International Journal of Agriculture and Biosciences 2025 14(6): 1397-1406.
https://doi.org/10.47278/journal.ijab/2025.140

RESEARCH ARTICLE eISSN: 2306-3599; pISSN: 2305-6622

The Influence of Micro-fertilizers on the Productivity of Sugar Beet Hybrids

Almagul Malimbayeva [1], Azamat Khidirov [1], Batyrgali Amangaliev [1], Erbol Zhusupbekov [1], Aigerim Shibikeyeva [2], Akerke Soltanayeva [1], Aina Sagimbayeva [1], Karlyga Rustemova [1] and Maksat Batyrbek [1,*]

[1]Kazakh Research Institute of Agriculture and Plant Growing, Almalybak Village, 040909, Karasai District, Almaty Region, Kazakhstan
[2]Kazakh National Agrarian Research University, Abay 8, Almaty, Kazakhstan
*Corresponding author: batyrbek-maksat@bk.ru

ABSTRACT

This study aimed to evaluate the effects of boron and zinc fertilizers, applied individually and in combination, on the productivity of newly developed domestic sugar beet hybrids in southeastern Kazakhstan. Two hybrids, Bolashak and Abulkhair, were treated with foliar applications of boron (YaraVita Bortrac150), zinc (YaraVita Zintrac700), and their combinations at various concentrations, alongside a basal dose of $N_{300}P_{150}K_{300}$. Treatments were applied at four key growth stages: 4–8 leaf stage, 10–12 leaf stage, leaf closure within rows, and between rows. The highest boron (47.0mg.kg^{-1}) and zinc (37.0mg.kg^{-1}) concentrations were found in Bolashak hybrid at row closure with Bortrac150 (1.5L ha^{-1}) and Zintrac700 (0.5L ha^{-1}). Boron uptake was generally higher than zinc, particularly by the Bolashak hybrid roots compared to the Abulkhair hybrid, especially when treated with "Background + B + Zn10" at 647.5g ha^{-1}. The highest zinc uptake was recorded in the Abulkhair hybrid leaves with the application of YaraVita Bortrac150 (1.5L ha^{-1}) and YaraVita Zintrac700 (0.5L ha^{-1}), amounting to 384.3g ha^{-1}. To produce one ton of biomass, Bolashak required 1256.3g ha^{-1} boron and 727g ha^{-1} zinc, while Abulkhair needed 1153.9 and 751.2g ha^{-1}, respectively. The highest root yield (82.0t ha^{-1}), sugar content (18.1%), and sugar yield (14.8t ha^{-1}) were recorded in Bolashak. Abulkhair reached a maximum root yield of 80.9t ha^{-1}, sugar content of 17.9%, and sugar yield of 14.4t ha^{-1} with combined B and Zn in "$N_{300}P_{150}K_{300}$ + B + Zn10" treatment. These findings suggest optimal B and Zn foliar applications can significantly improve sugar beet productivity and quality under local agro-climatic conditions.

Keywords: Sugar beet, Boron, Zinc, Foliar feeding, Yield.

Article History
Article # 25-295
Received: 22-May-25
Revised: 04-Jun-25
Accepted: 14-Jul-25
Online First: 31-Aug-25

INTRODUCTION

Sugar beet (*Beta vulgaris*) is a commercially cultivated hybrid crop that is commonly known for its root-based high sugar contents. Additionally, the entire beet, including rosette of leaves, molasses, and pulp residue, can be utilized as animal feed or as a feedstock for alcohol production (Duraisam et al., 2017). Although only 25% of the sugar produced worldwide comes from sugar beets (Gonzalez, 2022), it is an extremely valuable and profitable crop in the Republic of Kazakhstan and serves as the primary source of sugar production in the country (Abekova et al., 2022). In this context, food security remains a pressing issue, especially in arid regions like Kazakhstan, where frequent droughts pose significant challenges. Irrigation plays a vital role in stabilizing crop yields and enhancing productivity, particularly in the Almaty region, where soil and climatic conditions can be difficult for agriculture (Bastaubayeva, 2023; Bhatti et al., 2023). Inorganic fertilizers primarily contain the essential macronutrients nitrogen, phosphorus, and potassium, which play a crucial role in supporting both the vegetative and reproductive stages of plant development (Lamlom, 2023). In addition to these macronutrients, micronutrients such as boron (B), and zinc (Zn) are equally important, as they significantly contribute to improving the productivity and quality of agricultural crops (Sharafi et al., 2021). Boron contributes to maintaining the integrity and firmness of the plant cell wall, playing a key

Cite this Article as: Malimbayeva A, Khidirov A, Amangaliev B, Zhusupbekov E, Shibikeyeva A, Soltanayeva A, Sagimbayeva A, Rustemova K and Batyrbek M, 2025. The influence of Micro-fertilizers on the productivity of sugar beet hybrids. International Journal of Agriculture and Biosciences 14(6): 1397-1406. https://doi.org/10.47278/journal.ijab/2025.140

A Publication of Unique Scientific Publishers

role in preserving cell structure, enhancing plant strength, and supporting overall growth and development (González-Fontes, 2020). Similarly, zinc is an essential element required for the regulation of sugar and several enzymatic activities related to plant development, chlorophyll production, carbonic anhydrase activity, nitrogen uptake and protein quality (Suganya et al., 2020; Ayoubi et al., 2023; Lilay, 2024).

Microelements, in particular, contribute to the synthesis of a full spectrum of enzymes in plants, which allow for more efficient use of energy, water, and macroelements. They enhance plant immunity, resistance to diseases, and prevent physiological depression caused by natural-climatic stresses and pesticide exposure. Additionally, they influence various enzymatic processes as activators or inhibitors, improve metabolism and positively impact the yield and quality of plant products (Cozzolino et al., 2021; Shahzad et al., 2021; Salvage et al., 2024).

Microelements serve as cofactors for various enzymes and are involved in redox reactions, including water photolysis during photosynthesis. For instance, the specific role of boron in pollen formation, flower and fruit development, as well as its significance for plant growth and reproduction, is well-documented (Fang et al., 2019; Michailidis et al., 2023). Numerous studies have shown that foliar application of microelements to sugar beet factory fields positively influences all biochemical and physiological processes in plants. This enhances their resistance to the stressful effects of pesticides and abiotic environmental factors (Ahmadpoor Dehkordi et al., 2019; Zewail et al., 2020; Abd El-Mageed et al., 2021; Haqshenas et al., 2023). Microelements are required by plants in minimal amounts, constituting thousandths or ten-thousandths of a percent of the plant mass. However, each microelement performs strictly defined functions in metabolism and plant nutrition, and cannot be replaced by another element (Ahmad et al., 2017; Nieder et al., 2018; Nardi et al., 2021).

To ensure proper nutrition for sugar beet, it is essential to maintain optimal soil content and plant uptake of both key macroelements (nitrogen, phosphorus, and potassium) and microelements such as boron, copper, zinc, manganese, cobalt, iron, molybdenum, and others (Ishfaq et al., 2022). Most of the nutritional needs of sugar beet can be met through the application of base fertilizers in the fall-season (Varga et al., 2022). However, the deficiencies of nitrogen and microelements are better addressed during the crop's growing season. Foliar feeding ensures up to 90% absorption of microelements, compared to 20% via root feeding (Bana et al., 2022). Boron and zinc are more significant for sugar beet than other microelements. Sugar beet is highly sensitive to boron deficiency, which can result in core rot, reduced sugar content, and lower yields (Aghdam et al., 2023). Boron deficiency particularly affects young, growing organs, leading to disease and necrosis of growth points. In addition to boron, sugar beet has an increased demand for zinc (approximately $600gha^{-1}$), manganese (about $1000gha^{-1}$), and molybdenum (around $30gha^{-1}$). The role of zinc in plant growth is closely related to its involvement in nitrogen metabolism. Zinc improves the synthesis of sugars and starch, increases the overall content of carbohydrates, proteins, ascorbic acid, and chlorophyll, and enhances drought, heat, and cold tolerance in plants. Zinc deficiency in plants leads to the accumulation of reducing sugars, a decrease in sucrose and starch content, an increase in organic acid accumulation, reduced auxin levels, disrupted protein synthesis, and the accumulation of non-protein nitrogen compounds such as amides and amino acids (Zhao et al., 2023).

It has been established that boron fertilizers increase sugar content: by 0.7-1.4% with base application, by 0.3-0.9% with foliar feeding, and by 0.5-0.8% with seed treatment (Zhao et al., 2023). Research on the effectiveness of micronutrient fertilizers, especially Zn and B, as top dressings of mineral fertilizers on sugar beet crops has been limited in the Almaty and Zhetysu regions. In this context, effective methods and techniques for applying boron and zinc fertilizers to the crops of new sugar beet hybrids, Bolashak and Abulkhair, have been developed for the first time under the conditions of light chestnut irrigated soils in the southeastern region of Kazakhstan. Therefore, the objective of this study was to evaluate the individual and combined effects of boron and zinc foliar fertilization on the yield, quality indicators, and nutrient composition of the new sugar beet hybrids Bolashak and Abulkhair under irrigated conditions.

MATERIALS & METHODS

Location of the Study

The current study was conducted through field experiments on the irrigated experimental plot of the "Kazakh Research Institute of Agriculture and Plant Growing", in the Karasai district of the Almaty region, located in the foothill zone (43◦13′N, 76◦41′E, 740 m asl) (Fig. 1). The soil of the stationary field is light chestnut with a medium-thick humus horizon, low in humus, and of medium loam composition, containing 35-43% physical clay and 57-65% physical sand. The total humus content in the arable layer ranges from 1.60 to 1.90%, total nitrogen is 0.15%, total phosphorus is 0.21%, and total potassium is 1.67%. Soil levels of mineral nitrogen are very low, mobile phosphorus is low, and exchangeable potassium is moderate. The carbon-to-nitrogen ratio (C: N) is 9.8, and the CO_2 content (carbonates) is 3.1%. Among absorbed cations, calcium (Ca) predominates at 12.0mg-eq per 100g, followed by magnesium (Mg) at 2.5mg-eq per 100g, amounting to a total of 14.5mg-eq per 100g. The soil solution reaction is slightly alkaline (pH = 7.8), with no soil salinity, and a solid residue in the 1.5-meter layer does not exceed 0.1%.

The density of the arable soil layer is slightly compacted at $1.21gcm^{-3}$. The porosity of the arable layer is satisfactory at 53.4%. The silt fraction (< 0.001mm) in the 0-20cm layer constitutes 11-15%, and fine dust (0.005-0.001mm) 13-20%. In the 20-40cm layer, the silt fraction increases to 16-22%, and fine dust to 17-22%. Based on the content of agronomically valuable aggregates, this soil is rated as good to excellent within 54-78%. However, its resistance to water erosion is unsatisfactory at 10-20%. The sum of water-stable aggregates is unsatisfactory to moderately satisfactory at 10-30%. The soil's water permeability is good, at 76 mm per hour. Groundwater depth exceeds 5m and does not influence soil formation.

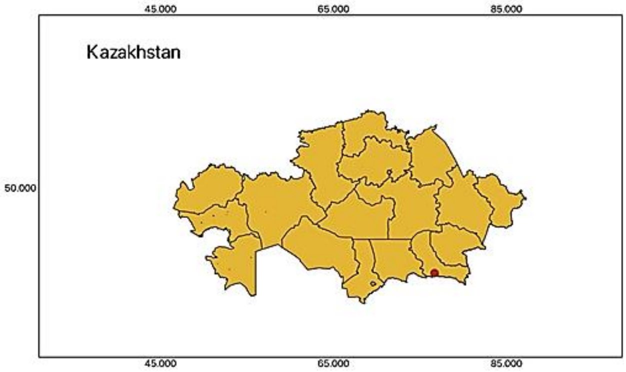

Fig. 1: Location map of studied area.

Experimental Design and Description

In the field experiment, two new domestic sugar beet hybrids, Bolashak and Abulkhair, were sown when the soil temperature warmed up to 8°C. Sowing was conducted using a Plancer 2.8 seeder at a depth of 2-3cm, with a seeding rate of 1.2-1.3 sowing units per hectare, or approximately six plants per linear meter. For base fertilization in spring, ammonium nitrate was applied at 300kg of active ingredient, while ammonium phosphate (150kg) and potassium chloride (300kg) were applied in the fall.

For foliar feeding of sugar beet hybrids, boron fertilizer YaraVita Bortrac150 and zinc fertilizer YaraVita Zintrac700 were applied during the 4-8 leaf phase, the 10-12 leaf phase, leaf closure within rows, and leaf closure between rows. The application rates for variant B_5 were 1.5Lha^{-1} (0.75% solution), for B_{10} - 3Lha^{-1} (1.5% solution), for Zn_5 - 0.5Lha^{-1} (0.25% solution), and for Zn_{10} - 1Lha^{-1} (0.5% solution). For the combined B+Zn_5 variant, 0.75Lha^{-1} of Bortrac150 + 0.25Lha^{-1} of Zintrac700 (0.5% solution) was used, while for B+Zn_{10}, 1.5Lha^{-1} of Bortrac150 + 0.5Lha^{-1} of Zintrac700 (1% solution) was applied, with a water consumption rate of 200Lha^{-1}. YaraVita Bortrac150 contains 150gL^{-1} of boron and 65gL^{-1} of nitrogen, while YaraVita Zintrac700 contains 700gL^{-1} of zinc and 18gL^{-1} of nitrogen. A trailer sprayer OPG-2000 was used for fertilizer application alongside herbicides to protect the sugar beet field from weeds.

The experiment was conducted in Randomized Complete Block Design (RCBD) with three replications. The plot arrangement was systematic, while the treatments within replications were randomized. The sowing area of each plot was kept 30m². The preceding crop for sugar beet was winter wheat. The experimental treatments were as follows:

1. Control-CK
2. $N_{300}P_{150}K_{300}$
3. $N_{300}P_{150}K_{300}$ +B_5
4. $N_{300}P_{150}K_{300}$+B_{10}
5. $N_{300}P_{150}K_{300}$ +Zn_5
6. $N_{300}P_{150}K_{300}$+Zn_{10}
7. $N_{300}P_{150}K_{300}$+B+Zn_5
8. $N_{300}P_{150}K_{300}$+B+Zn_{10}.

Basic Characteristics of the Soil Used

Random soil samples were taken throughout the field prior to the plowing and planting procedures in order to properly assess the experimental location. Using an augur, soil samples were taken in the field from 0 to 30cm below the surface of various treatments. Following the removal of debris, samples were passed through a <2mm sieve. Prior to the experiment, the main nutrients in the soil were identified using the applicable state requirements.

The analysis of key soil fertility indicators and product quality, including the content of essential nutrients nitrogen by Kjeldahl method (Bremner, 1960), while phosphorus and potassium were determined by Michigan method in modification of the Central Research Institute of Agrochemical Services for Agriculture State Standard 26205-91. Exchangeable potassium was calculated on a flame photometer following State Standard 26205-91 (Batyrbek et al., 2022).

Boron and zinc content in the leaves, beet tops, and roots of the sugar beet hybrids were determined using the atomic absorption method (Adarve et al., 1998). Harvesting and yield accounting of the two sugar beet hybrids were conducted during the technical maturity stage, when the roots had maximum mass and sugar content. Yield was determined by weighing cleaned roots from the accounting plots using platform scales.

Sugar content in the roots was analyzed using a modern polarimetric flow-through saccharimeter (Babeker, 2022). Sodium content in the sugar beet roots was measured by flame photometry (Škrbić et al., 2010). The α-amino nitrogen and ash content were analyzed using a spectrophotometer (Tillman, 2019). Statistical processing of the obtained research results was carried out using analysis of variance by SPSS.

Sugar Beet Yield and Sugar Content

To determine sugar beet productivity, both root yield and sugar yield were calculated. Sugar beet roots were harvested from a designated plot area of 10m² in each replicate. The total fresh weight of the roots was measured immediately after harvesting using a precision digital scale. The root yield was then expressed in tonnes per hectare (tha^{-1}) using the following formula:

$$Root\ Yield\ (t/ha) = \frac{Total\ root\ weight\ (kg) \times 10}{Harvested\ plot\ area\ (m^2)}$$

Sugar content (%) in the beet roots was determined using a polarimetric method in accordance with ICUMSA guidelines. Cleaned and homogenized root samples were extracted and the clarified juice was analyzed using a standard polarimeter.

Sugar yield (tha^{-1}) was calculated by multiplying root yield by sugar content, according to the following formula:

$$\text{Sugar Yield (t/ha)} = \frac{\text{Root Yield (t/ha)} \times \text{Sugar Content (\%)}}{100}$$

RESULTS

Dynamics of Microelements (B, Zn) Content in the Plants and uptake with the Yield of Sugar Beet Hybrids

Microfertilizers applied as top-dressing on the mineral fertilizers ($N_{300}P_{150}K_{300}$) had varying effects on the boron and zinc content in the root crops during the vegetative period of the sugar beet hybrids Bolashak and Abulkhair. The application of microfertilizers increased the boron content in the root crops of the Bolashak and Abulkhair hybrids during the leaf closure phase within rows by 2.4–6.2mgkg^{-1} and 2.2–7.2mgkg^{-1}, respectively, and during the leaf closure phase between rows by 3.5–11.7mgkg^{-1} and 10.0–15.5mgkg^{-1} compared to the control.

The zinc content in the Bolashak hybrid root crops showed a decrease of 0.8mgkg^{-1} during the leaf closure phase within rows in the variant with $N_{300}P_{150}K_{300}$ + B_5, but increased by 4.2mgkg^{-1} during the leaf closure phase between rows compared to the control. For other microfertilizer treatments, an increase in zinc content was observed in Bolashak root crops during the leaf closure phase within rows by 0.7–5.0mgkg^{-1} and during the leaf closure phase between rows by 1.7–7.0mgkg^{-1} compared to the control.

In the Abulkhair hybrid, an increase in zinc content in the root crops was observed across all micro fertilizer treatments during the leaf closure phase within rows and between rows by 1.7–9.0mgkg^{-1} and 3.7–9.0mgkg^{-1}, respectively, compared to the control. Mineral fertilizers at a rate of $N_{300}P_{150}K_{300}$ also increased the content of microelements, but only slightly, across all studied hybrids, plant growth phases, and microelements, by 1.0–4.0mgkg^{-1}. The exception was observed in the Bolashak hybrid during the leaf closure phase within rows and between rows, where there was a decrease in zinc content by 0.8mgkg^{-1} in both phases compared to the control.

In the leaves and tops of the Bolashak and Abulkhair hybrids during the studied plant development phases, an increase in boron and zinc content by 0.4–18.0mgkg^{-1} was observed compared to the control. The highest boron content in the tops of the Bolashak hybrid was recorded during the leaf closure phase between rows, with the combined application of the boron fertilizer YaraVita Bortrac 150 at a dose of 1.5Lha^{-1} and the zinc fertilizer YaraVita Zintrac 700 at a dose of 0.5Lha^{-1} with mineral fertilizers ($N_{300}P_{150}K_{300}$), reaching 47mgkg^{-1}. Meanwhile, the highest zinc content in the tops of the Abulkhair hybrid was recorded during the same phase, reaching 41.0mgkg^{-1} in the $N_{300}P_{150}K_{300}$+B+Zn_{10} variant.

The lowest boron and zinc levels were observed in the leaves of the Bolashak hybrid during the 10–12 leaf phase (7.0mgkg^{-1}) and in the tops of the Abulkhair hybrid during the leaf closure phase between rows (32.0mgkg^{-1}). Microfertilizers contributed to higher accumulation of boron and zinc in the leaves, beet tops, and roots of both hybrids during all development phases. The increase relative to the mineral fertilizer variant was 4.0–11.7mgkg^{-1} for boron and 6.0–15.0mgkg^{-1} for zinc, while the increase compared to the control ranged from 1.0–17.0mgkg^{-1} for boron and 0.7–18.0mgkg^{-1} for zinc (Table 1 and 2).

The studies indicate that the uptake of boron by the root crops of the Bolashak and Abulkhair hybrids, against the mineral fertilizers $N_{300}P_{150}K_{300}$, increased with the application of boron fertilizer B_5 at a dose of 1.5Lha^{-1} by 355.0gha^{-1} and 251.6gha^{-1} relative to the control. When boron fertilizer B_{10} was applied at a dose of 3Lha^{-1}, the uptake increased by 360.1gha^{-1} and 259.1gha^{-1}. Zinc fertilizer Zn_5, at a dose of 0.5Lha^{-1}, increased boron uptake by 258.7gha^{-1} and 296.5gha^{-1}. When zinc fertilizer Zn_{10} was applied at a dose of 1Lha^{-1}, the uptake increased by 249.8gha^{-1} and 313.0gha^{-1}. Joint application of boron fertilizer B at a dose of 0.75Lha^{-1} and zinc fertilizer at a dose of 0.25Lha^{-1} resulted in an increase of 387.1gha^{-1} and 360.0gha^{-1}. Finally, the application of boron fertilizer B at a dose of 1.5Lha^{-1} and zinc fertilizer Zn_{10} at a dose of 0.5Lha^{-1} led to an increase of 420.7gha^{-1} and 385gha^{-1}, respectively.

The boron uptake by the root of the Bolashak and Abulkhair hybrids increased by 302.4gha^{-1} and 203.0gha^{-1}, respectively, with the application of mineral fertilizers at the rate of $N_{300}P_{150}K_{300}$ compared to the control.

Table 1: Dynamics of Microelement Content in Bolashak Sugar Beet Hybrid Plants as Affected by Microfertilizer Application (mgkg^{-1} of Dry Matter)

Treatments	Phases of sugar beet development											
	4-8 leaves		10-12 leaves		Leaf canopy closure within the rows				Leaf canopy closure between rows			
	leaves		leaves		foliage		root		foliage		root	
	B	Zn	B	Zn	B	Zn	B	Zn	B	Zn	B	Zn
CK	11.0	8.4	9.0	7.0	20.0	25.0	15.0	8.0	30.0	14.0	18.0	11.0
$N_{300}P_{150}K_{300}$	12.0	9.0	11.5	10.0	22.0	30.0	16.0	7.2	42.0	15.0	19.0	10.2
$N_{300}P_{150}K_{300}$ +B_5	15.0	10.1	18.0	10.5	25.0	31.0	18.0	7.2	44.0	15.5	25.0	15.2
$N_{300}P_{150}K_{300}$+B_{10}	20.0	10.7	21.3	10.7	23.0	31.0	21.2	8.7	44.0	17.8	27.1	12.7
$N_{300}P_{150}K_{300}$+Zn_5	13.0	20.4	14.5	22.0	24.0	32.0	17.4	10.0	37.0	20.2	22.2	13.0
$N_{300}P_{150}K_{300}$+Zn_{10}	14.0	23.7	13.8	25.0	26.0	34.0	16.0	10.7	36.0	25.0	21.5	15.7
$N_{300}P_{150}K_{300}$+B+Zn_5	18.0	21.0	20.4	23.4	22.0	30.4	19.2	11.0	45.0	23.0	25.4	17.0
$N_{300}P_{150}K_{300}$+B +Zn_{10}	23.5	19.0	22.5	25.0	26.0	37.0	20.0	13.0	47.0	26.0	29.7	18.0

Table 2: Dynamics of Microelement Content in Abulkhair Sugar Beet Hybrid Plants Depending on Micronutrient Fertilizer Application (mgkg^{-1} of Dry Matter)

Treatments	Phases of sugar beet development											
	4-8 leaves		10-12 leaves		Leaf canopy closure within the Row				Leaf canopy closure between rows			
	leaves		leaves		foliage		Root		foliage		root	
	B	Zn	B	Zn	B	Zn	B	Zn	B	Zn	B	Zn
CK	8.0	7.1	8.0	8.0	15.0	15.0	14.0	9.0	25.0	12.0	14.0	10.0
$N_{300}P_{150}K_{300}$	10.0	8.0	9.5	9.0	12.0	20.0	16.7	10.2	32.0	14.0	18.0	11.2
NPK+B_5	11.0	9.5	11.0	9.5	15.4	21.0	18.0	11.2	34.0	16.5	24.0	14.2
NPK+B_{10}	12.0	8.7	11.0	9.7	14.0	21.0	21.2	10.7	34.0	18.8	25.6	13.7
NPK+Zn_5	13.0	11.4	12.0	12.2	14.8	22.0	17.4	14.0	37.0	24.2	24.2	13.8
NPK+Zn_{10}	11.0	15.7	10.8	15.0	16.7	24.6	16.0	17.7	38.0	26.0	26.8	14.7
NPK+B+Zn_5	17.0	14.2	14.7	13.4	12.0	20.4	19.2	17.0	40.0	27.0	27.4	18.0
NPK + B +Zn_{10}	20.0	15.0	15.5	15.0	16.0	27.0	20.0	18.0	41.0	27.0	29.5	19.0

The boron uptake by the foliage of the Bolashak and Abulkhair hybrids also increased with the application of fertilizers, though to a lesser extent than by the root. With the use of mineral fertilizers alone, boron uptake by the foliage of the Bolashak hybrid increased by 153.8gha^{-1} and by the Abulkhair hybrid by 170.6gha^{-1} compared to the control. In variants with micronutrients applied on a fertilized NPK, boron uptake by the foliage of the Bolashak and Abulkhair hybrids increased to 221.1–406.4gha^{-1} and 301.7–453.1gha^{-1}, respectively, compared to the control (Table 3).

The zinc uptake by the root and foliage of the Bolashak and Abulkhair hybrids was lower compared to boron uptake. Zinc uptake by the root of the Bolashak and Abulkhair hybrids, when foliar treatments were applied on the mineral fertilizers, increased by 99.1–245.2gha^{-1} and 123.0–284.3g.ha^{-1}, respectively, and with the application of mineral fertilizers at the rate of $N_{300}P_{150}K_{300}$, it increased by 83.2gha^{-1} and 81.5gha^{-1}. Zinc uptake by the foliage of the Bolashak and Abulkhair hybrids in treatments with foliar feeding on a fertilized NPK was higher than with the application of only mineral fertilizers. In treatments with root feeding on a mineral fertilizer NPK, the uptake of this micronutrient ranged from 156.1gha^{-1} to 281.8g ha^{-1}, while in the mineral fertilizer variant, it amounted to 92.9gha^{-1}.

The applied fertilizers increased the overall micronutrient uptake by the sugar beet hybrids, with the highest values for boron compared to zinc in terms of the formation of 1 ton of root crops. The total boron uptake by the Bolashak hybrid, depending on the application of micronutrients on a mineral fertilizer NPK, ranged from 900.1–1256.3gha^{-1}, with the use of $N_{300}P_{150}K_{300}$ at 885.5gha^{-1}, and the lowest was in the variant without their application, at 429.3gha^{-1}. Abulkhair hybrid, depending on the micronutrient variants on a mineral fertilizer NPK, the mineral fertilizer variant, and the control variant, took up less boron compared to the Bolashak hybrid, with values of 869.0–1153.9gha^{-1}, 689.3gha^{-1}, and 315.7gha^{-1}, respectively. The differences in total zinc uptake between the Bolashak and Abulkhair hybrids were not significant, with values for micronutrient foliar treatments on a mineral fertilizer NPK being 489.5–727.2gha^{-1} for Bolashak and 469.1–751.2gha^{-1} for Abulkhair. For the mineral fertilizer variants, the values were 380.3gha^{-1} and 359.6gha^{-1}, respectively, and for the control, they were 229.6gha^{-1} and 185.2gha^{-1}. Therefore, to produce 1 ton of root crops for the Bolashak hybrid, including foliage, with micronutrient foliar treatments on a mineral fertilizer NPK, 900.1–1256.3g of boron and 489.5–727.2g of zinc was taken up from the soil. With the application of mineral fertilizers $N_{300}P_{150}K_{300}$, this amount is 885.5g of boron and 380.3g of zinc, and without the use of fertilizers, it is 429.3g of boron. For the Abulkhair hybrid, to produce 1 ton of root crops with foliage, with foliar micronutrient treatments on a mineral fertilizer NPK, 869.0–1153.9g of boron and 469.1–751.2g of zinc is consumed. With the application of mineral fertilizers, the amounts are 689.3g of boron and 359.6g of zinc, and in the control, they are 315.7g of boron and 185.2g of zinc, respectively (Table 3).

Effect of Micronutrients on the Productivity of Sugar Beet Hybrids

The yield of the Bolashak hybrid was higher than that of the Abulkhair hybrid by 4.0tha^{-1} in the variant without fertilizer application, 5.2tha^{-1} in the $N_{300}P_{150}K_{300}$ variant, and 1.1–4.5tha^{-1} in the micronutrient treatments on a mineral fertilizer NPK. The use of high doses of mineral fertilizers $N_{300}P_{150}K_{300}$ increased the yield of the Bolashak and Abulkhair sugar beet hybrids to 75.0tha^{-1} and 69.8tha^{-1}, respectively, with increases exceeding the control by 30.0tha^{-1} and 28.8tha^{-1}, respectively. The use of foliar micronutrient treatments on a nitrogen-phosphorus-potassium NPK during the growing season further increased the yield of the Bolashak and Abulkhair hybrids to 78.1–82.0tha^{-1} and 74.2–79.2tha^{-1}, with increases relative to the control of 33.1–37.0tha^{-1} and 33.2–39.9tha^{-1}, respectively. Increasing the dose of boron fertilizer from 1.5Lha^{-1} to 3Lha^{-1} increased the yield of the Bolashak and Abulkhair hybrids by 0.7tha^{-1} and 1.3tha^{-1}, respectively. The zinc fertilizer dose increases from 0.5Lha^{-1} to 1.0Lha^{-1} led to a yield increase of 0.7tha^{-1} and 0.6tha^{-1}. When combining these fertilizers at doses of 0.75Lha^{-1} of YaraVita Bortrac150 and 0.25Lha^{-1} of YaraVita Zintrac700 to 1.5Lha^{-1} of YaraVita Bortrac150 and 0.5Lha^{-1} of YaraVita Zintrac700, the yield increased by 0.8tha^{-1} and 1.7tha^{-1}, respectively. The highest yield of Bolashak sugar beet root crops was obtained with the combined application of 1.5Lha^{-1} of YaraVita Bortrac150 and 0.5Lha^{-1} of YaraVita Zintrac700, reaching 82.0tha^{-1} (Table 4).

Boron fertilizers, like zinc fertilizers, used as foliar treatments on a fertilized NPK during the growing season of the Bolashak and Abulkhair hybrids, provided the highest sugar content in the root crops, ranging from 17.7% to 18.1% for Bolashak and from 17.5% to 17.9% for Abulkhair. The increase in sugar content was identical, at 0.5–0.9%. When only mineral fertilizers at the rate of $N_{300}P_{150}K_{300}$ were used, the sugar content in the root crops of the Bolashak and Abulkhair hybrids increased less, reaching 17.5% and 17.3%, respectively, which was 0.3% higher than the

Table 3: Micronutrient uptake with the yield of sugar beet hybrids (gha^{-1})

Treatments	Nutrient uptake by main (1) and (2)							
	Bolashak				Abulkhair			
	B		Zn		B		Zn	
	Main	by-products	Main	by-products	Main	by-products	Main	by-products
CK	226.8±9.1f	202.5±7.6g	105.8±15.6f	123.8±11.1f	172.2±10.5f	143.5±16.4g	82.7±9.5g	102.5±6.5f
$N_{300}P_{150}K_{300}$	529.2±9.0d	356.3±11.0f	189.0±15.7e	191.3±10.3e	375.2±11.7e	314.1±8.0f	164.2±8.9f	195.4±13.2e
$N_{300}P_{150}K_{300}+B_5$	581.8±11.0c	491.9±9.9d	204.9±12.0e	299.1±9.5c	423.8±8.9d	445.2±10.9e	205.7±8.5e	263.4±11.4cd
$N_{300}P_{150}K_{300}+B_{10}$	586.9±10.1c	536.0±12.3b	237.4±14.3d	252.1±8.7d	431.3±9.5d	483.2±12.7d	238.5±6.5d	258.6±10.5d
$N_{300}P_{150}K_{300}+Zn_5$	485.5±11.2e	429.6±8.1e	265.0±9.8c	253.8±13.0d	468.7±9.8c	456.2±12.4e	306.5±11.1c	260.1±9.4d
$N_{300}P_{150}K_{300}+Zn_{10}$	476.6±12.8e	423.6±11.0e	331.0±9.5b	309.3±7.1c	485.2±9.7c	509.2±8.7c	332.0±7.5b	279.3±10.1c
$N_{300}P_{150}K_{300}+B+Zn_5$	613.9±9.9b	515.6±9.4c	313.8±7.9b	345.1±9.1b	532.2±8.6b	542.5±10.1b	360.5±10.1a	356.4±8.0b
$N_{300}P_{150}K_{300}+B+Zn_{10}$	647.5±9.3a	608.9±9.8a	358.2±9.8a	369.0±10.6a	557.2±8.8a	596.6±10.3a	367.0±9.7a	384.3±6.3a

Data are shown as the mean±SD. Different letters indicate significant differences within rows at P≤0.05, as determined by the LSD test.

control in both cases. The maximum sugar accumulation was observed in the Bolashak root crops when boron fertilizer YaraVita Bortrac150 at a dose of $1.5Lha^{-1}$ and zinc fertilizer YaraVita Zintrac700 at a dose of $0.5Lha^{-1}$ were applied together, reaching 18.1%. For the Abulkhair hybrid, the highest sugar content in the root crops was observed in the variants with $N_{300}P_{150}K_{300}$+B+Zn_5 and $N_{300}P_{150}K_{300}$+B+Zn_{10}, reaching 17.9%.

The sugar yield was lowest in the treatment without fertilizer application for both hybrids, ranging from 6.9 to $7.7tha^{-1}$. The application of high doses of mineral fertilizers, $N_{300}P_{150}K_{300}$, significantly increased sugar yield, reaching $13.1tha^{-1}$ for the Bolashak hybrid and $12.0tha^{-1}$ for the Abulkhair hybrid. With the application of boron and zinc fertilizers and increasing their doses on a mineral fertilizer NPK, the sugar yield increased to 13.8–$14.8tha^{-1}$ for the Bolashak hybrid and to 13.0–$14.4tha^{-1}$ for the Abulkhair hybrid. The maximum sugar yield was achieved with the cultivation of the Bolashak hybrid, using $1.5Lha^{-1}$ of YaraVita Bortrac150 and $0.5Lha^{-1}$ of YaraVita Zintrac700, reaching $14.8tha^{-1}$ (Table 4).

In addition to sugar content as the main quality indicator of sugar beet root crops it is important to consider the main no sugary substances, as their increase leads to sugar loss in molasses. Research showed that the lowest content of potassium, sodium, and alpha-amino nitrogen in the root of the Bolashak hybrid was observed in the variants without fertilizer application, with values of 5.50mmol/100g of fresh weight, 0.60mmol/10g of fresh weight, and 1.25mmol/100g of fresh weight, respectively. The application of high doses of mineral fertilizers $N_{300}P_{150}K_{300}$ increased the potassium content by 0.37mmol/100g of fresh weight, sodium by 0.16mmol/100g of fresh weight, and alpha-amino nitrogen by 0.13mmol/100g of fresh weight compared to the control. When boron and zinc fertilizers were used separately or together on a mineral fertilizer NPK, the potassium content increased by 0.26–0.31mmol/100g of fresh weight, sodium by 0.12–0.20mmol/100g of fresh weight, and alpha-amino nitrogen by 0.07–0.14mmol/100g of fresh weight relative to the control.

A similar pattern in potassium, sodium, and alpha-amino nitrogen content was observed in the Abulkhair hybrid, but with generally lower values. The application of mineral fertilizers and micronutrient foliar treatments in this hybrid on a fertilized NPK resulted in increases in potassium content in the root crops by 0.70–0.90mmol/100g of fresh weight, sodium by 0.04–0.09mmol/100g of fresh weight, and alpha-amino nitrogen by 0.10–0.18mmol/100g of fresh weight compared to the control. The lowest amounts of potassium, sodium, and alpha-amino nitrogen in the root crops of the Abulkhair hybrid were observed in the control variant, with values of 4.90mmol/100g of fresh weight, 0.54mmol/100g of fresh weight, and 1.20mmol/100g of fresh weight, respectively. The ash content in the root of the Bolashak hybrid, depending on the fertilizer variants, was 0.1% higher than the control, while in the root crops of the Abulkhair hybrid, the ash content was the same across all variants of the experiment, at 0.7% (Table 5).

DISCUSSION

Effect of Microfertilzer Application on Zn and B Accumulation Sugar Beet Vegetative Tissues

It is very important to optimize the required micro- and macro-elements level of a crop to yield satisfactorily and produce product of best quality, for instance sugar yield and sugar contents in sugar beet. Besides, optimizing the methods of application of micronutrients at specific growth stage of sugar beet are equally important, whether it has to be applied in granular form, foliar spray or in combination. Here, we applied micro-fertilizers as top-dressing along with standard NPK dose to evaluate the Zn and B-content in the root and leaves of sugar beet hybrids. The application of micro-fertilizers as foliar top-dressing on a background of mineral fertilizers ($N_{300}P_{150}K_{300}$) significantly influenced the boron and zinc content in the root crops, leaves,

Table 4: The Impact of micronutrient application on the productivity of sugar beet hybrids

Treatments	Bolashak Hybrid, t ha^{-1}						Abulkhair hybrid, t ha^{-1}					
	Yield	Increase Relative to the Control	Sugar Content, %	Deviation from the Control	Sugar Yield, t/ha	Deviation from the Control	Yield	Increase Relative to the Control	Sugar Content, %	Deviation from the Control	Sugar Yield, t/ha	Deviation from the Control
CK	45.0	-	17.2	-	7.7	-	41.0	-	17.0	-	6.9	-
$N_{300}P_{150}K_{300}$ - NPK	75.0	30.0	17.5	0.3	13.1	5.4	69.8	28.8	17.3	0.3	12.0	5.1
NPK +B 5	78.7	33.7	17.8	0.6	14.0	6.3	74.2	33.2	17.6	0.6	13.0	6.1
NPK +B 10	79.4	34.4	17.9	0.7	14.2	6.5	75.5	34.5	17.7	0.7	13.3	6.4
NPK +Zn 5	78.1	33.1	17.7	0.5	13.8	6.1	75.4	34.4	17.5	0.5	13.1	6.2
NPK +Zn 10	78.8	33.8	17.8	0.6	14.0	6.3	76.0	35.0	17.6	0.6	13.3	6.4
NPK +B+Zn 5	81.2	36.2	18.0	0.8	14.6	6.9	79.2	38.2	17.9	0.9	14.1	7.2
NPK + B +Zn 10	82.0	37.0	18.1	0.9	14.8	7.1	80.9	39.9	17.9	0.9	14.4	7.5
$LSD_{0.5}$	5.5						6.9					

Table 5: The impact of micronutrient application on the technological quality indicators of sugar beet hybrids

Treatments	Bolashak hybrid, mmol/100g of fresh weight			ash, %	Abulkhair hybrid, mmol/100g of fresh weight			ash, %
	potassium	sodium	α-amino nitrogen		potassium	sodium	α-amino nitrogen	
CK	5.50	0.60	1.25	0.6	4.90	0.54	1.20	0.7
$N_{300}P_{150}K_{300}$	5.87	0.76	1.38	0.7	5.60	0.58	1.30	0.7
NPK+B_5	5.85	0.78	1.35	0.7	5.70	0.61	1.35	0.7
NPK+B_{10}	5.76	0.78	1.32	0.7	5.74	0.63	1.30	0.7
NPK+Zn_5	5.80	0.72	1.36	0.7	5.70	0.60	1.38	0.7
NPK+Zn_{10}	5.77	0.75	1.38	0.7	5.76	0.61	1.35	0.7
NPK+B_5+Zn_5	5.79	0.72	1.39	0.7	5.78	0.62	1.36	0.7
NPK+B_{10}+Zn_{10}	5.81	0.80	1.36	0.7	5.80	0.62	1.32	0.7

and tops of sugar beet hybrids Bolashak and Abulkhair. These findings are in line with previous studies that have reported the beneficial effects of micronutrient foliar application on improving the nutritional status and productivity of sugar beet under different soil and climatic conditions (Mekdad and Shaaban, 2020). The foliar feeding method proved to be effective, particularly when applied during key phenological stages such as leaf closure. The elevated boron content observed at this stage suggests an increased translocation efficiency likely driven by larger leaf surface area and intensified metabolic activity.

The micronutrients accumulation in crops have been investigated in different crops and found significantly influenced by growth phase at which micro-fertilizers were applied. The response of crop to *in-vitro* micro-fertilizers application were influenced by the genetic background of genotype of that crop (Jatav et al., 2020). The increase in boron content during the vegetative phases, particularly during the leaf closure stages, demonstrates the high responsiveness of both hybrids to foliar boron application. The highest increase was observed during the leaf closure between rows, suggesting greater uptake efficiency at this growth stage, possibly due to enhanced translocation mechanisms and leaf surface area (Tohma and Esitken, 2011). This aligns with studies showing that boron is crucial during active vegetative growth phases when cell division and sugar transport are at their peak (Day and Aasim, 2020). Similarly, zinc content dynamics varied between hybrids and fertilizer treatments. In the Bolashak hybrid, zinc levels decreased in some treatments, particularly with the application of boron alone ($NPK+B_5$), indicating possible antagonism between zinc and boron uptake pathways (Hossain et al., 2020). Conversely, in the Abulkhair hybrid, zinc content consistently increased across all treatments, highlighting potential varietal differences in micronutrient absorption and transport capacities (Grewal et al., 2020). These hybrid-specific behaviors underline the importance of tailoring fertilizer strategies based on genetic background. The combined application of boron and zinc showed synergistic effects, especially in improving micronutrient accumulation in the beet tops and foliage. The highest boron and zinc content in the tops was observed with the application of YaraVita Bortrac 150 ($1.5Lha^{-1}$) and YaraVita Zintrac 700 ($0.5Lha^{-1}$), suggesting the benefits of balanced micronutrient application for optimizing nutrient assimilation (Bhardwaj et al., 2021). Likewise, boron and zinc uptake by roots and foliage also showed significant increases with micronutrient applications. Uptake was generally higher for boron than zinc, which may be attributed to differences in solubility, mobility in plant tissues, and plant demand (Safdar et al., 2023). The uptake efficiency was highest with combined foliar treatments, especially in the B_5+Zn_{10} variants, indicating the effectiveness of multi-nutrient approaches in micronutrient-deficient soils (Pimentel et al., 2023).

It is noteworthy that the application of only mineral fertilizers also resulted in slight increases in micronutrient uptake, suggesting improved root development and soil nutrient availability. However, the increases were significantly lower than those observed with foliar micronutrient treatments, confirming the essential role of targeted foliar nutrition in addressing micronutrient deficiencies during critical growth stages (Stewart et al., 2021). These data demonstrate that foliar application of boron and zinc, particularly in combination, enhances nutrient accumulation and uptake efficiency in sugar beet hybrids. These findings support previous research emphasizing the importance of micronutrients in improving sugar beet quality and yield potential under intensive fertilization systems (Hao et al., 2021). The varietal response differences observed between Bolashak and Abulkhair further suggest the need for genotype-specific fertilizer strategies to optimize micronutrient management. Overall, the results strongly support the strategic use of foliar boron and zinc as part of an integrated nutrition management plan for sugar beet. The significant increases in nutrient accumulation in both roots and vegetative parts suggest improved metabolic functioning and potentially greater sugar transport and storage efficiency. Future research should further investigate the mechanisms behind nutrient interaction at the physiological and molecular level, as well as assess long-term impacts on soil nutrient balance and plant health.

Effect Micro-fertilizers on Yield, Quality and Sugar Contents of Sugar Beet Hybrids

Foliar application of micronutrients, particularly boron and zinc, had a significant effect on the yield and quality of sugar beet hybrids. These findings are consistent with earlier studies, which demonstrated the positive effects of boron on sugar accumulation and root yield (Artyszak and Gozdowski, 2021). In the current study, both Bolashak and Abulkhair hybrids responded positively to boron, but Bolashak exhibited a higher increase in root yield and sugar content, indicating a potentially greater sensitivity or efficiency in boron uptake and utilization. Zinc also played a crucial role in improving plant health and yield. This aligns with Hamzah Saleem et al. (2022), who reported that foliar spraying of micronutrients including zinc improved sugar beet quality under field conditions. Moreover, Kaya and Ashraf (2024) found that foliar-applied micronutrients mitigated the adverse effects of salinity stress, leading to improved root weight and sugar concentration. These results support the idea that targeted foliar applications can enhance nutrient availability and physiological performance in stress-prone or nutrient-deficient soils.

Our study further supports the notion that hybrid-specific responses to micronutrient treatments should be considered in sugar beet cultivation strategies. Bhadra et al. (2023) emphasized the importance of both boron and zinc in enhancing sugar beet growth and sugar yield, highlighting the need for balanced micronutrient management tailored to hybrid characteristics and environmental conditions. Finally, it is noteworthy that potassium levels, although not a direct focus in this study, remained consistent across treatments and did not appear to interfere with the observed micronutrient effects. This is in line with Xie et al. (2022), who noted that potassium fertilization supports sugar beet quality but does not overshadow the effects of micronutrients like boron and zinc when foliar applied. From a practical perspective, our findings offer clear implications for farmers and agronomists in semi-arid regions. Foliar application of boron and zinc, especially in combined form, is a viable strategy to increase both the yield and the commercial quality of sugar beet crops. Given that sugar beet is a nutrient-demanding crop, regular foliar micronutrient applications may be necessary to sustain high productivity, particularly in nutrient-deficient soils.

Conclusion

The boron content in the tops of the sugar beet hybrid Bolashak during the leaf closing phase in the inter-rows was higher than in the root crops by 0.3–29.0mgkg^{-1} across all experimental variants. The highest accumulation of boron was mainly observed in the tops of the hybrid Abulkhair during the same phase, with a range of 25.0–41.0mgkg^{-1}, and lower levels in the root crops – 14.0–29.5mgkg^{-1}. Zinc was generally present in smaller amounts compared to boron in the hybrids Bolashak and Abulkhair during their vegetation, in the leaves, tops, and root crops, with variations in the experimental variants ranging from 7.0mgkg^{-1}to 37.0mgkg^{-1}. The maximum amount of zinc was observed in the tops of the hybrid Bolashak during the leaf closing phase in the rows when boron fertilizer YaraVita Bortak150 at a dose of 1.5Lha^{-1} and zinc fertilizer YaraVita Zintrak700 at a dose of 0.5 Lha^{-1} were applied together 37.0mgkg^{-1}. The application of micronutrients as foliar fertilizers against the NPK of high rates of mineral fertilizers $N_{300}P_{150}K_{300}$ resulted in a higher removal of boron and zinc from the soil by the main and side products of the hybrids Bolashak and Abulkhair, exceeding the control by 470.8–827.0gha^{-1} and 259.9–497.6gha^{-1}, and 553.3–838.2gha^{-1} and 283.9–566.0gha^{-1}, respectively. The use of mineral fertilizers at the rate of $N_{300}P_{150}K_{300}$ contributed to a smaller overall removal of boron and zinc from the soil by the hybrids Bolashak and Abulkhair compared to the control – by 456.2gha^{-1} and 150.7gha^{-1}, and 373.6gha^{-1} and 174.4gha^{-1}, respectively. Foliar applications of boron and zinc fertilizers against the NPK of mineral fertilizers increased the root yield of the hybrids Bolashak and Abulkhair to 78.1–82.0tha^{-1} and 74.2–80.9tha^{-1}, sugar content 17.7–18.1% and 17.5–17.9%, and sugar yield 13.8–14.8tha^{-1} and 13.0–14.4tha^{-1}. The increase in root yield for the hybrids Bolashak and Abulkhair was 33.1–37.0tha^{-1} and 33.2–39.9tha^{-1}, sugar content 0.5–0.9% and 0.5–0.9%, and sugar yield 6.1–7.1tha^{-1} and 6.1–7.5tha^{-1} relative to the control.

DECLARATIONS

Funding: This article was published as part of the project AP23490632 "Developing effective methods for the application of boron and zinc fertilizers for new sugar beet hybrids in the Southeast of Kazakhstan," funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Acknowledgement: The authors extend their appreciation to the Researchers Supporting Project number (AP23490632) funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan. This article is published as part of the project "Developing effective methods for the application of boron and zinc fertilizers for new sugar beet hybrids in the Southeast of Kazakhstan", Kazakhstan.

Conflict of Interest: None

Data Availability: All the data is available in the article.

Informed Consent Statement: Not applicable. This manuscript does not contain data from any person.

Ethics Statement: The field experiments were conducted on the irrigated experimental plots of the Kazakh Research Institute of Agriculture and Plant Growing with the permission of the institute administration. This research did not involve human participants, animals, or endangered species. All experimental procedures complied with relevant institutional, national, and international guidelines and legislation.

Author's Contribution: AM and AK conceptualized the study; BA and EZ assisted with methodology and project administration; AM and AK helped with software, resources and writing—original draft preparation; NUK performed validation; SA carried out formal analysis; AS conducted investigation; KR curated the data; DKYT and MY contributed to writing—reviewing and editing; MB took part in visualization; AK and MY participated in supervision and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

REFERENCES

Abd El-Mageed, T.A., Rady, M.O., Semida, W.M., Shaaban, A., & Mekdad, A.A. (2021). Exogenous micronutrients modulate morpho-physiological attributes, yield, and sugar quality in two salt-stressed sugar beet cultivars. *Journal of Soil Science and Plant Nutrition*, 21, 1421-1436. https://doi.org/10.1007/s42729-021-00450-y

Abekova, A.M., Yerzhebayeva, R.S., Bastaubayeva, S.O., Konusbekov, K., Bazylova, T.A., Babissekova, D.I., & Amangeldiyeva, A.A. (2022). Assessment of sugar beet genetic diversity in the Republic of Kazakhstan by using RAPD markers and agromorphological traits. *SABRAO Journal of Breeding and Genetics*, 54(1), 67-78. http://doi.org/10.54910/sabrao2022.54.1.7

Adarve, M.J., Hernández, A.J., Gil, A., & Pastor, J. (1998). Boron, zinc, iron, and manganese content in four grassland species (Vol. 27, No. 6, pp. 1286-1293). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2134/jeq1998.00472425002700060003x

Aghdam, M.Z., & Valilue, R. (2023). Effect of iron, zinc and boron on sugar beet yield and quality. *Cross Current International Journal of Agriculture and Veterinary Sciences*, 5(1), 1-7. https://doi.org/10.36344/ccijavs.2023.v05i01.001

Ahmad, I., Ahmad, B., Ali, S., Kamran, M., Qing Fang, H., & Bilegjargal, B. (2017). Nutrients management strategies to improve yield and quality of sugar beet in semi-arid regions. *Journal of Plant Nutrition*, 40(15), 2109-2115. https://doi.org/10.1080/01904167.2016.1267207

Ahmadpoor Dehkordi, E., Tadayon, M.R., & Tadayyon, A. (2019). The effect of different fertilizers' sources on micronutrients' content and sugar quality of sugar beet. *Compost Science & Utilization*, 27(3),161-168. https://doi.org/10.1080/1065657X.2019.1630337

Artyszak, A., & Gozdowski, D. (2021). Influence of various forms of foliar application on root yield and technological quality of sugar beet. *Agriculture*, 11(8), 693. https://doi.org/10.1007/s12355-020-00918-8

Ayoubi, K.A., Eisvand, H.R., Heydari, S., & Mousavi-Fard, S. (2023). Effects of foliar application of iron and zinc micronutrient elements on quantitative and qualitative yield of saffron (Crocus sativus L.). *Journal of Saffron Research*, 11(1), 78-66. https://doi.org/10.22077/jsr.2023.6083.1206

Babeker, A.M., Ahmed, A.R., Mustafa, G.I., Abdalla, A.A., & Bakur, A. (2022). Determination of some heavy metals and microbial profile of raw sugar samples collected from Sudanese sugar industries in season 2017 in relation to EU. 1998 and ICUMSA, 1974 standards. *International Journal of Agricultural Science and Food Technology*, *8*, 202-208. https://dx.doi.org/10.17352/2455-815X.000164

Bana, R.S., Jat, G.S., Grover, M., Bamboriya, S.D., Singh, D., Bansal, R., Choudhary, A.K., Kumar, V., Laing, A.M., Godara, S., Bana, R.C., Kumar, H., Kuri, B.R., Yadav, A., & Singh, T. (2022). Foliar nutrient supplementation with micronutrient embedded fertilizer increases biofortification, soil biological activity and productivity of eggplant. Scientific Reports, 12(1), 5146. https://doi.org/10.1038/s41598-022-09247-0

Bastaubayeva, S.O., Amangaliev, B.M., Zhussupbekov, E.K., Tabynbayeva, L.K., Batyrbek, M., Raiymbekova, A.T., Memon, S. & Memon, S.A. (2023). Irrigation and mineral fertilizer effects on physical properties of light chestnut soil used in the cultivation of sugar beet (*Beta vulgaris* L.). *SABRAO Journal of Breeding and Genetics*, 55(1), 202-210. http://doi.org/10.54910/sabrao2023.55.1.19

Batyrbek, M., Abbas, F., Fan, R., & Han, Q. (2022). Influence of mineral fertilizer and manure application on the yield and quality of maize in relation to Intercropping in the Southeast Republic of Kazakhstan. *Plants*, 11(19), 2644. https://doi.org/10.3390/plants11192644

Bhadra, T., Mahapatra, C.K., Hosenuzzaman, M., Gupta, D.R., Hashem, A., Avila-Quezada, G.D., Abd_Allah, E.F., Hoque, M.A., & Paul, S.K. (2023). Zinc and boron soil applications affect Athelia rolfsii stress response in sugar beet (Beta vulgaris L.) plants. Plants, 12(19), 3509. https://doi.org/10.3390/plants12193509

Bhardwaj, E., Shukla, R., & Das, S. (2021). Plant roots and mineral nutrition: an overview of molecular basis of uptake and regulation, and strategies to improve nutrient use efficiency (NUE). *Plant Stress Biology: Strategies and Trends*, 131-184. https://doi.org/10.1007/978-981-15-9380-2_5

Bhatti, U.A., Masud, M., Bazai, S.U., & Tang, H. (2023). Investigating AI-based smart precision agriculture techniques. *Frontiers in Plant Science*, 14, 1237783. https://doi.org/ 10.3389/fpls.2023.1237783

Bremner, J.M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, *55*(1), 11-33. https://doi.org/10.1017/S0021859600021572

Cozzolino, E., Di Mola, I., Ottaiano, L., El-Nakhel, C., Rouphael, Y., & Mori, M. (2021). Foliar application of plant-based biostimulants improve yield and upgrade qualitative characteristics of processing tomato. *Italian Journal of Agronomy*, 16(2), 1825. https://doi.org/10.4081/ija.2021.1825

Day, S., & Aasim, M. (2020). Role of Boron in Growth and Development of Plant: Deficiency and Toxicity Perspective. In: Aftab, T., Hakeem, K.R. (eds) Plant Micronutrients. Springer, Cham. https://doi.org/10.1007/978-3-030-49856-6_19

Duraisam, R., Salelgn, K., & Berekete, A.K. (2017). Production of beet sugar and bio-ethanol from sugar beet and it bagasse: a review. *International Journal Eng Trends Technol*, 43(4), 222-233. www.http/doi.org/10.14445/22315381/IJETT-V43P237

Fang, K.F., Du, B.S., Zhang, Q., Xing, Y., Cao, Q.Q., & Qin, L. (2019). Boron deficiency alters cytosolic Ca2+ concentration and affects the cell wall components of pollen tubes in Malus domestica. *Plant Biology*, 21(2), 343-351. https://doi.org/10.1111/plb.12

Gonzalez, M.N.G., & Björnsson, L. (2022). Life cycle assessment of the production of beet sugar and its by-products. *Journal of Cleaner Production*, 346, 131211. https://doi.org/10.1016/j.jclepro.2022.131211

González-Fontes, A. (2020). Why boron is an essential element for vascular plants. *The New Phytologist*, 226(5), 1228-1230. https://doi.org/10.1111/nph.16033

Grewal, S.K., Sharma, K.P., Bharadwaj, R.D., Hegde, V., Tripathi, S., Singh, S., Jain, P.K., Agrawal, P.K., & Mondal, B. (2020). Understanding genotypic variation and identification of promising genotypes for iron and zinc content in chickpea (Cicer arietinum L.). Journal of Food Composition and Analysis, 88, 103458. https://doi.org/10.1016/j.jfca.2020.103458

Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science*, 13, 1033092. https://doi.org/10.3389/fpls.2022.1033092

Hao, B., Ma, J., Jiang, L., Wang, X., Bai, Y., Zhou, C., & Wang, Z. (2021). Effects of foliar application of micronutrients on concentration and bioavailability of zinc and iron in wheat landraces and cultivars. *Scientific Reports*, 11(1), 22782. https://doi.org/10.1038/s41598-021-02088-3

Haqshenas, A., Azizi, K., Ghasemi, S., Firouzabadi, F.N., & Hosseinpour, M. (2023). Nitrogen reduction and foliar application of zinc sulfate improve the physiological and biochemical characteristics of two autumn-sown sugar beet (Beta vulgaris L.). *Acta Physiologiae Plantarum*, 45(12), 134. https://doi.org/10.1007/s11738-023-03589-6

Hossain, A., Quddus, A., Alam, K., Naser, H.M., Anwar, B., Khatun, F., Rashid, H., Khatun, F., & Siddiky, A. (2020). Application of zinc, boron, and molybdenum in soil increases lentil productivity, nutrient uptake, and apparent balance. *Canadian Journal of Soil Science, 101*(1), 113–124. https://doi.org/10.1139/cjss-2019-01410

Ishfaq, M., Kiran, A., ur Rehman, H., Farooq, M., Ijaz, N.H., Nadeem, F., Azeem, I., Li, X., & Wakeel, A. (2022). Foliar nutrition: Potential and challenges under multifaceted agriculture. *Environmental and Experimental Botany*, 200, 104909. https://doi.org/10.1016/j.envexpbot.2022.104909

Jatav, H.S., Sharma, L.D., Sadhukhan, R., Singh, S.K., Singh, S., Rajput, V.D., Parihar, M., Jatav, S.S., Jinger, D., Kumar, S., & Sukirtee. (2020). An overview of micronutrients: Prospects and implication in crop production. In: Aftab, T., Hakeem, K.R. (eds) Plant Micronutrients. Springer, Cham. https://doi.org/10.1007/978-3-030-49856-6_1

Kaya, C., & Ashraf, M. (2024). Foliar Fertilization: A Potential Strategy for Improving Plant Salt Tolerance. *Critical Reviews in Plant Sciences*, 43(2), 94-115. https://doi.org/10.1080/07352689.2023.2270253

Lamlom, S.F., Irshad, A., & Mosa, W.F. (2023). The biological and biochemical composition of wheat (Triticum aestivum) as affected by the bio and organic fertilizers. *BMC Plant Biology*, 23(1), 111. https://doi.org/10.1186/s12870-023-04120-2

Lilay, G.H., Thiébaut, N., du Mee, D., Assunção, A.G., Schjoerring, J.K., Husted, S., & Persson, D.P. (2024). Linking the key physiological functions of essential micronutrients to their deficiency symptoms in plants. *New Phytologist*, 242(3), 881-902. https://doi.org/10.1111/nph.19645

Mekdad, A.A.A., & Shaaban, A. (2020). Integrative applications of nitrogen, zinc, and boron to nutrients-deficient soil improves sugar beet productivity and technological sugar contents under semi-arid conditions. *Journal of Plant Nutrition*, *43*(13), 1935-1950. https://doi.org/10.1080/01904167.2020.1757701

Michailidis, M., Bazakos, C., Kollaros, M., Adamakis, I. D.S., Ganopoulos, I., Molassiotis, A., & Tanou, G. (2023). Boron stimulates fruit formation and reprograms developmental metabolism in sweet cherry. *Physiologia Plantarum*, 175(3), e13946. https://doi.org/10.1111/ppl.13946

Nardi, S., Schiavon, M., & Francioso, O. (2021). Chemical structure and biological activity of humic substances define their role as plant growth promoters. *Molecules*, 26(8), 2256. https://doi.org/10.3390/molecules26082256

Nieder, R., Benbi, D.K., & Reichl, F.X. (2018). Microelements and Their Role in Human Health. In: Soil Components and Human Health. Springer, Dordrecht. https://doi.org/10.1007/978-94-024-1222-2_7

Pimentel, C., Pina, C.M., Müller, N., Lara, L.A., Melo Rodriguez, G., Orlando, F., & Fernández, V. (2023). Mineral Particles in Foliar Fertilizer Formulations Can Improve the Rate of Foliar Uptake. *Plants*, 13(1), 71. https://doi.org/10.3390/plants13010071

Safdar, M.E., Qamar, R., Javed, A., Nadeem, M.A., Javeed, H.M.R., Farooq, S., Głowacka, A., Michałek, S., Alwahibi, M.S., Elshikh, M.S., & Ahmed, M.A.A. (2023). Combined application of boron and zinc improves seed and oil yields and oil quality of oilseed rape (Brassica napus L.). Agronomy, 13(8), 2020. https://doi.org/10.3390/agronomy13082020

Salvage, R., Cannon, T., Kingsmill, P., Liu, F., & Fleming, C.C. (2024). A complex biostimulant based on plant flavonoids enhances potato growth and commercial yields. *Frontiers in Sustainable Food Systems*, 8, 1368423. https://doi.org/10.3389/fsufs.2024.1368423

Shahzad, R., Jamil, S., Ahmad, S., Nisar, A., Khan, S., Amina, Z., & Zhou, W. (2021). Biofortification of cereals and pulses using new breeding techniques: current and future perspectives. *Frontiers in Nutrition*, 8, 721728. https://doi.org/10.3389/fnut.2021.721728

Sharafi, S., Sharifdost, F., & Mohajeri, F. (2021). Effect of Fe, Zn and Cu on quantity and quality characteristics and nutrient accumulation in wheat. *Journal of Crop Science and Biotechnology*, 24, 469-476. https://doi.org/10.1007/s12892-021-00095-4

Škrbić, B., Đurišić-mladenović, N., & Mačvanin, N. (2010). Determination of metal contents in sugar beet (Beta vulgaris) and its products: empirical and chemometrical approach. *Food science and technology research*, 16(2), 123-134. https://doi.org/10.3136/fstr.16.123

Stewart, Z.P., Paparozzi, E.T., Wortmann, C.S., Jha, P.K., & Shapiro, C.A. (2021). Effect of foliar micronutrients (B, Mn, Fe, Zn) on maize grain yield, micronutrient recovery, uptake, and partitioning. *Plants*, 10(3), 528. https://doi.org/10.3390/plants10030528

Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (Zea mays L.) grains: An overview. *Communications in Soil Science and Plant Analysis*, 51(15), 2001-2021. https://doi.org/10.1080/00103624.2020.1820030

Tillman, P.B. (2019). Determination of nutrient values for commercial amino acids. *Journal of Applied Poultry Research*, 28(3), 526-530. https://doi.org/10.3382/japr/pfz010

Tohma, O., & Esitken, A. (2011). Response of salt stressed strawberry plants to foliar salicylic acid pre-treatments. *Journal of Plant Nutrition*, *34*(4), 590-599. https://doi.org/10.1080/01904167.2011.538285

Varga, I., Jović, J., Rastija, M., Markulj Kulundžić, A., Zebec, V., Lončarić, Z., & Antunović, M. (2022). Efficiency and management of nitrogen fertilization in sugar beet as spring crop: A review. *Nitrogen*, 3(2), 170-185. https://doi.org/10.3390/nitrogen3020013

Xie, X., Zhu, Q., Xu, Y., Ma, X., Ding, F., & Li, G. (2022). Potassium determines sugar beets' yield and sugar content under drip irrigation condition. *Sustainability*, 14(19), 12520. https://doi.org/10.3390/su141912520

Zewail, R.M.Y., El-Gmal, I.S., Khaitov, B., & El-Desouky, H.S. (2020). Micronutrients through foliar application enhance growth, yield and quality of sugar beet (Beta vulgaris L.). *Journal of Plant Nutrition*, 43(15), 2275-2285. https://doi.org/10.1080/01904167.2020.1771580

Zhao, X., Song, B., Ishfaq, M., Adil, M.F., Lal, M.K., Wu, Z., Jia, Q., Huang, W. (2023). Zinc amendment increases the yield and industrial quality of Beta vulgaris L. cultivated in Northeast China. *Field Crops Research*, 298, 108973. https://doi.org/10.1016/j.fcr.2023.108973