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Effect of Boron, Potassium Sources and Rates on Soil Fertility, Sugar Beet Yield and Quality Cultivated in Saline Clay Soil in Egypt

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Two field experiments were conducted at a private farm in El-QantaraSharq, Ismailia Governorate, Egypt, during the 2021/22 and 2022/23 winter growing seasons. The study aimed to assess the effect of boron and potassium sources and rates on sugar beet yield quality and soil fertility. The experiments were arranged in a split-split plot design. The main plots had foliar boron (B) application (without and with 4 g B/L), while the sub-main plots had potassium sources: K-sulfate, K-silicate, and K-humate. The sub-plots had potassium rates (0, 4, 8, and 12 g/L) applied as foliar spray at three intervals: 30, 45, and 75 days after planting. Results indicated that foliar boron

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application led to a 17.17% decrease in soil electrical conductivity (EC) compared to without boron spraying. However, there was no significant change in pH values. The study showed a significant increase in soil available N, P, K, Fe, Mn, Zn, and B with the application of 4 g/L of boron or K-humate at a rate of 12 g/L individually. Sugar beet yield, quality and root nutrients content were notably influenced by potassium sources in the following order: K-humate > K-silicate > K-sulfate. The interaction between boron spray and potassium sources and rates had a significant effect on various parameters, with the highest values for root length (cm), fresh root weight (kg/plant), root and top yield (t/ha), protein (%),sugar content (%) and sugar yield (t/ha) achieved by foliar application of boron combined with K-humate at a rate of 12 g/L.

Keywords: Boron; soil fertility; sugar beet; potassium fertilizer.

1. INTRODUCTION

In Egypt, sugar beet (*Beta vulgaris* L.) has emerged as a significant crop for sugar production. In the 2018 season, the total cultivated area reached approximately 521,427 hectares, with a total production exceeding 11.223 million tons of roots, averaging 21.523 hectares per year (FAO, 2020). As one of the crops most tolerant of salinity and a wide range of climates, sugar beet could be economically grown in recently reclaimed soils, such as in the northern parts of Egypt. The total quantity of sugar produced is insufficient to meet our needs. Therefore, one of the key national goals is to reduce the difference between sugar production and consumption by increasing the area under cultivation and the amount of sugar produced per unit area (El-Zayat, 2022). Enhancing sugar beet yield can be accomplished by using the right source and rate of potassium for foliar application. Additionally, the ideal rate of potassium fertilizer for soil application can improve the production of sugar beets (Hamada, 2019).

Potassium (K) is a primary macronutrient that plays a crucial role in various plant functions such as protein synthesis, photosynthesis, osmoregulation, stomatal movement, energy transfer, phloem transport, cation-anion balance, and stress resistance (Wang et al., 2013; Lenka& Das, 2019). Additionally, potassium is essential for the translocation of sugars from leaves to storage roots in plants. Increasing potassium levels up to 24 kg K_2O/fad has been shown to enhance plant growth, chlorophyll levels, and overall performance in sugar beet leaves during different seasons (El-Kalawy, 2021). Potassium silicate is a highly soluble source of potassium and silicon. Although silicon is beneficial for plants, it is not considered essential. It is important to reduce the plant's vulnerability to biotic and a biotic environmental stresses (Sacala, 2009). Seadh et al. (2024) found that the highest values of leaf chemical constituents (NPK, %), chlorophyll, plant height, and top fresh weight were obtained with a combined treatment of borax (0.25 cm^3L^{-1}) and potassium silicate (1.25 cm^3L^{-1}).

Potassium humate (K-humate) is widely produced as a source of potassium that contains many elements necessary for plant development (Okba et al., 2021). Foliar application of humic substances is becoming more popular in agricultural practice. The mechanism of the possible growth-promoting effect is usually attributed to a hormone-like impact, activation of photosynthesis, acceleration of cell division, increased permeability of plant cell membranes, improved nutrient uptake, reduced toxic element uptake, and improved plant response to salinity (Verlinden et al., 2009). In this concern, Ibrahim et al. (2017) found that potassium humate at a rate of 8g/L resulted in the highest significant values for top length, leaves, and root length, with percentages of 15%, 34%, 11%, 21%, 30%, 36%, and 3%, while potassium silicate treatment at 8g/L recorded the second-highest values for top length and leaves.

Boron (B) is essential for plant growth. It is important for the synthesis of cell walls, cell division, cell development, hormone development and metabolism of auxin and indole acetic acid (IAA), synthesis of proteins and amino acids, regulation of carbohydrate metabolism, sugar transport, RNA metabolism, and respiration. Additionally, boron is possibly the most important micronutrient for achieving high-quality crop yields. Boron availability in soil was influenced by dynamic soil properties like soil pH, organic matter, texture, cultivation, drought, and microbial activity. The availability of boron decreases as pH increases, and plants typically cannot use most of the boron in the soil. When calcium (Ca) is available, plants require more B for growth and yield. Hence, foliar fertilization is a highly effective method for supplying boron to plants, leading to increased crop yield and plant health (Kuntoji et al., 2019). Spraying sugar beet plants with boron at a rate of 100 mg l^{-1} resulted in the highest values for foliage and root fresh and dry weights, root length, root diameter, yield components, and quality characters such as N, P, K, Na, B, α-amino N, impurity, TSS, sucrose, juice purity, and extractable white sugar (Ibrahim et al., 2020). Increasing boron fertilization levels from 0 to 80, 160, and 240 ppm/fed led to a gradual and significant improvement in sugar beet growth traits, including chlorophyll a and b content, root length, and diameter in both growing seasons (Elmasry and Al-Maracy, 2023). Moreover, Ali and Nasef (2024) showed that 4g/L of borax was a more effective concentration for enhancing table beet yield and vegetative growth.

The objective of this was to examine the impact of boron and different sources and rates of potassium on soil fertility, growth, yield, and quality traits of sugar beet (*Beta vulgaris* L.) in saline clay soil conditions.

2. MATERIALS AND METHODS

2.1 Experimental Location and Treatments

A field experiment was conducted over two successful winter seasons (2021/2022 and 2022/2023) at a private farm in El-QantaraSharq, Ismailia Governorate, Egypt. The farm is located at coordinates 30° 51' 59.6628"N and 32° 21' 4.7916"E. The study aimed to evaluate the effects of boron, potassium sources, rates, and their interaction on some soil chemical properties, as well as sugar beet productivity and quality under saline soil conditions. The soil's main physical and chemical properties, as shown in Table 1, were determined before planting using methods outlined by Page et al. (1982), Cottenie et al. (1982), and Klute (1986).

Each experiment was conducted using a split-split plot design with three replicates. The main plots were assigned for foliar application of boron (with and without), while the potassium sources (potassium sulfate, silicate, and humate) were allocated to the subplots, and the potassium rates (0, 4, 8, and 12 g/L) were arranged in the sub-sub plots. Each plot had an area of 5 x 10 m, divided into rows of 60 cm. The sugar beet cultivar used was Mirador. All agricultural practices were completed before planting. Super phosphate (15.5% P_2O_5) was applied at a rate of 200 kg/fed before planting. Urea (46% N) was applied at a rate of 100 kg/fed three times after 30, 45, and 75 days from planting. Potassium sulfate (48% K_2O), potassium silicate (12% K_2O, 30% Si_2O), and potassium humate (12% K_2O) were sprayed at rates of 0, 4, 8, and 12 g/L water were sprayed to coat the leaf surface and drenched the soil around the plants after 30, 45, and 75 days from planting. Boric acid (H_3BO_3 17% B) was sprayed at a rate of 4 g/L (400 g/ 400L water /fed) in two equal doses after 30 and 75 days from planting. A surface-flow irrigation system was used to apply the irrigation water from the El-Salam Canal, which is a Nile water mixture with agricultural daring (1:1).

Sugar beet was sown on October 20th for the 2021 and 2022 seasons. Three seeds were planted in each hill, and after 30 days, they were thinned to one plant per hill. After 150 days, the harvest occurred. Data was recorded by selecting 10 plants at random from each treatment in three replications to determine the following growth trails: Root length (cm), Root diameter (cm), fresh weight of root (kg/plant), weight of root yield (t/ha) and weight of top yield (t/ha).

Table 1. Physical and chemical properties in soil study before planting

Coarse sand (%)	Fine sand(%)	Silt (%)	Clay (%)	Texture		OM (%)	CaCO$_3$ (%)	
4.66	23.80	12.75	41.21	Clay		0.62	12.88	
pH(1: 2.5)	ECe(dSm^{-1})	Cations (meq l^{-1})				Anions (meq l^{-1})		
		Ca^{++}	Mg^{++}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-
8.15	8.22	10.60	23.74	51.98	0.88	9.22	44.50	28.48
Macronutrients (mg kg^{-1})				Micronutrients (mg kg^{-1})				
N	P	K		B	Fe	Mn	Zn	
30.55	4.95	173.80		0.08	2.88	1.12	0.52	

2.2 Soil Chemical Analysis

Soil pH was determined using a 1:2.5 soil-water solution (Jackson, 1973). The soil electrical conductivity (ECe) was measured in the saturated soil paste extract (dSm^{-1}) using an EC meter (Klute, 1986). Available soil nitrogen was estimated using the micro-Kjeldahl procedure after nitrogen extraction with 2M potassium chloride (Burt, 2004). The spectrophotometer was set at a wavelength of 550 nm to measure available soil phosphorus after extraction with 0.5 M sodium bicarbonate solution at pH 8.5 (Olsen, 1954). Extractable soil potassium was measured using flame photometry after extraction with the ammonium acetate procedure at pH 7.0 (Jackson, 1973). Available Fe, Zn, Mn, and Cu were extracted with NH_4HCO_3-DTPA and determined using an atomic absorption spectrophotometer, Perkin-Elmer 372 (Soltanpour and Schwab, 1977).

2.3 Plant Analysis

A 0.5 g of each oven dried ground plant sample was digested using H_2SO_4, $HClO_4$ mixture according to the method described by Chapman and Pratt (1961). The plant content of N, P, K, Fe and Mn were determined in plant digestion using the methods described by Cottenie et al. (1982) and Page et al (1982). The protein percentage of the root was determined by multiplying the nitrogen percentage by a factor of 6.25, as described by Hymowitz et al. (1972).

Sucrose (%) was estimated in fresh sugar beet root according to the method described in the A.O.A.C. (2005). Sugar yield (t/ha) was calculated by multiplied sucrose % × root yield (t/ha). Photosynthetic pigments (total chlorophyll were estimated in fresh leaves as described by Witham et al (1971). Proline content was estimated according to the methods described by Bates et al (1973).

2.4 Statistical Analysis

The data were analyzed using the COSTAT Software statistical package. Mean values for three replicates of each treatment were interpreted using ANOVA. Duncan's Multiple Range Test was used for comparisons between different sources of variance as per Steel & Torrie (1984).Pearson's correlation analysis of the data was performed using the "srplot" software, an online tool for data analysis and visualization (Tang et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Soil Chemical Properties

3.1.1 Soil pH

The results in Table 2 indicate that pH values were not affected by boron treatments. There were no significant differences among the potassium sources, but potassium rates had a significant impact on soil pH. The lowest mean values (7.91) were observed with potassium humate at a rate of 12 g/L. Shaaban et al. (2011) observed a slight increase in sandy soil pH after sugar beet removal, but it decreased to 7.0 after maize cultivation with different potassium sources. AbdElghany et al. (2019) indicated that the soil pH ranged between slightly to moderately alkaline, with values continuously ranging from 8.27 to 8.05. However, using a high rate of potassium humate had a significant impact on lowering soil pH. The positive effect of potassium humate on reducing soil pH values may be referred to the organic acid and applied microorganisms accelerate the decomposition process. Abdeen (2020) also suggested that the values of soil pH were slightly decreased by increasing K-humate. Humates transfer H^+ ions to soil Na^+, thereby decreasing Na^+ content and increasing H^+levels, which in turn decreases soil pH.

3.1.2 Soil salinity (EC dSm^{-1})

The data in Table 2 showed that the impact of boron, potassium sources, and rates on electrical conductivity (EC) in soil at harvest. The addition of boron resulted in a 17.17% decrease in EC compared to the untreated plots. The results are aligned with Ghazi and Ahmed (2022) who reported that the lowest soil EC value was observed with the combined treatment of both boron and salicylic acid (SA) (100 mgL^{-1}). The highest soil EC value was recorded in the control treatment without spraying. This could be due to the stimulants studied (boron and SA) enhancing the absorption of elements from the soil, leading to a reduction in soil EC value.

Among the potassium sources, K-humate had the lowest EC at harvest (3.49 dSm^{-1}).Increasing potassium rates generally led to lower EC values, with the application of 12 g/L potassium showing a 52.42% decrease in EC compared to the control. Ammari et al. (2008) indicated that

Table 2. Chemical properties of saline clay soil as affected by boron, potassium sources, and rates (combined analyses of two seasons)

Treatments	Soil pH (1:2.5)	Soil EC (dSm^{-1})	Available macronutrients ($mgkg^{-1}$)			Available micronutrients ($mgkg^{-1}$)			
			N	P	K	B	Fe	Mn	Zn
A. Boron (4 g/L)									
without	7.97	4.31	42.96	6.09	183.83	0.21	4.14	2.02	0.76
with	7.97	3.57	48.06	7.00	197.6	0.27	4.20	2.50	0.76
LS.D at (0.05)	n.s	0.03	0.529	0.429	0.690	0.018	n.s	0.005	n.s
B. Potassium source									
K- sulphate	7.99	4.56	42.15	6.57	191.02	0.22	4.24	2.2	0.76
K- silicate	7.98	3.78	43.98	6.26	187.01	0.24	3.88	2.1	0.71
K- humate	7.95	3.49	50.41	6.8	194.13	0.26	4.39	2.46	0.81
LS.D at (0.05)	n.s	0.01	0.910	0.153	0.073	0.013	0.101	0.008	0.013
C. Potassium rates (g/L)									
0	8.04	5.57	38.72	6.18	184.49	0.16	3.71	1.89	0.66
4	7.99	4.47	44.76	6.47	188.39	0.23	4.03	2.18	0.73
8	7.95	3.08	48.58	6.68	193.05	0.27	4.31	2.41	0.79
12	7.91	2.65	49.99	6.84	196.93	0.3	4.63	2.55	0.85
LS.D at (0.05)	0.058	0.02	0.672	0.121	0.485	0.015	0.078	0.011	0.013
Interaction effects									
A xB	n.s	***	**	n.s	**	**	*	***	n.s
A xC	n.s	***	***	n.s	***	n.s	***	***	n.s
B xC	n.s	***	***	*	***	n.s	***	***	***
A xBxC	n.s	***	***	n.s	***	n.s	n.s	***	n.s

*ns=not significant, *p<0.05 **p<0.01*

the soil EC was significantly reduced from 60 dSm^{-1} to 17 dSm^{-1}, for the leached soil cultivated with fodder beet. In the harvested above-ground biomass fodder beet removed Na^{+} 156 kg ha^{-1} from the topsoil (0-10 cm depth). The decreases in soil EC could be attributed to the application of potassium humate leading to improved soil aggregation, water movement and leaching of excessive soluble salts (Shaban et al., 2014). These results are consistent with those obtained by El-Sheref et al. (2024), who mention that potassium humate is an effective biostimulant that can reduce soil pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), and bulk density, while simultaneously increasing soil organic matter content and fertility.

3.1.3 Macronutrients availability ($mgkg^{-1}$)

The application of boron had a significant impact on the availability of soil macronutrients, as shown in Table 2. The addition of boron resulted in an increase of 11.87%, 14.94%, and 7.49% in available NPK, respectively, compared to the control without boron. Altaf et al. (2019) found similar results, indicating that the use of boron had a significant impact on the soil availability of nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium after the tomato harvest.Soil N, P and K availability also increased significantly with the application of potassium sources. Statistical analyses indicated that the addition of potassium humate led to the highest increase in available NPK. These findings align with the results reported by Zahran (2025), who found that a soil application of potassium humate at a concentration of 5 g/L was the most effective biostimulant in reducing pH levels and increasing nutrient availability (NPK) in calcareous soil for onion plants compared to untreated plants during both seasons. This positive impact on soil properties is attributed to the presence of decomposed anionic acids and organic complexes in potassium humate, such as carboxyl ($COOH^{-1}$) and phenol (OH^{-1}) groups, which have a beneficial effect on soil properties (Schnitzer, 1992).Increasing potassium levels up to 12 g/L resulted in a more pronounced increase in available NPK values by 29.11%, 10.68%, and 6.74%, respectively compared to no addition on average over two growing seasons. Spraying sugar beet plants with 12 g/L K-silicate was the second most effective treatment, following plants treated with K-sulfate at the same rate.

Table 2 demonstrated that the interaction of boron and potassium sources and rates significantly affected macronutrient availability except for available P. Specifically; the combination of 4 g/L boron with potassium humate at a rate of 12 g/L had a notable effect on soil available nitrogen and potassium. Similarly, Habib et al. (2020) found that applied potassium fertilizer and boron increased soil N, P, K and B levels. This increase in nutrients after harvesting may be attributed to the enhancement of root hair nodules in broad bean plants and post-harvest compost analysis. However, this rise did not lead to adequate levels of N, P, K and B in the soil after harvesting.

3.1.4 Micronutrients availability ($mgkg^{-1}$)

The results in Table 2 showed that boron only affected the availability of soil B and Mn. boron at a rate of 4 g/L increased soil available B and Mn by 28.57% and 23.76%, respectively, compared to no boron addition. Our findings were consistent with those of Mishra et al. (2020) that boron availability in post-harvest soil of potato significantly increased with higher boron levels and the application of Rhizobium. The highest boron availability was observed with the application of RDF (recommended dose of fertilizer) +2.0 kg boron ha^{-1}. This could be attributed to the fact that applying boron to the soil helped increase the boron levels in the post-harvest soil.

Regarding to potassium sources, data in Table 2 indicate that the availability of B, Fe, Mn, and Zn was affected by potassium sources in the following order: K-humate>K-silicate>K-sulfate. AbdElghany et al. (2019) indicated that soil watered every ten days and treated with potassium humate at a rate of 6 g/L exhibited the highest values of available micronutrients. The increased availability of micronutrients can be attributed to organic compounds acting as chelating and ion exchange agents. These compounds aid in retaining micronutrients in the soil, thereby preventing leaching through irrigation water. Regarding potassium rates, the availability of micronutrients increased gradually with higher rates of applied potassium. The maximum values of B, Fe, Mn, and Zn availability were 0.26, 4.39, 2.46, and 0.81 mg kg^{-1}, respectively, when potassium was applied at a rate of 12 g/L over two growing seasons. These results are consistent with a study by AbdElghany (2019) which found that increasing the application of potassium humate (up to 6 g/L) and irrigation periods significantly enhanced the availability of macro and micronutrients such as

N, P, K, Fe, Mn, and Zn in the saline soil after harvesting carrot.

The interaction effects of A x B and B x C were found to have significant effects on available B, Fe, and Mn. Specifically, the interaction between A x C (boron with potassium at a rate of 12 g/L) resulted in the highest values of available Fe and Mn. In the case of the three-way interaction (A x B x C), available Mn was significantly affected by the combined effects of boron, potassium sources, and rates (Table 2).

3.2 Concentration of Macronutrients (N, P, and K) in Sugar Beet Roots

Nitrogen, phosphorus, and potassium concentrations in sugar beet roots were significantly increased due to the application of different treatments (Table 3). The data showed that N, P, and K concentrations had a positive effect when boron was applied at a rate of 4 g/L compared to without boron addition. These results are consistent with those reported by Ali and Nasef (2024), who concluded that roots of plants sprayed with a 4 g/L dose showed the highest content of N, P, and K. The B content in the roots increased gradually as the amount of borax applied during the foliar period increased from 0 to 6 g/L in both seasons. The results presented in Table 3 indicate the influence of potassium sources on N, P, and K concentrations in roots. The results showed a significant increase in N, P, and K concentrations by applying K-humate at a rate of 12 g/L. Several studies have shown that increasing the levels of potassium humate up to 5 cm L^{-1} can enhance the N, P, and K content in sweet fennel leaves (El-Sawy et al., 2021). The benefits of potassium humate are due to its high content of humic acid, which acts as a biocatalyst that stimulates the activity of phytohormones. It also stimulates the release of antioxidants and regulates the absorption of soluble substances such as vitamin E and vitamin C (Idrees et al., 2020).

Regarding interaction (Table 3), the combination treatment of boron and potassium humate showed the highest increase in N content. Statistical analyses revealed that the combination of boron and potassium rates resulted in a significant increase in N, P, and K content in sugar beet roots. The most significant increases in N and P concentrations were achieved in roots treated with potassium humate at a rate of 12 g/L or with a combination of boron and potassium humate at the same rate. Similarresults were obtained by Ibrahim et al. (2020) who found that foliar spraying of a potassium silicate + potassium humate mixture in combination with 100 mg/L of boron had a significant effect on NPK concentration, yield components, quality characteristics and total yield of sugar beet.

3.3 Concentration of Micronutrients (B, Fe, Mn and Zn) in Sugar Beet Roots

Table 3 demonstrated a notable increase in micronutrient concentrations (B, Fe, Mn, and Zn) in sugar beet roots when different boron and potassium sources were added at varying rates. The study found that applying boron at a rate of 4 g/L resulted in a significant increase in the concentration of B, Fe, Mn, and Zn in the roots compared to without boron. Similar results were found by Ahmed et al. (2011), who observed that the application of boron to cotton increases the availability and uptake of various plant nutrients in the soil, thereby enhancing the uptake and transfer of phosphorus, nitrogen, potassium, zinc, iron, and copper in leaves, shoots, and seeds.

Additionally, the study observed a trend of increasing B, Fe, Mn, and Zn content in roots with higher application rates of potassium treatments (12 g/L). The recent findings support previous research, as this increment could be attributed to humic substances acting as chelators or ligands capable of forming organic complexes with micronutrient ions, enhancing their availability to plants. This leads to improved micronutrient uptake by plant roots (Erro et al., 2016 and AbdElghany et al., 2019).

The interaction between boron and potassium sources had a significant effect only on the concentrations of B and Fe in sugar beet roots (Table 3). The highest values of B, Fe, Mn, and Zn in roots were observed when sugar beets were treated with foliar spraying of boron along with K-humate, or K-humate at a rate of 12 g/L. A significant increase in B and Mn content only was achieved with the application of boron at a rate of 4 g/L in combination with K-humate at a rate of 12 g/L.

3.4 Yield and Yield Component

The results in Table 4 indicated that the application of sugar beet was affected by foliar spraying with boron, potassium sources, rates, and their interactions, which had a significant effect on traits of sugar beet, including root length (cm), root diameter (cm), root fresh weight (kg/plant), root yield and top yield (t/ha). Plots treated with 4g B/L showed notable improvements in these traits compared to the control (without boron addition). The highest root length (32.13 cm), root diameter (14.45 cm), root fresh weight (1.17 kg/plant), root yield, and top yield (54.78 and 32.60 t/ha respectively) were observed for the treatments receiving 4 g B/L. However, the lowest values were realized for treatments without boron. This could be attributed to boron's role in regulating cytokine levels in plants, which enhances cell division and meristem cell activity, leading to increased root length and diameter. Moreover, boron has a stimulatory effect on the rate of photosynthesis by improving carbohydrate metabolism and making it easier for photosynthetic products to move from the leaves to the storage roots, which explains its important functions in root growth and foliage development (Aly et al.,2020 and Bhatnagar et al. 2021). Similar findings were reported in a sugar beet study by Ali and Nasef (2024) who found that the maximum diameter, length, fresh weight, dry matter and yield of root were observed with 4 g/L of borax as a foliar application.

Regarding the potassium sources, the highest values for root length (30.41cm), root diameter (14.47 cm), root fresh weight (1.1 kg/plant), root yield (51.03 t/ha), and top yield (30.89 t/ha) were observed in the K-humate treatment. Furthermore, increasing the potassium application rate from 0 to 4, 8, and 12 g/L resulted in significant enhancements in root length, root diameter, root fresh weight (kg/plant), root yield, and top yield (t/ha). Notably, the application of K-fertilizer at 12 g/L led to a 54.53% increase in root length, a 30.69% increase in root diameter, a 28.57% increase in root fresh weight, a 71.24% increase in root yield, and an 86.17% increase in top yield compared to the control (0 g/L). These findings are supported by Ibrahim et al. (2017) who reported that potassium humate at a concentration of 8 g/L achieved the highest significant mean values for top length, fresh and dry leaf yield per plant, fresh yield per feddan, root length, root diameter, and fresh and dry root yield/plant, as well as fresh yield (ton/fed). The percentage increases were 22%, 53%, 71%, 15%, 24%, 20%, 62%, 51%, and 8.6%, respectively, compared to the control treatment. These increases may be attributed to potassium humate, which plays a crucial role in enhancing plant viability and downstream processing. It not only promotes plant growth and increases leaf area but also facilitates the transfer of essential nutrients to storage areas like seeds. Additionally, potassium humate increase the plant's efficiency in converting carbon metabolism products into seeds, leading to fuller and more productive growth (Madghash and Ali, 2023).

The results indicate a significant interaction effect between boron and potassium sources on root length, diameter, fresh weight, and yield (Table 5). The greatest increase was observed with the addition of 4 g B/L in combination with potassium humate. With respect to the effect of interaction between boron and potassium rates, applying 4 g B/L with potassium at a rate of 3 g/L realized the maximum significant increment of root fresh weight, root yield, and top yield. Also, statistical analyses (Table 5) revealed that potassium sources and rates had a significant effect on all yield and yield component traits, except for root length and diameter. The highest increase was observed with the application of potassium humate at a rate of 12 g/L.

3.5 Quality Parameters and Sugar Yield

Statistical analyses of the data presented in Table 5 revealed values of root quality traits (protein, proline, sugars (%), sugar yield (t/ha) and chlorophyll) of sugar beet plants, which were influenced by foliar application of boron, different sources and rates of potassium and their interactions at harvest as a mean of the two growing seasons. Data in Table 2 indicated that the values of all mentioned traits were significantly influenced by boron foliar spraying. The highest values for most traits were observed in plants sprayed with 4 g B/L compared to those not treated. Similarly, Rashed (2020) demonstrated that the application of boric acid (200 ppm) significantly increased sugar percentage and sugar yield. Furthermore, El-Kalawy (2021) reported that spraying sugar beet with boron at 250 ppm resulted in the highest concentration of B in the shoots, sucrose content in the root juice, juice purity, and total sugar yield. The observed enhancement in quality parameters can be attributed to the important role that boron plays in various plant functions such as sugar transport, cell division, cell-wall synthesis, root elongation, cytoskeletal proteins, plasma membrane enzymes, nucleic acids, indoleacetic acid, polyamines, ascorbic acid, and

Table 3. Nutrients concentration in sugar beet roots grown in saline soilas affected by boron, potassium sources, and rates (combined analyses of two seasons)

Treatments	Concentrations of macronutrients(%)			Concentrations of micronutrients ($mgkg^{-1}$)			
	N	P	K	B	Fe	Mn	Zn
A. Boron (4 g/L)							
without	1.66	0.46	3.05	29.86	117.48	51.64	29.73
with	1.85	0.67	3.43	44.86	136.14	60.38	39.24
LS.D at (0.05)	0.005	0.032	0.202	1.10	7.03	1.84	0.468
B. Potassium source							
Potassium sulphate	1.62	0.49	3.10	33.63	119.47	52.21	31.23
Potassium silicate	1.77	0.56	3.26	37.54	125.63	56.05	34.35
Potassium humate	1.88	0.64	3.36	40.90	135.33	59.78	37.89
LS.D at (0.05)	0.012	0.022	0.119	0.635	2.57	1.07	0.570
C. Potassium rates (g/L)							
0	1.37	0.31	2.80	25.72	103.04	43.78	24.96
4	1.55	0.52	3.13	35.86	124.37	54.65	31.86
8	1.92	0.66	3.45	42.15	137.66	60.60	38.30
12	2.18	0.76	3.57	45.69	142.17	65.01	42.84
LS.D at (0.05)	0.020	0.019	0.114	0.980	2.87	1.77	0.892
Interaction effects							
A xB	***	n.s	n.s	**	**	n.s	n.s
A xC	***	***	**	***	***	***	***
B xC	***	***	n.s	***	***	***	***
A xBxC	***	***	n.s	**	n.s	n.s	*

*ns=not significant, *p<0.05 **p<0.01*

Table 4. Yield and yield components of sugar beet grown in saline soilas affected by boron, potassium sources, and rates (combined analyses of two seasons)

Treatments	Root Length (cm)	Root diameter (cm)	Fresh weight of root (kg/plant)	Weight of root yield (t/ha)	Weight of top yield (t/ha)
			A. Boron (4 g/L)		
without	23.38	11.31	0.73	37.00	21.32
with	32.13	14.45	1.17	54.78	32.60
LS.D at (0.05)	1.31	2.29	0.047	3.71	1.67
			B. Potassium source		
K- sulphate	25.25	11.58	0.81	40.32	23.04
K- silicate	27.6	12.59	0.94	46.31	26.95
K- humate	30.41	14.47	1.1	51.03	30.89
LS.D at (0.05)	0.433	1.17	0.019	0.650	0.32
			C. Potassium rates (g/L)		
0	20.85	11.34	0.84	32.34	17.76
4	27.63	12.38	0.91	44.28	26.74
8	30.32	12.99	0.96	51.54	30.17
12	32.22	14.82	1.08	55.38	33.16
LS.D at (0.05)	0.412	1.29	0.015	0.650	0.271
			Interaction effects		
A xB	***	*	**	**	***
A xC	n.s	**	***	***	ns
B xC	n.s	n.s	***	***	***
A xBxC	***	n.s	***	***	***

*ns=not significant, *p<0.05 **p<0.01*

Table 5. Quality parameters and sugar yield of sugar beet grown in saline soil as affected by boron, potassium sources, and rates (combined analyses of two seasons)

Treatments	Protein (%)	Proline (mg/g.f.w)	Sugar (%)	Sugar yield (t/ha)	Chlorophyll (mg/g.f.w.)
A. Boron (4 g/L)					
without	10.39	53.42	14.49	5.49	6.54
with	11.56	36.56	16.51	9.10	6.55
LS.D at (0.05)	0.042	2.75	1.01	0.354	n.s
B. Potassium source					
K- sulphate	10.11	50.96	14.85	5.96	6.33
K- silicate	11.08	45.55	15.27	7.25	6.47
K- humate	11.73	38.47	16.39	8.68	6.83
LS.D at (0.05)	0.088	0.914	0.205	0.211	0.160
C. Potassium rates (g/L)					
0	8.59	64.79	13.93	4.37	5.02
4	9.71	48.57	15.17	6.85	6.56
8	11.98	36.03	16.16	8.59	6.97
12	13.6	30.58	16.74	9.38	7.63
LS.D at (0.05)	0.128	0.738	0.273	0.177	0.185
Interaction effects					
A xB	***	***	n.s	***	n.s
A xC	***	***	n.s	***	***
B xC	***	***	*	***	n.s
A xBxC	***	***	*	**	n.s

*ns=not significant, *p<0.05 **p<0.01*

phenol metabolism and transport (Mandal et al., 2023). However, proline content decreased significantly when boron (4 g/l) was applied, indicating that osmotic balance was controlled and proline accumulation was reduced under stress. Proline levels that are declining could be a sign of an ideal stress response, which would enable plants to focus their energy on growth rather than stress adaptation. Decreasing stress on the cellular environment by lowering lipid oxidation and raising antioxidant activity may enable plants to devote more energy and resources to development activities. (Younis et al. 2024).

In terms of potassium sources, the results in Table 5 show that all the mentioned traits, except for proline, increased when potassium humate was added compared to potassium sulfate. The positive impact of potassium humate treatments may be attributed to the beneficial role of potassium in plant growth, development, and productivity, as previously mentioned. It is important to distinguish between the direct and indirect effects of humic acid on plant growth. Furthermore, foliar spraying with humic molecules has been shown to enhance leaf water retention, photosynthetic activity, and antioxidant metabolism (Fahramand et al. 2014).The data also indicate that increasing the potassium level from zero to 12 g/L led to a significant rise in protein content, sugar percentage, sugar yield, and chlorophyll. Conversely, proline content in sugar beet significantly decreased. Similar results were obtained by Ibrahim et al. (2017) who found that potassium treatments led to a significant decrease in proline concentration, reaching its lowest level with potassium humate at a rate of 8 g/L.

The interactions between the studied treatments are shown in Table 5. It was observed that the interaction between A×B had a highly significant effect on protein, proline, and sugar yields. The interaction between A×C was significant for all the above parameters except sugar content. The interactions between B×C and A×B×C had a significant effect on protein, proline, sugar percentage, and sugar yield.

3.6 Simple Correlation Matrix

Correlation coefficients between all pairs of studied traits are presented in Fig. 1, The results indicate a highly significant positive correlation between sugar yield and the following traits: root length (0.95**), root yield (0.99**), top yield (0.97**), protein (0.84**), sugar % (0.92**), root Fe (0.94**), root Mn (0.94**), root Zn (0.96**), and root B (0.96**). These results align with findings from previous studies by NemeatAlla et al. (2019).Conversely, highly significant negative correlations were observed between proline and the following traits: root length (-0.94**), root yield (-0.93**), top yield (-0.93**), protein (-0.78**), sugar yield (-0.93**), chlorophyll (-0.78**), root Fe (-0.92**), root Mn (-0.93**), root Zn (-0.93**), and root B (-0.88**).

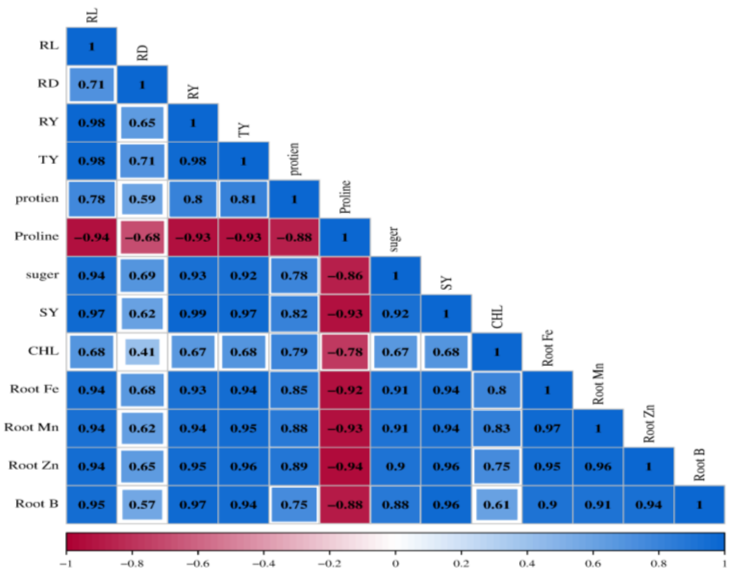

Fig. 1. Correlation matrix between yield quality and its components of sugar beet

RL: Root length, RL: Root diameter, RY: Root yield t/ha TY: Top yield t/ha, protein, Proline, sugar percentage, sugar yield t/ha, and CHL:chlorophyll, Root Fe, Root Mn, Root Zn and Root B

4. CONCLUSION AND RECOMMENDATION

The application of boron and potassium sources, particularly potassium humate has a significant impact on soil nutrient availability, enhancing the growth, yield, and quality of sugar beet. Macronutrient availability is notably influenced by the interaction of boron and potassium sources, except for available phosphorus. The availability of boron, iron, manganese, and zinc is affected by potassium sources. Boron plays a crucial role in regulating cytokine levels, enhancing cell division and meristem activity, leading to improved root traits. The optimal combination of boron with potassium humate (12 g/L) results in significant increases in root length, diameter, fresh weight, root yield, top yield, protein, sugar percentage, sugar yield and chlorophyll content.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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