugar beet plants naturally adapt to tolerate salinity up to electric conductivity of 7.0 dS m\(^{-1}\) in growth media without a considerable yield reduction, and each additional EC unit causes a 5.9% yield loss (Grieve et al. 2012). Salinity adversely affects crop growth and survival by instigating osmotic and drought stressors, which results in ionic misbalance due to high accretion of sodium (Na\(^+\)) and chlorine (Cl\(^-\)) ions, leading to specific ions cytotoxicity (Wu et al. 2015b; Dadkhah and Rassam 2017; Abd-Elrahman et al. 2022; Makhlouf et al. 2022). When Na\(^+\) accretion surpasses the normal level, it turns to be highly deleterious to plant growth owing to cell ionic homeostasis discrepancy by prompting cytosolic K\(^+\) flux from cells (Shabala and Pottosin 2014; Semida et al. 2015). High osmotic pressure with more Na\(^+\) and Cl\(^-\) influx into root cells results in deficiency for essential nutrients uptake, particularly potassium, K\(^+\); calcium, Ca\(^{2+}\); magnesium, Mg\(^{2+}\); and nitrate, NO\(_3\)^\(^-\), leading to ionic misbalance in plant cells (Wang et al. 2017). On another side, ionic stress drives early leaf senescence, reducing photo assimilates supply for growth-supporting at cost of yield diminution even under low or medium salinity conditions (Negrao et al. 2017). When salinity and phytonutrient deficiency have the same adverse effect on plant growth, a mitigation salinity stress by correcting nutrient deficiency can improve crop returns (Hatam et al. 2020; Shaaban et al. 2022). To counteract the salinity-induced adverse effects on crop plants, various strategies in genetic, chemical, physical, and biological terms have been implemented.

Mineral nutrition plays a beneficial role in developing environmental stress tolerance in crop plants, including salinity (Wu et al. 2015a; Mekdad and Rady 2016; Jan et al. 2017; Mekdad et al. 2021c). Among elements, K\(^+\) remains one of the greatest essential phytonutrients for the life cycle of most crop species, including sugar beet (Marschner 2012). K\(^+\) is a phyto-beneficial macroelement that performs a pivotal role in organizing physio-biochemical processes to support plant survival against abiotic stresses, including salinity (Merwad 2016; Mekdad et al. 2021a). Keeping a higher ratio of cytosolic K\(^+\)/Na\(^+\) by expelling Na\(^+\) from cytosol to sequester into the intracellular vacuoles to limit cellular deterioration is an important adaptive mechanism for cytosolic K\(^+\) homeostasis, better crop establishment and survival, and effective CO\(_2\) assimilation, even under salinity stress conditions (Wakeel 2013; Pi et al. 2016; Yu et al. 2020). The active compartmentalization of Na\(^+\) into the intracellular vacuoles is mediated by the activities of Na\(^+\)/H\(^+\) antiporters localized in tonoplast, which are fundamentally based on the electrochemical H\(^+\) gradients produced by the vacuolar H\(^+\) pumps (Wu et al. 2019). The proton’s driving energy used by the vacuolar Na\(^+\)/H\(^+\) antiporters is produced by the tonoplast H\(^+\)-transferring enzymes like plasma membrane-bound H\(^+\)-ATPase (PM H\(^+\)-ATPase) being a key mediator for membrane polarization, which is catalyzed by K\(^+\) element (Wakeel et al. 2011). When salt-affected soil is poor in available K\(^+\) content, its high Na\(^+\) content restricts the K\(^+\) uptake by root cells and causes a change in membrane polarity to prevent outwardly K\(^+\) through cationic efflux channels (Cuin et al. 2008). Thus, adequate K\(^+\) nutrition has been shown to mediate PM H\(^+\)-ATPase activation to increase protons extrusion under abiotic stresses (Weng et al. 2020). Because breeding programs to develop salt-tolerant crop plants have had very limited success (Schubert et al. 2009), as a result, physiological approaches such as maintaining K\(^+\)/Na\(^+\)-homeostasis should be given utmost attention through developed field management strategies, e.g., external K\(^+\) supplementation for crop plants grown in salt-affected soils (Merwad 2016; Mekdad et al. 2021a). Accordingly, deficit K\(^+\) can interrupt many interlinked physio-biochemical activities, plant growth weakness, and premature leaf senescence, resulting in early crop maturity; thus, judicious K\(^+\) addition under saline soil conditions could enhance the crop productivity (Salem et al. 2022). However, to the best of the author’s knowledge, relatively little information is available about the beneficial effects of exogenous K\(^+\) application for supporting salinity tolerance in sugar beet under semiarid conditions. Accordingly, the current study hypothesized that potassium has different ameliorating influences against salinity impact for tolerant and sensitive sugar beet cultivars. From an agro-physio-biochemical aspect, this investigation was conducted to outstanding how the useful influences of potassium could improve salinity stress tolerance in two sugar beet cultivars?

2 Materials and Methods

2.1 Experimental Site

Two experiments were conducted at two different sites, selected in Sinnuris District, El Fayoum region, Egypt, between latitudes 29°02´ and 29°35´ N and longitudes 30°22´ and 31°05´ E (Fig. 1) during two cropping seasons from October to April 2018/2019 and 2019/2020. Salinity levels of selected two sites were measured as the electrical conductivity (ECe) of a saturated-paste extract of the soil of each site. Based on the soil taxonomy (IUSS Working Group WRB 2015), the soil is Typic Torripsamments, siliceous,
hyperthermic, and moderately deep. In addition, the main physical and chemical characteristics of the soil of both sites were measured according to Page et al. (1982) and Klute and Dirksen (1986). The experimental soil was sandy loam having sand (78.4–77.6%), silt (11.3–12.4%), clay (10.3–10.0%), bulk density (1.5–1.6 g cm$^{-3}$), pH (7.7–7.6), ECe (3.54–9.28 dS m$^{-1}$), cation exchange capacity (11.8–11.1 cmol kg$^{-1}$), calcium carbonate (5.5–4.7%), organic carbon (0.66–0.64%), available N, (58.5–56.3 mg kg$^{-1}$ soil), available P (5.1–4.7 meq 100$^{-1}$ g soil), and available K (47.0–45.1 meq 100$^{-1}$ g soil) for the two sites, respectively. The experimental location is classified as an arid zone with cool winters and nonsignificant precipitation.

The meteorological data collected during the two growing seasons revealed that the averages of minimum air temperature were 9.2–10.9 °C, maximum air temperature were 22.3–23.8 °C, relative humidity were 41.0–41.6%, wind speed were 2.0–1.8 m sec$^{-1}$, and precipitation were 0.51–0.85 MJ mm day$^{-1}$, respectively.

### 2.2 Treatments and Experimental Design

The experimental layout was a split-split plot system based on a randomized complete block design with three replications. Soil salinity (i.e., low = 3.54 and high = 9.28 dS m$^{-1}$) levels were fallen in the main plots, while cultivars (i.e., Romulus; multigermer and Francesca; monogerm) were allocated in the subplots, and potassium fertilizer (i.e., 0, 48, 96, and 144 kg ha$^{-1}$) levels were distributed in sub-subplots. Each experimental plot includes five ridges, 0.6 m apart and 6.0 m long, shaping an area of 18.0 m$^2$ (3 m x 6 m) and about 0.20-m interplant distance within the ridge. The K rates in the form of potassium sulphate ($\text{K}_2\text{SO}_4$; 48% $\text{K}_2\text{O}$) were added as soil application twice at planting and 30 days from planting (DFP).

### 2.3 Crop Management Practices

Health seeds of multi- and mono-germ sugar beet (Beta vulgaris L. cvs. Romulus and Francesca) were obtained from the Crop Research Institute, Agricultural Research Center, Egypt. These commercial high-production cultivars were chosen based on their widespread in the areas of sugar beet cultivation in Egypt. Seeds were manually planted on 20th and 25th of October, and roots were harvested on 25th and 28th of April in both 2018/2019 and 2019/2020 seasons, respectively. At 4-leaf stage (~30 DFP), the thinning process was done to keep one plant hill$^{-1}$. Based on recommendations of the Egyptian ministry of agriculture and land Reclamation, the tested soil supplied with 90 kg P ha$^{-1}$ (625-kg calcium monophosphate; 15.5% $\text{P}_2\text{O}_5$) and 290 kg N ha$^{-1}$ (850 kg ammonium nitrate; 33.5% N). During the growth and development, plants received 4 irrigations through surface irrigation system. The cultural, diseases, fertilization program, and pest management were identical as local commercial sugar beet production.

### 2.4 Measurements

#### 2.4.1 Physiological Traits

At 95 DFP, 3 sugar beet plants randomly taken, the maximum quantum yield of PSII in a dark-adapted state (variable fluorescence by maximum fluorescence; $F_v/F_m$ and...
photosynthetic performance index; PPI) was measured using a fluorimeter (Handy PEA, Hansatech Instruments Ltd, Kings Lynn, UK) as shown by Clark et al. (2000); Maxwell and Johnson (2000), respectively. Also, the leaf relative turgidity (LRT%) and membrane stability index (MSI%) of the fully expanded fresh leaves were determined (Premachandra et al. 1990). The relative chlorophyll concentration (SPAD chlorophyll) was determined using a chlorophyll meter (SPAD502, KONICAMINOLTA. Inc., Tokyo).

### 2.4.2 Biochemical Traits

**Total Soluble Sugars (TSS)** Freshly prepared phenol (1 ml of 5%) was added to 0.1 ml of a carbohydrate solution (samples were prepared at a concentration of 1 mg mL^{-1}) in a test tube. Subsequently, 5 mL of concentrated sulfuric acid is added rapidly to the mixture. After allowing the test tubes to stand for 10 min, they are vortexed for 30 s and placed for 20 min in a water bath at room temperature for color development. Then, the absorbance was measured at 490 nm with VWR 6300 double beam UV–visible spectrophotometer with Hitachi software (Labconco, USA). The TS sugar content in the samples was calculated from a standard curve using pure glucose.

**Total Phenolic Content (TPC)** The amount of total phenolic in the plant extract was determined by Folin-Ciocalteu reagent using the procedure of (Yu et al. 2002). A 200 μl of each sample were mixed with 500 μl of the Folin-Ciocalteu reagent and 1.5 ml of 20% sodium carbonate. The mixture was shaken thoroughly and made up to 10 ml using distilled water. After 2 h of incubation at room temperature, the absorbance was measured at 765 nm. The assay was carried out in triplicate and the mean values were calculated. The concentration was determined from the standard curve prepared using serial concentrations of standard gallic acid solution. Total phenolic contents in plant extracts were expressed as mg gallic acid equivalent (GAE) per g plant extract after reading the concentration of phenolic (mg mL^{-1}) from the calibration line and calculated using Eq. 1:

\[ C = \frac{cV}{m} \]  

where \( C \) is the total content of phenolic compounds in mg GAE per g dry extract; \( c \) is the concentration of gallic acid obtained from the calibration curve (mg mL^{-1}); \( V \) is the volume of extract (ml); and \( m \) is the weight (g) of plant extract.

**Total Flavonoid Content (TFC)** Total flavonoid content in the plant extract was determined using the method described by (Lamaison and Carnet, 1990). Briefly, 200 ml of each sample was transferred to a test tube and evaporated to dryness. To the residue, 5 ml of 0.1 M AlCl₃ was added and shaken.

The absorbance of the samples was measured at 415 nm after keeping the samples for 40 min at room temperature. Total flavonoid content was expressed as mg rutin equivalent (RE) per g plant extract and calculated using Eq. 2:

\[ X = \frac{A \times m_o}{A_o \times m} \]  

where \( X \) is the total flavonoid content in mg per g dry extract; \( A \) is the absorption of plant extract solution; \( A_o \) is the absorption of standard rutin solution; \( m \) is the weight of extract in mg, and \( m_o \) is the weight of rutin in the solution in mg.

**Total Antioxidant Activity** DPPH radical-scavenging activity of all the extracts was measured by the modified method according to (Brand-Williams et al. 1995). A 2.0 ml of ethanolic solution of each extract at a concentration of 50 μg mL⁻¹ was added to a 2.0-ml solution of DPPH (25 mg l⁻¹) in ethanol. The DPPH solution was prepared freshly every day, and the reaction mixture was shaken vigorously. After incubation at room temperature (28 ± 2 °C) in the dark for half an hour, the absorbance is then determined at 517 nm by VWR 6300 double beam UV–visible spectrophotometer with Hitachi software (Labconco, USA). Ascorbic acid was used as positive control. The percentage inhibition of DPPH free radical-scavenging activity of each extract was calculated using Eq. 3:

\[ \text{Inhibition} \% = \frac{A_c - A_s}{A_c} \times 100 \]  

where \( A_c \) refers to the absorbance of a DPPH solution without extract and \( A_s \) is the absorbance of the tested extract. Triplicate measurements were taken, and mean values calculated. The ascorbic acid calibration curve was prepared for a concentration range from 10 to 200 μg ml⁻¹, and IC₅₀ values were obtained.

### 2.4.3 Agronomic Traits

At harvest (200 and 210 DFP) in both seasons, respectively, ten individual plants of each experimental plot were sampled randomly. Plants were utilized to measure leaf area plant⁻¹ by digital planimeter (Planix 7). The root length was measured by meter-scale from the point where the top was separated to the taproot tip with a diameter of about 1 cm. The root diameter was measured by vernier caliper at the widest area of the root. The root fresh weight plant⁻¹ was measured using digital balance. Moreover, all sugar beet plants in each experimental plot in addition to the ten sugar beet plants, sampled previously, were collected, cleansed, topped, and weighed, for estimate root yield (t ha⁻¹). White sugar yield (t ha⁻¹) was also computed by multiplying root yield by white sugar content (%).
2.4.4 Leaf Mineral Contents

For assessment of the macronutrient (i.e., nitrogen, N; phosphorus, P; potassium, K; calcium, Ca; and sodium, Na) concentrations in plant tissues, sugar beet leaves (n = 10) were dried and milled into powder before chemical analysis. Using a micro-Kjeldahl apparatus (Ningbo Medical Instruments Co., Ningbo, China), the N content was determined following the methods of (AOAC, 2012). The P content was assessed by quantification according to (Jackson, 1973) using standard reagents of H2MoO7S, molybdenum blue, diluted H2MoO7S, and 8% (w/v) NaHSO3–H2SO4. Additionally, the Ca2+ content was assessed using an atomic absorption spectrophotometer (Perkin–Elmer, Model 3300) described by Chapman and Pratt (1961). Finally, K+ and Na+ contents were assessed according to Lachica et al. (1973) in a 50-mg freeze-dried leaf powder suspension and centrifuged at 3.000 × g for 10 min at 25 °C.

2.4.5 Beet Juice Quality

The beet juice quality attributes, i.e., gross sugar content (%) (i.e., polarity %), was estimated as outlined in McGinnus (1971). The non-sucrose impurities, i.e., sodium and potassium contents, were measured using a flame photometer, while alpha-amino-nitrogen was colorimetrically determined by a spectrophotometer. Moreover, the true sugar (TS %) was computed as follows:

\[
\text{white sugar content (\%)} = \text{gross sugar content (\%)} - \left(0.343(\text{sodium + potassium}) + 0.0939(\text{alpha} - \text{nitrogen} + 0.029)\right)
\]

\[(4)\]

2.5 Statistical Analysis

Microsoft Excel 2016 was used to compute means ± standard error and prepare the figures. Also, pre-running the variance analysis for both seasons and error variance homogeneity for all variables was tested. The analysis for the two seasons was performed based on a split-split plot in RCBD using GenStat statistical package (version 12) (VSN International Ltd, Oxford, UK). Means for all variables were separated using Fisher’s least-significant difference test at p ≤ 0.05 (GENSTAT 2007).

3 Results

3.1 Main Effects

3.1.1 Physiological Changes

Distinctive declines in cell membrane stability, relative water content, Fv/Fm, performance index, and SPAD-reading were obtained with high soil salinity than low soil salinity (Table 1). Romulus cultivar had values of membrane stability, relative water content, Fv/Fm performance index, and SPAD-reading greater than Francesca cultivar with increases of 12.2, 9.4, 2.5, 18.3, and 18.6% respectively. Progressive increase in K levels showed increases in sugar beet physiological traits. In this respect, K at a rate of 144 kg ha−1 achieved 19.8, 12.9, 6.3, 218.9, and 57.9% increases in cell membrane stability, relative water

| Variable                  | Physiological traits | Biochemical traits |
|---------------------------|----------------------|--------------------|
|                           | CMSI (%) | RWC (%) | Fv/Fm | Performance index | SPAD-reading | TSS (mg g−1 DW) | TPC (mg GA 100−1 g DW) | TPC (mg RE 100−1 g DW) | TAA (%) |
| Salinity level             |           |         |       |                  |             |                  |                          |                          |         |
| Low                       | 70.8±1.0a  | 79.8±0.7a | 0.83±0.003a | 9.68±0.58a | 55.6±1.6a | 1.78±0.06b | 403.5±3.2b | 251.6±1.5b | 83.2±0.6b |
| High                      | 68.6±1.0b  | 72.2±0.8b | 0.81±0.004b | 8.68±0.49b | 45.2±1.3b | 2.01±0.06a | 416.9±5.3a | 255.6±1.0a | 84.5±0.7a |
| Cultivar                  |            |         |       |                  |             |                  |                          |                          |         |
| Romulus                   | 73.7±0.8a  | 79.4±0.8a | 0.83±0.003a | 9.95±0.56a | 54.7±1.7a | 1.77±0.06b | 410.2±3.8a | 254.1±1.0a | 83.9±0.6a |
| Francesca                 | 65.7±0.9b  | 72.6±0.8b | 0.81±0.004b | 8.41±0.49b | 46.1±1.3b | 2.01±0.06a | 410.2±5.1a | 253.2±1.6a | 83.9±0.7a |
| K rate (kg ha−1)          | 0         | 1.1d    | 0.79±0.004d | 4.23±0.17d | 38.5±1.2d | 1.66±0.07d | 366.6±2.6c | 240.5±1.3c | 78.2±0.4c |
|                           | 48        | 1.2c    | 0.82±0.003c | 8.20±0.28c | 47.3±1.4c | 1.76±0.07c | 418.7±3.3b | 255.2±1.0b | 83.3±0.6b |
|                           | 96        | 1.3b    | 0.83±0.004b | 10.82±0.33b | 55.0±1.6b | 1.89±0.05b | 421.5±4.8b | 259.0±0.5a | 86.6±0.4a |
|                           | 144       | 1.0a    | 0.84±0.003a | 13.49±0.40a | 60.8±1.9a | 2.26±0.9a | 434.0±3.1a | 259.8±0.7a | 87.3±0.7a |

Low and high soil salinity refer to an electrical conductivity; ECe=3.54 and 9.28 dS m−1, respectively. CMSI cell membrane stability index, RWC relative water content, Fv/Fm efficiency of PSII maximal quantum, SPAD Soil plant analysis development, TSS total soluble sugars, TPC total phenolic content, TFC total flavonoid content, and TAA total antioxidant activity. Means not sharing the common letters for each factor in each column differ significantly at p ≤ 0.05 based on Student–Newman–Keuls test
content, \( F_v/F_m \), performance index, and SPAD-reading, respectively, compared to no K application.

### 3.1.2 Biochemical Changes

Total soluble sugars, total phenolic content, total flavonoid content, and total antioxidant activity were higher under high salinity than low salinity (Table 1). Variation the two sugar beet cultivars in biochemical constituents was only obtained for total soluble sugars. In this respect, total soluble sugars value of Francesca cultivar was greater by 1.13 times than those of Romulus cultivar. Application of K at a rate of 144 kg ha\(^{-1} \) (for all assessed biochemical constituents), in addition to K at a rate of 96 kg ha\(^{-1} \) (for total flavonoid content, and total antioxidant activity), possessed the maximum increases.

### 3.1.3 Leaf Mineral Contents

Sugar beet leaf N (Fig. 2a), P (Fig. 2b), K\(^+ \) (Fig. 2c), Na\(^+ \) (Fig. 3a), Ca\(^{2+} \) (Fig. 3b), and Na\(^+\)/K\(^+ \) (Fig. 3c) were significantly influenced by salinity level, cultivar, and K rate except Ca\(^{2+} \) with salinity level and K\(^+\):Na\(^+ \) with cultivar. Owing to high salinity, decreases in N, P, K\(^+ \), and K\(^+\):Na\(^+ \) were approximately 21.4, 11.0, 2.8, and 6.6%, respectively, while Na\(^+ \) was higher (12.3%) compared to low level of soil salinity. The leaves of Romulus cultivar contained higher values of N, P, K\(^+ \), and K\(^+ \) and lower values of Na\(^+ \) and Ca\(^{2+} \).

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**Fig. 2** Leaf N (a), P (b), and K\(^+ \) (c) contents of sugar beet as influenced by salinity, cultivar, and potassium (K) rate (kg ha\(^{-1} \)). Low and high soil salinity refer to an electrical conductivity; EC\(e = 3.54 \) and 9.28 dS m\(^{-1} \), respectively. Means not sharing the common letters for each factor, in each bar, differ significantly at \( p \leq 0.05 \) based on student–Newman–Keuls test. N, nitrogen; P, phosphorus; and K\(^+ \), potassium.
as compared to Francesca one. Application of K at a rate of 144 kg ha\(^{-1}\) possessed the maximum increases in N, P, K\(^{+}\), Ca\(^{2+}\), and K\(^{+}/\)Na\(^{+}\) surpassing the other K rates, except the rate of 48 kg K ha\(^{-1}\) for Ca\(^{2+}\). Unlike, the maximal Na\(^{+}\) was obtained with no K addition (0 K kg ha\(^{-1}\)).

3.1.4 Agronomic Traits

All agronomic traits of sugar beet markedly responded to salinity level, cultivar, and K rate (Table 2). As expected, the values of root length, root diameter, root fresh weight, leaf area plant\(^{-1}\), root yield ha\(^{-1}\), and white sugar yield ha\(^{-1}\) were lower with high salinity than low salinity. Romulus cultivar was more efficient for recording improved agronomic traits higher than Francesca cultivar. Romulus cultivar exceeded Francesca cultivar by about 15.6, 19.5, 47.5, 62.1, 19.2, and 24.5% for root length, root diameter, root fresh weight, leaf area plant\(^{-1}\), root yield ha\(^{-1}\), and white sugar yield ha\(^{-1}\), respectively. Increases in all crop traits of sugar beet due progressive increase the K level supply were observed.
Herein, application of K at a rate of 144 ha\(^{-1}\) caused 1.33, 1.27, 2.36, 2.13, 1.70, and 2.26 folds in root length, root diameter, root fresh weight, leaf area plant\(^{-1}\), root yield ha\(^{-1}\), and white sugar yield ha\(^{-1}\), respectively, comparing to no K application.

### 3.1.5 Beet Juice Quality

Gross sugar content (Fig. 4a), sodium (Fig. 4b), potassium (Fig. 4c), alpha-amino-nitrogen (Fig. 5a), and white sugar content (Fig. 5b) of sugar beet were statistically affected by salinity, cultivar, and K application. Compared to low soil salinity (ECe of 3.54 dS m\(^{-1}\)), soil with ECe of 9.28 dS m\(^{-1}\) caused 1.5, 17.9, 9.2, and 1.2% increases in sugar content, sodium, alpha-amino-nitrogen, and white sugar content, respectively, as well as 0.8% decrease in potassium. Romulus cultivar produced higher gross sugar content and white sugar content as well as lower sodium, potassium, and alpha-amino-nitrogen than that of Francesca cultivar. More gross and white sugar content, in addition to more potassium, were accumulated in roots of sugar beet plants fertilized with 144 kg K ha\(^{-1}\). Sodium and alpha-amino-nitrogen were more pronounced in K-unfertilized plants.

### 3.2 Interactions

### 3.2.1 Physiological Changes

Salinity level × cultivar interaction had significant effects on performance index and SPAD-reading, while cell membrane stability, relative water content, and \(F_v/F_m\) did not affect (Table 3). Romulus cultivar recorded the highest values of performance index and SPAD-reading in low salinity soil. K application enhanced the physiological traits of sugar beet whether with or without salt stress. Generally, K addition at a rate of 144 kg ha\(^{-1}\) was the effective practice for enhancing cell membrane stability, relative water content, and performance index under both low and high salinity. Especially under high salinity, K at a rate of 144 kg ha\(^{-1}\) enhanced cell membrane stability, relative water content, and performance index by 1.17, 1.01, and 2.73 times, respectively, compared to low salinity × no K addition as well as 1.21, 1.17, and 3.07 times, respectively, compared to high salinity × no K addition. The interaction of cultivar × K application revealed that Romulus plants fertilized with 144 kg K ha\(^{-1}\) had the maximum relative water content, \(F_v/F_m\) and performance index, while the highest SPAD-reading was obtained with Francesca plants fertilized with 96 kg K ha\(^{-1}\).

### 3.2.2 Biochemical Changes

Under high salinity, Francesca cultivar showed the highest amounts of total soluble sugars and total phenolic content, while Romulus cultivar recorded the maximum increase in total antioxidant activity (Table 3). Fertilizing sugar beet grown in low salinity soil by 144 kg K ha\(^{-1}\) gave the maximum total soluble sugars. Under high salinity addition of 48 and 144 kg K ha\(^{-1}\) recorded, the highest values of total phenolic content and total antioxidant activity, respectively. Application of 96 or 144 kg K ha\(^{-1}\) whether with low or high salinity showed similar values of total flavonoid content. The interaction of sugar beet cultivar and potassium fertilization cleared that fertilizing Francesca cultivar with 144 kg K ha\(^{-1}\) was the potent combination for increasing the total soluble sugars, total phenolic content, total flavonoid content, and total antioxidant activity.

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**Table 2** Agronomic traits of sugar beet as influenced by salinity, cultivar, and potassium application

| Variable | Root length (cm) | Root diameter (cm) | Root fresh weight (kg plant\(^{-1}\)) | Leaf area plant\(^{-1}\) (dm\(^2\)) | Root yield (t ha\(^{-1}\)) | White sugar yield (t ha\(^{-1}\)) |
|----------|-----------------|-------------------|--------------------------------------|-----------------------------------|-----------------------------|-------------------------------|
| Salinity level |                  |                   |                                      |                                   |                             |                               |
| Low      | 28.7 ± 0.72a     | 14.5 ± 0.30a       | 1.51 ± 0.08a                         | 575.0 ± 29.6a                     | 72.7 ± 2.3a                 | 12.7 ± 0.58a                  |
| High     | 25.2 ± 0.50b     | 12.5 ± 0.25b       | 0.99 ± 0.06b                         | 452.2 ± 30.1b                     | 57.7 ± 1.9b                 | 10.2 ± 0.51b                  |
| Cultivar |                  |                   |                                      |                                   |                             |                               |
| Romulus  | 28.9 ± 0.64a     | 14.7 ± 0.29a       | 1.49 ± 0.09a                         | 635.2 ± 29.7a                     | 70.9 ± 2.4a                 | 12.7 ± 0.61a                  |
| Francesca| 25.0 ± 0.58b     | 12.3 ± 0.21b       | 1.01 ± 0.06b                         | 391.9 ± 20.6b                     | 59.5 ± 2.0b                 | 10.2 ± 0.48b                  |
| K rate (kg ha\(^{-1}\)) |          |                   |                                      |                                   |                             |                               |
| 0        | 22.9 ± 0.40d     | 11.8 ± 0.31d       | 0.76 ± 0.06d                         | 332.4 ± 25.4d                     | 48.4 ± 1.6d                 | 7.1 ± 0.24d                   |
| 48       | 25.6 ± 0.49c     | 13.2 ± 0.34c       | 1.08 ± 0.08c                         | 431.4 ± 29.2c                     | 59.1 ± 1.8c                 | 9.6 ± 0.34c                   |
| 96       | 28.6 ± 0.72b     | 14.1 ± 0.33b       | 1.37 ± 0.08b                         | 580.6 ± 37.3b                     | 71.0 ± 2.3b                 | 13.1 ± 0.50b                  |
| 144      | 30.6 ± 1.05a     | 15.0 ± 0.45a       | 1.80 ± 0.10a                         | 710.0 ± 39.9a                     | 82.4 ± 2.5a                 | 16.1 ± 0.52a                  |

Low and high soil salinity refer to an electrical conductivity; ECe = 3.54 and 9.28 dS m\(^{-1}\), respectively. Means not sharing the common letters for each factor, in each column, differ significantly at \(p \leq 0.05\) based on student–Newman–Keuls test.
3.2.3 Leaf Mineral Contents

Only N, K+, and K⁺:Na⁺ responded to the different salinity level × cultivar, while P, Na⁺, and Ca²⁺ did not affect (Table 4). Romulus plants grown in low salinity conditions showed the highest N, K⁺, and K⁺:Na⁺ content. Overall, interaction between salinity level and K fertilization revealed that sugar beet plants fertilized with 144 kg K ha⁻¹ under low salinity level recorded the maximum N, K⁺, Ca²⁺, and K⁺:Na⁺. The highest leaf Na⁺ content was obtained with no K application under high salinity. Fertilizing Romulus cultivar by 144 kg K ha⁻¹ achieved the maximum values of N, K⁺, Ca²⁺, and K⁺:Na⁺ significantly equaling Romulus × 96 kg K ha⁻¹ (for N) as well as Romulus × 48 kg K ha⁻¹ and Francesca × 48 kg K ha⁻¹, 96 kg K ha⁻¹, or 144 kg K ha⁻¹ (for Ca²⁺).

![Graph showing leaf mineral contents](image)
3.2.4 Agronomic Traits

The potent combination of salinity level and cultivar for enhancing root diameter, root fresh weight, and leaf area plant$^{-1}$ was low salinity $\times$ Romulus (Table 5). Under low salinity, application of 144 kg K ha$^{-1}$ produced the maximum increases in root length, root yield ha$^{-1}$, and white sugar yield ha$^{-1}$. Without K application high salinity caused reduction in root yield by about 11.8 t ha$^{-1}$ ($-21.7\%$ decrease) compared to low salinity (Table 5). On the contrary, K supplying (144 kg K ha$^{-1}$) compensated such reduction with higher increase by about 19.5 t ha$^{-1}$ ($35.9\%$ increase). Romulus cultivar fertilized with 144 kg K ha$^{-1}$ was the best practice for improving all agronomic traits of sugar beet.

3.2.5 Beet Juice Quality

The maximum sodium content in sugar juice was obtained under high salinity with Francesca cultivar. Under high salinity, gross sugar content, and white sugar content (with 144 kg K ha$^{-1}$) and sodium content (without K fertilizer) gave the maximum values (Table 6). In K-unfertilized plots cultivated by Francesca cultivar, sodium, and alpha-amino-nitrogen showed the highest values, while plots of Francesca cultivar receiving 144 kg K ha$^{-1}$ recorded the maximum potassium content in sugar juice.
Table 3  Effect of the interaction between salinity, cultivar, and potassium application on physiological and biochemical traits of sugar beet

| Variable                      | Physiological traits | Biochemical traits |
|-------------------------------|----------------------|--------------------|
|                               | CMSI (%) | RWC (%) | $F_{/F_m}$ | Performance index | SPAD-reading | TSS (mg g$^{-1}$ DW) | TPC (mg GA 100$^{-1}$ g DW) | TFC (mg RE 100$^{-1}$ g DW) | TAA (%) |
| Salinity level × cultivar     |           |         |           |                |              |                   |                             |                             |        |
| Low                           |           |         |           |                |              |                   |                             |                             |        |
| Romulus                       | 75.2 ± 1.1a | 83.3 ± 0.7a | 0.84 ± 0.004a | 10.8 ± 0.9a | 60.6 ± 2.4a | 1.68 ± 0.08c | 407.9 ± 4.4c | 252.5 ± 1.8a | 82.5 ± 0.6c |
| Francesca                     | 66.4 ± 1.2a | 76.2 ± 0.7a | 0.82 ± 0.004a | 8.5 ± 0.7c  | 50.7 ± 1.7b | 1.88 ± 0.08b | 399.1 ± 4.6d | 250.7 ± 2.4a | 84.0 ± 1.0b |
| High                          |           |         |           |                |              |                   |                             |                             |        |
| Romulus                       | 72.2 ± 1.2a | 75.4 ± 1.0a | 0.82 ± 0.005a | 9.1 ± 0.7b  | 48.8 ± 1.8c | 1.87 ± 0.08b | 412.6 ± 6.2b | 255.6 ± 0.9a | 85.2 ± 0.9a |
| Francesca                     | 65.1 ± 1.4a | 69.0 ± 0.9a | 0.81 ± 0.006a | 8.3 ± 0.7c  | 41.5 ± 1.6d | 2.15 ± 0.08a | 421.2 ± 8.6a | 255.6 ± 1.9a | 83.8 ± 1.0b |
| Salinity level × K rate (kg ha$^{-1}$) |           |         |           |                |              |                   |                             |                             |        |
| Low                           |           |         |           |                |              |                   |                             |                             |        |
| 0                             | 64.1 ± 1.4 cd | 76.3 ± 0.7c | 0.80 ± 0.004a | 4.5 ± 0.3f  | 42.5 ± 1.3a | 1.35 ± 0.05 g | 373.6 ± 1.9e | 235.8 ± 1.1d | 78.8 ± 0.5e  |
| 48                            | 71.9 ± 1.6b | 79.6 ± 1.4b | 0.83 ± 0.003a | 8.9 ± 0.4d  | 52.1 ± 1.1a | 1.69 ± 0.02f | 400.8 ± 3.6d | 252.3 ± 1.4b | 81.8 ± 0.5d  |
| 96                            | 71.3 ± 2.2b | 80.0 ± 1.6b | 0.84 ± 0.003a | 10.7 ± 0.5c | 61.0 ± 1.8a | 1.69 ± 0.03f | 413.2 ± 4.6c | 259.2 ± 0.8a | 86.9 ± 0.2b  |
| 144                           | 75.8 ± 1.4a | 83.3 ± 1.0a | 0.85 ± 0.003a | 14.7 ± 0.6a | 66.7 ± 2.7a | 2.38 ± 0.04a | 426.3 ± 0.9b | 259.2 ± 1.0a | 85.5 ± 1.2bc |
| High                          |           |         |           |                |              |                   |                             |                             |        |
| 0                             | 62.2 ± 1.6d | 65.9 ± 0.8f | 0.78 ± 0.005a | 4.0 ± 0.2f  | 34.5 ± 1.0a | 1.97 ± 0.07d | 359.7 ± 4.0f | 245.2 ± 1.5c | 77.6 ± 0.5e  |
| 48                            | 65.8 ± 1.4c | 71.4 ± 1.4e | 0.81 ± 0.005a | 7.5 ± 0.3e  | 42.4 ± 1.5a | 1.83 ± 0.13e | 442.2 ± 2.2a | 258.0 ± 1.0a | 84.9 ± 0.8e  |
| 96                            | 71.0 ± 1.5b | 74.4 ± 0.8d | 0.83 ± 0.005a | 11.0 ± 0.3c | 48.9 ± 1.4a | 2.09 ± 0.06c | 424.1 ± 3.3b | 258.8 ± 0.8a | 86.4 ± 0.7bc |
| 144                           | 75.6 ± 1.4a | 77.3 ± 1.2c | 0.83 ± 0.004a | 12.3 ± 0.3b | 54.9 ± 1.3a | 2.15 ± 0.18b | 441.6 ± 5.4a | 260.4 ± 1.0a | 89.0 ± 0.3a  |
| Cultivar × K rate (kg ha$^{-1}$) |           |         |           |                |              |                   |                             |                             |        |
| Romulus                       | 66.6 ± 0.5a | 73.3 ± 1.6e | 0.80 ± 0.004c | 4.8 ± 0.2g   | 41.6 ± 1.0f | 1.70 ± 0.15c | 372.2 ± 3.5d | 244.4 ± 1.7d | 79.4 ± 0.4e  |
| 48                            | 72.8 ± 1.4a | 79.6 ± 1.3c | 0.83 ± 0.004c | 8.7 ± 0.4e  | 35.5 ± 1.1g | 1.62 ± 0.03f | 361.1 ± 3.2e | 236.6 ± 1.3c | 83.7 ± 1.0d  |
| 96                            | 75.7 ± 0.8a | 81.2 ± 1.3b | 0.84 ± 0.004b | 11.7 ± 0.3c | 50.7 ± 1.4d | 1.53 ± 0.04g | 421.2 ± 2.0bc | 255.2 ± 1.1c | 86.8 ± 0.7b  |
| 144                           | 79.7 ± 0.5a | 83.5 ± 0.9a | 0.85 ± 0.004a | 14.6 ± 0.6a | 43.8 ± 1.9e | 2.00 ± 0.08b | 416.3 ± 5.4c | 255.2 ± 1.8c | 85.5 ± 1.1c  |
| Francesca                     | 59.7 ± 1.5a | 68.9 ± 1.7f | 0.79 ± 0.005f | 3.7 ± 0.2h  | 59.9 ± 2.1b | 1.95 ± 0.10c | 422.9 ± 6.9bc | 258.8 ± 0.8b | 76.9 ± 0.3f  |
| 48                            | 64.9 ± 1.3a | 71.1 ± 1.5f | 0.82 ± 0.005d | 7.7 ± 0.4f  | 50.0 ± 1.4d | 1.82 ± 0.03d | 420.8 ± 7.0bc | 259.2 ± 0.8b | 83.0 ± 0.4d  |
| 96                            | 66.6 ± 1.8a | 73.5 ± 0.8e | 0.83 ± 0.005c | 10.0 ± 0.4d | 66.6 ± 2.7a | 1.92 ± 0.11c | 425.5 ± 1.2b | 258.0 ± 0.4b | 86.5 ± 0.3b  |
| 144                           | 71.7 ± 1.0a | 77.1 ± 1.1d | 0.84 ± 0.004b | 12.3 ± 0.4b | 55.0 ± 1.4c | 2.61 ± 0.04a | 442.4 ± 5.1a | 261.6 ± 1.2a | 89.0 ± 0.5a  |

Low and high soil salinity refer to an electrical conductivity; ECe=3.54 and 9.28 dS m$^{-1}$, respectively. CMSI, cell membrane stability index; RWC, relative water content; Fv/Fm, efficiency of PSII maximal quantum; SPAD, soil plant analysis development; TSS, total soluble sugars; TPC, total phenolic content; TFC, total flavonoid content; TAA, total antioxidant activity. Means not sharing the common letters for each factor in each column differ significantly at p≤0.05 based on student–Newman–Keuls test.
Table 4  Effect of the interaction between salinity, cultivar, and potassium application on leaf nutrient contents of sugar beet

| Variable | N (mg g⁻¹ leaf dry weight) | P | K⁺ | Na⁺ | Ca²⁺ | K⁺: Na⁺ |
|----------|---------------------------|---|----|-----|------|--------|
| Salinity level×cultivar | | | | | | |
| Low | Romulus | 40.4 ± 0.8a | 7.22 ± 0.32a | 35.94 ± 1.52a | 28.41 ± 0.56a | 27.2 ± 1.4a | 1.25 ± 0.07a |
| | Francesca | 39.2 ± 1.1b | 6.19 ± 0.33a | 34.79 ± 1.49b | 30.22 ± 0.69a | 28.2 ± 1.1a | 1.16 ± 0.07c |
| High | Romulus | 34.2 ± 0.7c | 6.51 ± 0.36a | 34.80 ± 1.39b | 31.62 ± 0.74a | 24.0 ± 0.9a | 1.19 ± 0.08b |
| | Francesca | 28.4 ± 0.4d | 5.49 ± 0.32a | 33.92 ± 1.34c | 34.13 ± 0.97a | 27.6 ± 1.3a | 1.06 ± 0.07d |
| Salinity level×K rate (kg ha⁻¹) | | | | | | |
| Low | 0 | 33.2 ± 0.8b | 4.74 ± 0.16a | 28.99 ± 0.24f | 33.48 ± 1.22c | 23.7 ± 1.0 cd | 0.81 ± 0.02 g |
| | 48 | 41.9 ± 1.1a | 5.83 ± 0.20a | 31.68 ± 0.24d | 29.59 ± 0.49e | 30.3 ± 1.7a | 1.02 ± 0.02e |
| | 96 | 41.8 ± 0.5a | 7.68 ± 0.16a | 34.68 ± 0.13b | 27.92 ± 0.94f | 25.3 ± 1.7bc | 1.23 ± 0.02c |
| | 144 | 42.2 ± 0.7a | 8.56 ± 0.22a | 46.10 ± 0.25a | 26.26 ± 0.29g | 31.3 ± 1.4a | 1.76 ± 0.03a |
| High | 0 | 27.9 ± 0.7d | 4.04 ± 0.16a | 27.00 ± 0.17g | 38.49 ± 0.24a | 21.9 ± 1.0d | 0.75 ± 0.01 h |
| | 48 | 30.1 ± 0.8c | 5.12 ± 0.24a | 30.12 ± 0.24e | 34.37 ± 0.75b | 26.5 ± 1.5bc | 0.93 ± 0.03f |
| | 96 | 33.4 ± 1.2b | 6.98 ± 0.16a | 34.34 ± 0.22c | 31.14 ± 0.81d | 27.9 ± 2.1b | 1.13 ± 0.05d |
| | 144 | 33.6 ± 1.1b | 7.86 ± 0.20a | 45.98 ± 0.24a | 27.50 ± 0.33f | 26.8 ± 1.4bc | 1.69 ± 0.05b |
| Cultivar×K rate (kg ha⁻¹) | | | | | | |
| Romulus | 0 | 32.8 ± 0.9d | 4.84 ± 0.13a | 28.36 ± 0.40g | 34.72 ± 1.47a | 21.5 ± 1.0b | 0.82 ± 0.01 g |
| | 48 | 35.3 ± 0.9c | 6.07 ± 0.13a | 31.44 ± 0.27e | 30.93 ± 0.95a | 28.1 ± 2.0a | 1.03 ± 0.03e |
| | 96 | 40.2 ± 1.0a | 7.77 ± 0.14a | 34.96 ± 0.16c | 28.34 ± 0.99a | 22.4 ± 0.7b | 1.25 ± 0.04c |
| | 144 | 40.7 ± 1.2a | 8.79 ± 0.15a | 46.72 ± 0.12a | 26.08 ± 0.35a | 30.3 ± 1.4a | 1.80 ± 0.04a |
| Francesca | 0 | 28.3 ± 0.8e | 3.95 ± 0.14a | 27.63 ± 0.29h | 37.25 ± 1.73a | 24.2 ± 1.0b | 0.74 ± 0.01 h |
| | 48 | 36.6 ± 2.7b | 4.88 ± 0.15a | 30.36 ± 0.31f | 33.03 ± 0.86a | 28.8 ± 1.4a | 0.92 ± 0.02f |
| | 96 | 35.0 ± 1.6c | 6.89 ± 0.13a | 34.07 ± 0.09d | 30.73 ± 0.72a | 30.8 ± 2.0a | 1.12 ± 0.04d |
| | 144 | 35.2 ± 1.5c | 7.63 ± 0.13a | 45.37 ± 0.15b | 27.68 ± 0.37a | 27.8 ± 1.6a | 1.65 ± 0.03b |

Low and high soil salinity refer to an electrical conductivity; ECe = 3.54 and 9.28 dS m⁻¹, respectively. N, nitrogen; P, phosphorus; K⁺, potassium; Na⁺, sodium; and Ca²⁺, calcium. Means sharing the same letter in each column are not significantly different by student–Newman–Keuls test.

4 Discussion

It has been documented that growing various crop plants in adverse edaphic or climatic environments undoubtedly leads to exposure to several stresses and ultimately poor yield (El-Metwally et al. 2021; El-Metwally and Saudy 2021a; Saudy et al. 2021a; El-Bially et al. 2022b), which requires confronting such conditions to ensure food (El-Metwally and Saudy 2021b; Mubarak et al. 2021; Salem et al. 2021; Saudy et al. 2021b). Under salinity stress, it is the accumulation of salts around the plant root system causes reduction in water movement from soil to the plant with reducing the plant’s internal water potential and ceasing nutrients transport towards the plant. Accordingly, the current findings proved that soil salinity caused perturbations in the physiological state of sugar beet plant. Consequently, leaf nutritional status, growth and yield, and juice quality were affected. In this regard, inside the plant cells, the excess soluble salts damage the leaves and thereby reduce the process of photosynthesis (Arraouadi et al. 2011). Under salinity, the excess chloride and sodium ions cause ionic imbalance with reducing the uptake of several ions, i.e., Ca, K, and P (Abbasi et al. 2015). Thus, salinity adversely affects all plant growth phases including germination, seedlings, vegetative, and maturity (Nawaz and Ashraf 2010; Abbasi et al. 2015). Disturbance in different physiological pathways i.e., respiration, photosynthesis, and carbohydrates metabolism could be occurred owing to ionic toxicity and osmotic stress of salinity (Abbasi et al. 2016). Under high level of salts, the water potential of root surrounding environment is reduced that makes the plant unable to absorb water from the soil solution by roots (Abbasi et al. 2014). As salt stress minimizes the soil solution’s osmotic potential, it disrupts water and phytonutrients uptake from the soil, thus directly impairs crop growth and productivity (Abd El-Mageed et al. 2021). Salinity-induced osmotic and ionic phases prompted oxidative stress, ending up reactive oxygen species (ROS) overaccumulation (Liu et al. 2020). ROS, being highly reactive under the absence of any defensive mechanism, causes cell structure disintegration by lipids peroxidation, DNA and protein deterioration, and enzyme deactivation (Wang et al. 2017).
Salt tolerance is a complex mechanism, including tolerance to osmotic and ionic stresses caused by high soil salinity (Chiconato et al. 2019). An increase in cellular concentrations of Na⁺ and Cl⁻ and a decrease of K⁺ concentrations are the distinctive outputs of high salt concentration in plant growth media (Deinlein et al. 2014; Munns and Gilliam 2015; Abbasi et al. 2016). Accordingly, the regulation of Na⁺ uptake is so important for avoiding toxicity of accumulated Na⁺ in leaves with maintaining a high K⁺/Na⁺ which is important for the activity of K⁺-dependent enzymes (Shabala and Pottosin 2014). On the other hand, salt stress can induce the accumulation of ROS, which could highly influence plant photosynthesis, metabolism, signal transduction, and other physio-biochemical processes. Increased ROS production greater than the cell’s tolerance capacity will cause plant damage by spoiling the cell membrane structure or interposing apoptosis (Xue et al. 2013). Therefore, a decrease in leaf expansion, stomatal closure, inhibition of photosynthesis, and reduced biomass associated salt stress (Zhang and Shi 2013).

Metabolic turbulences in several physiological and biochemical processes such as nutrition, respiration, organic solutes/osmolyte synthesis, enzyme activities, and photosynthesis could be occurred due to salinity (Siddiqui et al. 2010; Wu et al. 2013). Nevertheless, plants have developed various levels of adaptability and defensive mechanisms, based on plant species and cultivar, to survive in salt conditions (Manaa et al. 2011). Therefore, different performance to soil salinity between Romulus and Francesca cultivars was obtained. Herein, Romulus had higher adaptability to salt stress, since its values of cell membrane stability index, relative water content, Fv/Fm, and performance index were greater than Francesca. Adaptive mechanisms of plant genotypes to salt stress tolerance occur at molecular level (Yuan et al. 2016) and the physio-biochemical levels (Kong et al. 2016; Leng et al. 2018). Gantang7’ cultivar maintained the lower shoot Na⁺/K⁺ and root Na⁺/Ca⁺² ratios than the other tested cultivars (Wu et al. 2013). The differential expressions of salt-related tolerance genes, i.e., OsCCCI (Kong et al. 2011), AtZFP1 (Han et al. 2014), and PcAPX (Cao et al. 2017), drive the salt-stress responses at the physiological and biochemical levels (Cui et al. 2018). In this context, presence of apoplastic barriers via Casparian bands and suberin lamellae could prevent Na⁺ transport.

### Table 5  Effect of the interaction between salinity, cultivar, and potassium application on agronomic traits of sugar beet

| Variable                  | Root length (cm) | Root diameter (cm) | Root fresh weight (kg plant⁻¹) | Leaf area plant⁻¹ (dm²) | Root yield (t ha⁻¹) | White sugar yield (t ha⁻¹) |
|---------------------------|------------------|--------------------|--------------------------------|-------------------------|---------------------|-----------------------------|
| **Salinity level×cultivar** |                  |                    |                                |                         |                     |                             |
| Low                       | Romulus          | 30.5 ± 2.0a        | 15.9 ± 1.0a                    | 1.81 ± 0.11a            | 714.0 ± 31.9a       | 78.7 ± 3.3a                 | 14.0 ± 0.87a               |
|                           | Francesca        | 26.8 ± 1.0a        | 13.0 ± 0.9c                    | 1.20 ± 0.07b            | 436.0 ± 29.6c       | 66.7 ± 2.7a                 | 11.5 ± 0.69a               |
| High                      | Romulus          | 27.2 ± 1.6a        | 13.5 ± 0.7b                    | 1.16 ± 0.10b            | 556.5 ± 45.4b       | 63.0 ± 2.8a                 | 11.4 ± 0.77a               |
|                           | Francesca        | 23.2 ± 1.3a        | 11.6 ± 0.5d                    | 0.82 ± 0.07c            | 347.9 ± 26.3d       | 52.4 ± 2.2a                 | 9.0 ± 0.58a                |
| **Salinity level×K rate (kg ha⁻¹)** |                  |                    |                                |                         |                     |                             |
| Low                       | 0                | 23.6 ± 0.7f        | 12.8 ± 0.6a                    | 0.97 ± 0.08a            | 411.4 ± 37.4a       | 54.3 ± 1.9f                 | 7.9 ± 0.30e                |
|                           | 48               | 26.6 ± 1.4d        | 14.2 ± 0.5a                    | 1.38 ± 0.11a            | 511.2 ± 37.5a       | 66.5 ± 1.5d                 | 10.8 ± 0.34d               |
|                           | 96               | 31.7 ± 1.4b        | 14.8 ± 0.8a                    | 1.64 ± 0.11a            | 608.3 ± 55.9a       | 79.0 ± 2.1b                 | 14.6 ± 0.46b               |
|                           | 144              | 32.8 ± 2.8a        | 16.0 ± 1.6a                    | 2.04 ± 0.16a            | 769.1 ± 51.8a       | 90.9 ± 3.0a                 | 17.5 ± 0.66a               |
| High                      | 0                | 22.2 ± 0.6g        | 10.8 ± 0.5a                    | 0.55 ± 0.03a            | 253.4 ± 13.1a       | 42.5 ± 1.2g                 | 6.3 ± 0.21f                |
|                           | 48               | 24.7 ± 1.4e        | 12.7 ± 0.8a                    | 0.77 ± 0.03a            | 351.5 ± 31.4a       | 51.7 ± 1.4f                 | 8.3 ± 0.27e                |
|                           | 96               | 25.5 ± 1.5e        | 13.3 ± 0.8a                    | 1.10 ± 0.09a            | 552.8 ± 44.1a       | 62.9 ± 2.4e                 | 11.6 ± 0.56c               |
|                           | 144              | 28.4 ± 1.9c        | 13.9 ± 1.0a                    | 1.56 ± 0.08a            | 650.9 ± 57.7a       | 73.8 ± 2.2c                 | 14.7 ± 0.55b               |
| **Cultivar×K rate (kg ha⁻¹)** |                  |                    |                                |                         |                     |                             |
| Romulus                   | 0                | 24.3 ± 0.9c        | 12.6 ± 0.5ef                   | 0.89 ± 0.09f            | 408.0 ± 37.8d       | 52.4 ± 2.1f                 | 7.8 ± 0.28f                |
|                           | 48               | 27.0 ± 1.2b        | 14.3 ± 0.5c                    | 1.27 ± 0.13d            | 534.3 ± 30.8c       | 63.2 ± 2.2d                 | 10.4 ± 0.42d               |
|                           | 96               | 29.8 ± 1.6a        | 15.3 ± 0.7b                    | 1.67 ± 0.09b            | 727.0 ± 24.0b       | 77.9 ± 2.5b                 | 14.6 ± 0.49b               |
|                           | 144              | 34.4 ± 1.7a        | 16.7 ± 1.0a                    | 2.12 ± 0.13a            | 871.6 ± 26.6a       | 89.9 ± 3.2a                 | 17.9 ± 0.54a               |
| Francesca                 | 0                | 21.5 ± 0.7d        | 11.0 ± 0.3 g                   | 0.62 ± 0.06g            | 256.8 ± 15.5f       | 44.3 ± 1.9 g                | 6.4 ± 0.27 g               |
|                           | 48               | 24.3 ± 1.1c        | 12.1 ± 0.6f                    | 0.88 ± 0.07f            | 328.5 ± 26.1e       | 55.0 ± 2.5e                 | 8.7 ± 0.42e                |
|                           | 96               | 27.4 ± 1.5b        | 12.9 ± 1.8de                   | 1.07 ± 0.07e            | 434.1 ± 26.3d       | 64.0 ± 2.7d                 | 11.6 ± 0.50c               |
|                           | 144              | 26.8 ± 1.2b        | 13.3 ± 1.0d                    | 1.48 ± 0.07c            | 548.4 ± 34.6c       | 74.8 ± 2.5c                 | 14.3 ± 0.46b               |

Low and high soil salinity refer to an electrical conductivity; ECₑ = 3.54 and 9.28 dS m⁻¹, respectively. Means sharing the same letter for each factor in each column are not significantly different by student–Newman–Keuls test.
Table 6  Effect of the interaction between salinity, cultivar, and potassium application on juice quality of sugar beet

| Variable                  | Gross sugar content (%) | Sodium (mmol 100 g⁻¹ root) | Potassium | Alpha-amino-nitrogen | White sugar content (%) |
|---------------------------|-------------------------|-----------------------------|-----------|----------------------|-------------------------|
| **Salinity level×cultur** |                         |                             |           |                      |                         |
| Low                       |                         |                             |           |                      |                         |
| Romulus                   | 19.7 ± 0.4a             | 2.44 ± 0.13c                | 3.31 ± 0.12a | 0.96 ± 0.03a         | 19.7 ± 0.4a             |
| Francesca                 | 19.3 ± 0.4a             | 2.49 ± 0.12c                | 3.46 ± 0.11a | 1.00 ± 0.03a         | 19.3 ± 0.4a             |
| High                      |                         |                             |           |                      |                         |
| Romulus                   | 20.2 ± 0.4a             | 2.80 ± 0.14b                | 3.29 ± 0.10a | 1.06 ± 0.03a         | 20.2 ± 0.4a             |
| Francesca                 | 19.4 ± 0.4a             | 3.00 ± 0.11a                | 3.42 ± 0.09a | 1.08 ± 0.04a         | 19.4 ± 0.4a             |
| **Salinity level×K rate (kg ha⁻¹)** |                   |                             |           |                      |                         |
| Low                       |                         |                             |           |                      |                         |
| 0                         | 17.0 ± 0.1f             | 3.23 ± 0.03b                | 2.78 ± 0.10a | 1.17 ± 0.02a         | 14.5 ± 0.09 g           |
| 48                        | 18.6 ± 0.2d             | 2.64 ± 0.05d                | 3.26 ± 0.08a | 1.04 ± 0.02a         | 16.2 ± 0.16e            |
| 96                        | 20.9 ± 0.2c             | 2.37 ± 0.03e                | 3.53 ± 0.07a | 0.91 ± 0.01a         | 18.5 ± 0.16c            |
| 144                       | 21.5 ± 0.1b             | 1.61 ± 0.05 g               | 3.97 ± 0.15a | 0.79 ± 0.02a         | 19.3 ± 0.12b            |
| High                      |                         |                             |           |                      |                         |
| 0                         | 17.4 ± 0.1e             | 3.52 ± 0.04a                | 2.80 ± 0.06a | 1.29 ± 0.02a         | 14.8 ± 0.13f            |
| 48                        | 18.6 ± 0.2d             | 3.13 ± 0.07b                | 3.20 ± 0.05a | 1.16 ± 0.01a         | 16.1 ± 0.23e            |
| 96                        | 20.9 ± 0.3c             | 2.92 ± 0.08c                | 3.47 ± 0.04a | 0.96 ± 0.02a         | 18.3 ± 0.27d            |
| 144                       | 22.3 ± 0.2a             | 2.04 ± 0.13f                | 3.95 ± 0.09a | 0.86 ± 0.02a         | 19.9 ± 0.22a            |
| **Cultivar×K rate (kg ha⁻¹)** |                   |                             |           |                      |                         |
| Romulus                   |                         |                             |           |                      |                         |
| 0                         | 17.4 ± 0.1a             | 3.37 ± 0.05a                | 2.64 ± 0.06f | 1.18 ± 0.02b         | 15.0 ± 0.10a            |
| 48                        | 18.9 ± 0.2a             | 2.82 ± 0.09c                | 3.19 ± 0.08d | 1.12 ± 0.02c         | 16.4 ± 0.18a            |
| 96                        | 21.2 ± 0.2a             | 2.67 ± 0.10d                | 3.46 ± 0.06c | 0.94 ± 0.02d         | 18.8 ± 0.22a            |
| 144                       | 22.3 ± 0.2a             | 1.63 ± 0.06f                | 3.91 ± 0.13b | 0.79 ± 0.02f         | 20.0 ± 0.19a            |
| Francesca                 |                         |                             |           |                      |                         |
| 0                         | 17.0 ± 0.1a             | 3.38 ± 0.06a                | 2.94 ± 0.08e | 1.28 ± 0.03a         | 14.4 ± 0.07a            |
| 48                        | 18.4 ± 0.2ab            | 2.96 ± 0.10b                | 3.27 ± 0.05d | 1.09 ± 0.03c         | 15.9 ± 0.18a            |
| 96                        | 20.5 ± 0.1a             | 2.62 ± 0.11d                | 3.53 ± 0.05c | 0.93 ± 0.02d         | 18.1 ± 0.16a            |
| 144                       | 21.5 ± 0.1a             | 2.03 ± 0.13c                | 4.01 ± 0.12a | 0.87 ± 0.02e         | 19.1 ± 0.09a            |

Low and high soil salinity refer to an electrical conductivity; ECe = 3.54 and 9.28 dS m⁻¹, respectively. Means sharing the same letter for each factor in each column are not significantly different by student–Newman–Keuls test.

to plant shoots (Krishnamurthy et al. 2011). Salt-tolerance mechanism could be attributed to maintaining a high shoot sugar content which is enabled by protecting photosystems structures, stimulating photosynthetic rate and sucrose synthetase activity, and inhibiting sucrose degradation (Yang et al. 2020). Genotypic variations clarified strength association between salt tolerance and high activities of superoxide dismutase, catalase and glutathione peroxidase enzymes, and proline, total soluble sugars, and glycine betaine contents under salt stress conditions (Gholipor et al. 2022). Additionally, salinity damage can be mitigated if the plant tissue effectively accumulates compatible solutes (Sun et al. 2015).

The presence of these compounds relieves the osmotic pressure induced by soil salinity and thus allows the plant to continue taking up water, stabilize the photosystem II complex, protect the structure of enzymes and proteins, maintain membrane integrity, and protect cells against oxidative damage by scavenging ROS (Szabados and Savouré 2010; Gupta and Huang 2014). Many physio-adaptation strategies to overcome salinity have been reported in sugar beet plants, including selective uptake and transportation of salt ions, compartmentalization and sequestration of salt ions, and enhancement of enzymatic and nonenzymatic capacities (Wang et al. 2017; Mari et al. 2018). Boosting enzymatic (e.g., peroxidase, catalase, superoxide dismutase, ascorbate peroxidase, etc.) and nonenzymatic (e.g., total proteins, total soluble sugars, free proline, etc.) antioxidants are necessitated for ROS scavenging resulting from oxidative stress (Liu et al. 2020). Recently, proteomic profiles study of Wang et al. (2019) revealed that the tricarboxylic acid cycle, cell wall synthesis, and ROS scavenging showed differential changes between the sensitive and tolerant cultivars, indicating that these pathways may participate in the salt tolerance of sugar beet. Salt-tolerant genotypes respond to salinity by increasing anti-oxidative defense systems for detoxification of ROS (Sun et al. 2011). Hence, the varietal variations between Romulus and Francesca cultivars led to discrepancy in agronomic traits and juice quality.

As suppression of plant growth is the prevailing influence of salinity stress, physiological and growth parameters of sugar beet were declined with increasing salt concentration. For instance, by comparing the effect of low and high salinity on sugar beet physiological traits under no K application, it should be noted that the damage impact of salinity on cell...
memebrane stability, relative water content, and performance index were –2.9, –13.6, –11.1%, respectively. Contrariwise, K supply (144 kg ha\(^{-1}\)) alleviated such effect by 21.5, 17.3, and 207.5%, respectively. One approach to minimize effects of salinity is use of K application to increase tolerance of plant to salinity by alleviating Na\(^+\) and Cl\(^-\) injury (Gul et al. 2019). Keeping adequate potassium levels is great of importance for survival of plants in saline medium (Abbasi et al. 2014). Despite the findings of the present research revealed that salinity induced reduction in agronomic and quality traits of sugar beet, potassium counteracted the salinity effect. Addition of potassium under salinity increased root length, shoot fresh weight, and root fresh weight (Mehmood et al. 2020). Salt tolerance in plants increased by increasing K\(^+\) uptake which leads to increasing K/Na ratio in plant cells (Ali et al. 2019). In this respect several kinds of K\(^+\) and Na\(^+\) transport systems, such as inward-rectifier shaker K\(^+\) channel (AKT1), high-affinity K\(^+\) transporter 5 (HAK5), shaker-like K\(^+\) outward rectifying channel (SKOR), high-affinity K\(^+\) transporter 1:5 (HKT1;5), tonoplast Na\(^+\)/H\(^+\) antiporter 1 (NHX1), and plasma membrane Na\(^+\)/H\(^+\) antiporter 1 (SOS1) have been documented to synergistically regulate ion (K\(^+\) and Na\(^+\)) homeostasis in sugar beet under saline condition (Li et al. 2022). Moreover, application of potassium induced salt tolerance as the production of malondialdehyde content and electrolyte leakage decreased, while growth parameters, chlorophyll contents, antioxidant enzymes, gas exchange characteristics, and sugar contents were improved (Parveen et al. 2021). Potassium also played an important role in plant water relation under salinity stress and helped the plants to absorb more water to attain turgidity and membrane stability (Abbasi et al. 2016). K is a key element for crop growth and productivity (Hasanuzzaman et al. 2018). It is an essential nutrient for photosynthesis and the transport of assimilates (Wang et al. 2015). Potassium affects the osmotic adjustment of the plant and by enhancing the translocation of assimilates and maintaining osmotic charge (Marschner 2012; Mubarak et al. 2016). Since the transport of Na\(^+\) from roots to leaves can also be restricted by a high-affinity K\(^+\) transporter (Byrt et al. 2014), K supply is a crucial act for crop protection in saline soils.

Complementary effect between K addition and genotypic performance of sugar beet exhibited that K positively affected almost physiological and agronomic traits and mitigated the negative impact of salinity on growth with superiority of Romulus cultivar. Accordingly, gene expression response could be improved with K application under saline soil conditions. In consistence with the current research, fertilizing sugar beet, whether highly or moderately tolerant genotype to salt stress, with adequate K fertilizer raise the plant potentiality to counteract the salinity hazards. In this regard, Deinlein et al. (2014) stated that potassium is considered a major osmotically active solute of plant cell, where it enhances water uptake and root permeability and acts as a guard cell controller, beside its role in increasing water use efficiency.

5 Conclusions

The findings of the current work could summarize the significance of complementary effect of potassium and varietal differences for improving the physio-biochemical, yield, and quality traits of sugar beet under saline soils. In this connection, Romulus cultivar fertilized by potassium at a rate of 144 kg per hectare exhibited high membrane stability index, relative water content, efficiency of photosynthesis, leaf nutrient contents, sugar yield with low sodium, and alphamino-nitrogen in beet sugar juice. Hence, providing Romulus cultivar with 144-kg potassium per hectare regarded as a promising practice for sugar beet production under soil electric conductivity of 9.28 dS m\(^{-1}\). As a new approach, sugar beet breeders should focus not only on yield and its components but also plant physiological properties for achieving distinctive progress in sugar beet genotypes that have high tolerant degrees to salinity. Furthermore, since the highest potassium rate showed the best performance of sugar beet cultivars against salinity, further studies could be implemented using higher potassium rates than 144 kg ha\(^{-1}\).

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Declarations

Conflicts of Interest The authors declare that they have no conflict of interests concerning the current research publication.

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