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RESEARCH ARTICLE

The Effects of Nitrogen and Boron on the Yield and Biochemical Traits of Sugar Beets (*Beta vulgaris* L.)

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Abstract

H. Azaryar, F. Jalili, J. Khalili Mahalleh, A. Nasrollahzadeh Asl, and M. Roshdi. 2024. The Effects of Nitrogen and Boron on the Yield and Biochemical Traits of Sugar Beets (*Beta vulgaris* L.). Int. J. Agric. Nat. Resour. 176-188. An experiment was performed to reveal how nitrogen and boron fertilizers affect the yield and quality of sugar beets. A split-plot design with random blocks was used, and the experiment was repeated three times in two areas of northwest Iran (Khoy and Naqadeh) from 2019-2020. Nitrogen fertilizer was used in the main plot at four levels: N_1 (300 kg ha^{-1} of urea with 50% consumption at planting and 50% at the 6-8 leaf stage), N_2 (300 kg ha^{-1} of urea with 50% consumption at planting and 50% at the 8-12 leaf stage), N_3 (1.5 times that of N_1), N_4 (1.5 times that of N_2), and boron fertilizer was used as a subagent at four levels: B_1 (no boron, used as a control), B_2 (boron used as boric acid at the rate of 20 kg ha^{-1}), B_3 (foliar spray with Boroplus, a liquid fertilizer with 10% boron, used at the 6-8 leaf and 8-12 leaf stages), and B_4 (foliar spray with Boroplus at the 12-8 and 16-20 leaf stages). The results revealed that as more nitrogen and boron were applied, the leaf dry weight, root yield, sugar content, and pure sugar yield increased. However, the percentage of sugar in the roots decreased as more nitrogen was added. Therefore, the maximum root yield was reached in the N_4 treatment, and the maximum percentage of sugar (21.4%) was reached in the B_4 treatment, which represented the minimum level of nitrogen. The maximum pure sugar yield (1228.8 g m^{-2}) was reached in the N_1B_4 treatments. Therefore, nitrogen and boron should be applied following the N_1B_4 treatment for sugar beet planting.

Keywords: Fertilizer, root yield, sugar percentage.

Highlights

- Quality factors of sugar beet are affected by nutritional elements.
- Geographical region affects sugar beet growth characteristics through soil and climate factors.
- This article suggests that in order to improve the quantitative and qualitative properties of sugar beet, pay attention to factors such as the amount, method and time of using chemical fertilizers, the soil and the climate of the region.

Introduction

Sugar beet is a plant with a two-year life cycle. It belongs to the spinach family and is an annual

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plant (Jovzi & Zare Abyaneh, 2015). The global production of sugar beets is 277.72 million, and the crops are grown on 4.56 million hectares of land. In Iran, sugar beet is grown on 110,211 hectares, with an average yield of 71.32 tons per hectare (FAO,2022). According to the FAO, more than 30% of the world's soils are missing one or more microelements (micronutrients), and this problem is worsening. In addition to the use of essential elements, many studies have focused on the use of low amounts of elements to achieve the best quantity and quality (Shukla et al., 2018). The management of fertilizers and nutrients is key to effectively growing crops such as sugar beets. Therefore, understanding this process is important for increasing sugar beet production (Chandan et al., 2020). Nitrogen is an essential element for plant growth. Nitrogen helps improve production and enhances sugar beet quality. However, the use of nitrogen during the end of growing season can reduce sugar levels (Chandan et al., 2020). Sugar beets require more boron than other plants (Tlili et al.,2018). Boron is a key micronutrient for plants. Foliar spraying impacts various physiological and biochemical processes during plant growth. In sugar beet, boron helps with sugar movement and impacts the stability of cell walls and membranes. These changes lead to improved root performance and increased sugar content (Kabu & Akosman, 2019). A study by Afshar et al. (2019) revealed that as the nitrogen application rate increased, the production of sugar beet roots also increased linearly. However, increased nitrogen also decreased the sucrose content and increased the amount of impurities in the roots. Rahimi et al. (2017) reported that boron had a greater effect than other micronutrients on sugar levels and extraction efficiency. Kandil et al. (2020) reported that using both boron and nitrogen together resulted in the highest root yields and sugar levels. The increase in root yield and sugar content due to increased nitrogen might be because nitrogen improves plant nutrition, increases vegetative growth by increasing leaf area, and increases chlorophyll levels, which improves photosynthesis and increases root weight. Mahapatra et al. (2020) reported that the use of boron with other nutrients improved growth, yield components (15%), sugar content (1.8%) and extractable sugar content (2.1%). Sugar beet is grown in many parts of Iran. In particular, it is one of the strategic crops in West Azerbaijan and plays direct and indirect roles to support the needs of people in Iran. Therefore, using nitrogen and boron fertilizers in a balanced way will increase it's the yield and quality of sugar beet. This method will also help reduce the use of chemical inputs in farming, protect soil health and prevent environmental pollution in agricultural lands. Many sugar beet farmers do not have sufficient knowledge of when and how much nitrogen and boron to apply. For this reason, this study aims to explore how nitrogen and boron affect the yield and quality of sugar beet in two areas with different climates: Khoy and Naqadeh.

Materials and Methods

According to the meteorological information and Koppen climate classification, both the Khoy and Naqadeh regions have a semiarid climate with dry summers. The specific climate features of these areas are shown in Table 2. This research took place during the 2019-2020 crop year at two locations: Khoy (at a latitude of 38 degrees and 32 minutes, a longitude of 44 degrees and 55 minutes, and an altitude of 1139 m above sea level) and Naqadeh (at a latitude of 37 degrees and 22 minutes, a longitude of 45 degrees and 27 minutes, and an altitude of 1286 m above sea level). The soils in both regions where the experiment was conducted had silty clay loam textures with pH values of 7.8 and 7.5 (Table 1).

The experiment was designed as a split plot on the basis of a randomized complete block design, with three replications in two areas: Khoy and Naqadeh. The main experimental factors included nitrogen from urea applied at four levels: N_1 (300 kg ha^{-1} of urea, 50% applied at planting and 50% at the 6-8 leaf stage), N_2 (300 kg ha^{-1} of urea, 50% applied at planting and 50% at the 8-12 leaf stage),

Table 1. Physio-chemical properties of experimental soil (the physical and chemical features of the soil used in the experiment)

Experimental Location	Soil Texture Class	Index Saturation	pH	Ce %	Organic Carbon (%)	Electrical Conductivity (dS.m^{-1})	Total Nitrogen (%)	P	K	Fe	Mn	Zn	Cu	B
Naqadeh	loam	53	7.5	4	1.22	0.72	0.18	12.3	310	8.50	8.42	2.01	1.87	0.98
Khoy	Loam clay	52	7.8	6.3	1.18	0.87	0.15	10.3	290	7.24	5.63	1.3	1.65	0.83

N_3 (1.5 times the amount of N_1), and N_4 (1.5 times the amount of N_2).

Boron was applied to the subplots at four levels: B_1 (control), B_2 (soil), B_3 (foliar spray at the 6-8 and 8-12 leaf stages), and B_4 (foliar spray at the 8-12 and 8-16 leaf stages). Boron was applied to the soil before planting at a rate of 20 kg ha^{-1} using boric acid (Borax), and for foliar application, Boroplus liquid fertilizer (manufactured by Vatan Plast Azar, containing 10% boron) was used at a rate of two liters per hectare. The seed used in both regions was Pirola (produced by the German kws company), which is a monogerm cultivar resistant to Rhizomania and Rhizoctonia and is suitable for cultivation in semiarid weather conditions such as in West Azerbaijan. The land was plowed and levelled before planting, which took place on March 27th. The rows were spaced 50 cm apart, with plants 18 cm apart within each row, and the plants were planted to a depth of 2.5 cm via a 6-row pneumatic planter manufactured by Tarashkedeh Company. Each subplot contained 4 rows, each 6 meters long. To prevent competition and interference between plots, there was a 2-meter gap between plots and a 3-meter gap between blocks. For the soil analysis, 100 kg ha^{-1} triple superphosphate, 100 kg ha^{-1} potassium sulfate, and nitrogen fertilizer from urea source were used in the experimental treatments. All the phosphate and potassium fertilizers were mixed into the soil during plowing before planting.

During the growth period, both locations were watered through a pressurized irrigation system. When the sugar beet plants reached the four-leaf stage, a thinning operation was performed. An herbicide called Bethanal (phenmedipham) was used to weed out (remove weeds) broad-leaved weeds. For narrow-leaved weeds, super Gallent Herbicide (GALLENT SUPER 10.8% EC) was applied after the plants emerged. At the end of

Table 2. Meteorological statistics of experimental places during the growing season

Month	City	Ave. Max.Temp. (°C)	Ave. Min. Temp. (°C)	Ave. RH (%)	Precipitation (mm)
March 2019	(Khoy)	11.8	0.1	59	30.7
	(Naqadeh)	11.6	-0.6	63	67.5
April 2019	(Khoy)	15.0	4.7	65	92.8
	Naqadeh)	15.7	3.8	65	159.3
May 2019	(Khoy)	22.9	9.1	54	26.2
	(Naqadeh)	21.5	6.6	57	30.2
June 2019	(Khoy)	31.6	15.1	44	3.0
	(Naqadeh)	30.1	13.3	44	2.7
July 2019	(Khoy)	34.6	18.6	39	3.5
	(Naqadeh)	33.4	14.6	40	0.1
August 2019	(Khoy)	35.3	19.4	39	0.4
	(Naqadeh)	34.3	16.1	41	0.2
September 2019	(Khoy)	30.1	14.7	47	9.5
	(Naqadeh)	30.6	12.4	57	0.1
October 2019	(Khoy)	26.9	9.7	54	10.4
	(Naqadeh)	26.8	8.1	48	10.0

the growing season in October, harvesting took place on the 30th after removing one meter from the beginning and end of the rows, as well as from the outer rows of each plot, with a focus on the middle four rows. Boron was measured using a spectrophotometric device (Emami, 1996). The number of roots that grew in each square meter was determined by weighing the roots collected from a small, standard area.

To assess quality characteristics, a root paste was made from the sampled roots and immediately frozen. From the frozen samples, quality traits such as sugar content and the percentages of pure and gross sugars were measured using a Betalyzer refractometer. This instrument includes a polarimeter and a flame photometer (model400) (Reinefeld et al., 1974). To determine the percentage of molasses sugar, we used the method developed by Dutton and Buller (1984), along with the following formula: molasses sugar MS=0.343x (sodium+potassium) + 0.094x (alpha-amino nitrogen) + 0.29. This equation represents sodium, potassium and alpha–amino nitrogen in millimole kg^{-1}. The pure sugar percentage (extractable sugar percentage) was obtained from the difference between the gross sugar percentage and molasses sugar percentage using the following formulas (Jovzi & Zare Abyaneh, 2015): The white sugar content is equal to WSC (%) = SC root sugar content (%) – sugar molasses MS (%). Sugar yield (gross sugar yield) SY (kg ha^{-1}) = root yield RY (kg ha^{-1}) × root sugar content SC (%). White sugar yield (pure sugar yield) WSY (kg ha^{-1}) = root yield RY (kg ha^{-1}) × WSC (white sugar content) (%).

The data were checked for similar variations, and then SAS software was used for analysis (SAS 9.1.3, SAS Institute, Inc., Cary, NC, USA). The means of the data were compared using the Duncan multiple range test. The significance level was set at 5%, and we used Excel to create the figures.

Results and Discussion

The analysis of the combined variance revealed that the interactions among location, nitrogen, and boron had significant effects on the leaf dry weight, leaf boron content, and sugar content at the 1% probability level ($P \leq 0.01$). The interactions also affected the root yield at the 5% probability level ($P \leq 0.05$). Additionally, the interaction between nitrogen and boron significantly affected the root dry weight, leaf boron content, sugar content, and pure sugar yield at the 5% probability level ($P \leq 0.05$) and the root yield at the 1% probability level ($P \leq 0.01$). Furthermore, root dry weight, root yield, leaf boron content, root boron content, sugar content, and pure sugar yield were significantly affected at the 1% probability level ($P \leq 0.01$), whereas root length and leaf dry weight were influenced at the 5% probability level ($P \leq 0.05$) by the interactions between location and nitrogen (Table 3).

Root length

The boron treatment increased the root length, with the longest root length recorded at 23.45 cm in treatment B_2 (soil application of boron) (Figure 1). The average root length in Naqadeh was greater than that in Khoy. In Naqadeh, the maximum root length of 24.66 cm was found in treatment N_2 (using 450 kg of nitrogen, with 50% applied at planting and 50% at the 6-8 leaf stage), whereas the lowest root length of 20.83 cm occurred in Khoy in treatment N_3 (using 450 kg of nitrogen, with 50% applied at planting and 50% at the 8-12 leaf stage) (Table 4). Previous studies have indicated that relatively high levels of nutrients such as nitrogen and boron in the soil can lead to increases in both the number and length of roots (Seyed Esmail Zadeh, 2011). Consequently, nitrogen can contribute to the increase in root length by activating enzyme activity and increasing the degree of growth regulation. The growth and productivity of plants are significantly impacted by boron, a crucial nutrient. The absence of boron can hinder the absorption of essential nutrients from the soil in a range of crops, including sugar crops (Zhang et al., 2014). The positive impact of adding boron may be due to its essential physiological role in the growth and development of plants, as its absence can severely affect performance (Armin & Asgharipour, 2012). In this study, the soil application of boron was more effective than foliar spraying at improving beet quality, likely because it allows long-term access to this vital nutrient (Chandan et al., 2020).

Root dry weight

In both regions, the dry weight of the roots increased gradually with increasing nitrogen consumption. The maximum root dry weight for Naqadeh was 2139.39 g m^{-2} in treatment N_4 (450 kg of nitrogen, with 50% applied at planting and 50% at the 8-12 leaf stage), which was 40% greater than that in the same treatment in Khoy (Table 4). The trend of root dry weight was similar to that of root yield; the highest root dry weight was noted in the N_3B_1 treatment, which was not significantly different from that in the N_1B_3 treatment (Table 4). When sugar beet roots produce a greater yield, they also contain more sugar (Draycott, 2003). Compared with the absence of boron, the application of low-use elements such as boron significantly increases the percentage of root dry matter (Yarnia et al., 2009). Research has shown that the use of boron can lead to increases in the length, diameter, dry weight, and wet weight of sugar beet roots, as well as increases in the levels of nitrogen, phosphorus, potassium, calcium, and magnesium in the leaves and roots of sugar beets (Zewail et al., 2020). Last et al. (2020) reported that the ratio of root dry matter to total dry matter in sugar beet increased over the growing period and was influenced by nitrogen fertilizers. In their experiments, root dry matter accounted for 20% of the total dry matter in late June but accounted for 70% of the dry matter at harvest. Overall, nitrogen consumption at the end of the growing season decreased the allocation of dry matter to the above-ground parts of the plant by approximately 6%.

Leaf dry weight

The simple effects of location, nitrogen, and boron, as well as the interaction effects of location with nitrogen, location with boron, and the three-way interaction effects among location, nitrogen, and boron on leaf dry weight, were significant (Table 3). Similar to the fresh weight of leaves, the dry weight of sugar beet leaves was greater in Naqadeh than in Khoy. The B_4 treatment (foliar application of boron at the 8-12-leaf and 16-20-leaf stages)

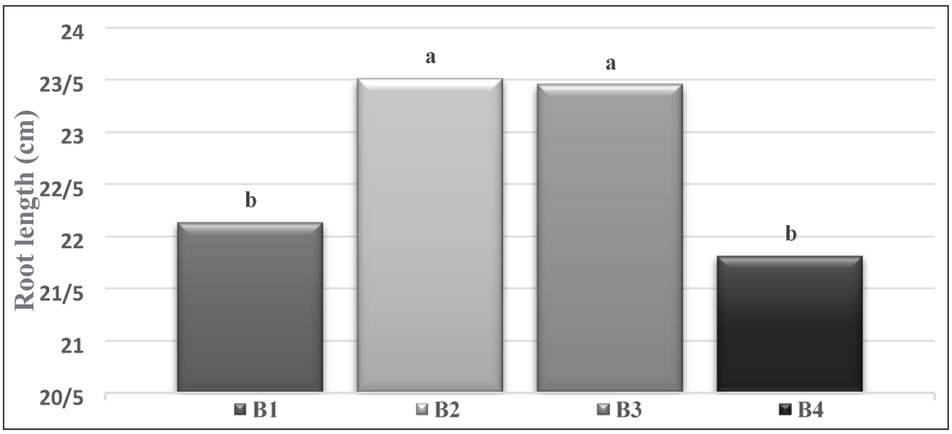

Figure 1. Comparison of the average main effects of boron on root length

resulted in the highest leaf dry weight across all nitrogen levels and both locations, with no significant difference from the B_3 treatment (boron foliar application at the 6-8-leaf and 8-12-leaf stages) (Table 6). In both Khoy and Naqadeh, the dry weight of the leaves decreased in the order of $N_4B_4 > N_3B_3 > N_2B_2 > N_1B_1$. Nitrogen is a crucial nutrient that significantly influences the development of above-ground parts, supports plant metabolic processes, and improves the quality of sugar products (Mahfouz et al., 2015). According to Helal et al. (2009), combining nitrogen and boron enhances the distribution of nitrogen, potassium, and iron in both the roots and aerial parts of sugar beet plants. Boron aids in increasing the transfer rate of sugars produced during photosynthesis from mature leaves to growing roots, thereby increasing the percentage of leaf dry matter (Yarnia et al., 2009). Research by Kandil et al. (2020) revealed that foliar application of nitrogen fertilizer enhances the ability of leaves to absorb nutrients. This increase in absorptive capacity increases photosynthesis and the production of its byproducts, leading to improved leaf durability and increased leaf dry matter. Additionally, these researchers reported that nitrogen application can increase the chlorophyll concentration and dry weight of above-ground parts by the end of the growing season.

Root yield

The two-way interaction effects of location with nitrogen and nitrogen with boron, as well as the three-way interaction effects of location, nitrogen, and boron on root yield, were significant (Table 3). At both locations, the root yield steadily increased with increasing nitrogen consumption. The highest root yield (9838 grams per square meter) was recorded in the N_4 treatment (450 kg of urea, with 50% applied at planting and 50% at the 8-12 leaf stage) at the third level of boron (B_3) in Naqadeh, which was 38% greater than that in the same treatment in Khoy (Table 5). In terms of the nitrogen × boron interaction, the highest root yield was 8479.2 grams per square meter for the N_4B_3 treatment, which was similar to that of the N_4B_4 treatment within the same statistical group (Table 5).

Table 3.- Combined analysis of variance of two locations (Khoy and Naqadeh) and effect of different levels of boron and nitrogen on morpho-physiological properties of sugar beet

		Means of square								
S.o.V	(df)	root length	Root dry weight	Leaf dry weight	Root yield	(B of leaf)	Root boron	Sugar content	Pure of sugar yield	Sugar productivity reduction coefficient
Location (L)	1	194.228^{ns}	6722978.01^{**}	1256935.74^{**}	13347860.90^{**}	0.01^{ns}	190.57^{**}	670.33^{**}	1137404.66^{**}	11.575^{**}
R×L	4	51.597	2586.91	124.165	41036.50	0.78	0.25	0.12	3009.73	0.032
Nitrogen (N)	3	18.666^{ns}	1144683.77^{*}	52620.14^{*}	18452958.10^{**}	18.48^{*}	10.93^{**}	55.61^{*}	31785.47^{ns}	0.484^{**}
L×N	3	42.531^{*}	68600.30^{**}	3098.66*	438043.50^{**}	2.77^{**}	23.48^{**}	3.37^{**}	91557.42^{**}	0.217^{**}
e_1	12	9.790	1682.54	610.98	27768.90	0.39	1.00	0.031	867.94	0.018
Boron (B)	3	4.599^{**}	60367.45^{ns}	31289.41^{**}	9642740.80^{**}	1783.33^{**}	45.75^{**}	6.41^{*}	88819.50^{**}	0.15^{ns}
L×B	3	0.129^{ns}	7099.59^{ns}	4291.44^{**}	104386.50^{ns}	26.44^{**}	4.24^{**}	0.22^{**}	1857.70^{ns}	0.020^{ns}
N×B	9	6.319^{ns}	9600.07^{*}	1142.24^{ns}	1562526.40^{*}	10.94^{*}	2.84^{**}	0.25^{ns}	6999.19^{*}	0.036^{ns}
L N×B	9	6.814^{ns}	6082.82^{ns}	2493.23^{**}	152380.50^{ns}	3.20^{**}	1.08^{ns}	0.24^{**}	1424.18^{ns}	0.032^{ns}
e_2	48	9.20	3876.84	663.740	62307.20	0.244	0.93	0.05	2274.63	0.019
CV (%)		13.34	3.39	9.38	3.39	1.30	9.89	1.38	4.26	5.92

ns, * and ** are nonsignificant and significant at 5% and 1% probability levels, respectively. The difference between the means of each column with common letters is not statistically significant at the l 5% probability level.

The lowest root yield was 5016.2 grams per square meter, resulting from nitrogen application at 50% during planting and 50% at the 6-8 leaf stage (N_1) combined with boron applied to the soil (B2) (Table 5). As nitrogen consumption increased, so did root yield, with the greatest effectiveness of boron in increasing root yield observed at the fourth level of nitrogen (450 kg per hectare of urea, with 50% at planting and 50% at the 8-12 leaf stage) (Table 5). This research indicated that increasing nitrogen consumption from N_1 to N_4 resulted in increased root yields. Gaderi et al. (2020) reported that the highest root yield of 52.8 tons per hectare was obtained from treatments involving chemical fertilizers based on soil tests along with the addition of 10 tons of compost per hectare. These findings also revealed that root yield increased with increasing nitrogen levels. Soils lacking sufficient nitrogen can experience severe reductions in root and biomass yields, which often fall to less than half of their optimal production potential (Herget, 2010). Other studies have reported increases in root yield with up to 100 kg of nitrogen per hectare. Noshad et al. (2014) noted significant root yield increases with increased nitrogen application, with boron also positively influencing this parameter; the combined use of these elements yielded 82.7 tons per hectare (Abbas et al., 2020). The beneficial impact of boron may stem from its crucial physiological roles in the plant's life cycle and growth, as its deficiency can severely affect crop yield (Armin & Asgharipour, 2012; Camacho-Cristobal et al., 2008).

Leaf boron

The simple effects of boron, along with the interaction effects of location with nitrogen, location with boron, and nitrogen with boron, as well as the three-way interaction effects of location, nitrogen, and boron, were significant for the leaf boron content (Table 3). The application of boron treatment increased the concentration of boron in the leaves. The lowest leaf boron content (22.78 mg/kg) was recorded in both regions when no boron was applied in conjunction with the N_1 treatment (Table 6). Conversely, the highest leaf boron content of 48.63 mg kg^{-1} was observed in the Khoy region for plants treated with B_4N_1, followed closely by those in the B_4N_2 treatment (Table 6). According to Helal et al. (2009), the combined application of nitrogen and boron enhances the distribution of nitrogen, potassium, and iron within the roots and aerial parts of sugar beet plants. These findings suggest a positive mutual relationship between boron and nitrogen. The simultaneous application of 100 mg of nitrogen per kg of soil and 50 mg of boron per

Table 4. Comparison of the mean effect of "location × nitrogen" on some morphophysiological traits of sugar beet plants

(Location)	(Nitrogen)	Root length	Root dry weight	Root yield	Root boron	Pure sugar yield	Sugar productivity reduction coefficient
		(cm)	(g.m^2)	(g.m^2)	(mg.kg^{-1})	(g.m^2)	(%)
Naqadeh	(N_1)	24.19bc	2045.92d	7334.56d	8.56a	1377.99c	2.50b
	((N_2)	24.66a	2089.88c	7835.70c	12.03a	1384.09c	2.86a
	(N_3)	23.77abc	2110.36b	9241.73b	11.98b	1570.82a	2.62b
	(N_4)	23.98ab	2139.39a	9697.46a	12.24bc	1516.02b	2.92a
Khoy	(N_1)	21.49c	1513.0 g	5459.37 h	6.94c	813.82d	2.03cd
	(N_2)	21.92c	1513.42f	5875.28 g	8.53d	781.91e	2.22c
	(N_3)	20.83abc	1603.57e	6416.01f	8.70d	757.72f	1.89d
	(N_4)	20.97d	1638.48d	6925.56e	9.37c	741.81f	1.99d

Means in a column of each treatment followed by the same letter are not significantly different at P≤0.05.

kg resulted in a nutritional balance that promoted the growth of the aerial parts of sugar beet. In research conducted by Gangvar and Srivastava (2009), the use of 0.5 mg of boron per kilogram of soil or its foliar application at a concentration of 0.2% during the growth period led to an increase in the ratio of roots to aerial organs and the leaf area index, as well as increased boron absorption. Baker and Pilbeam (2007) noted that sugar beet requires a significant amount of boron, indicating that it eases the transfer of sugars produced during photosynthesis from mature leaves to the developing roots of the sugar beet.

Root boron

The simple effects of location and boron, along with the interaction effects of location with nitrogen and location with boron, were significant for the root boron content (Table 3). The highest root boron concentration (12.39 mg kg^{-1}) was recorded in Naqadeh under the N4 treatment, which involved the application of 450 kg of nitrogen—50% during planting and 50% at the 8-12 leaf stage. In contrast, the lowest root boron content (6.94 mg kg^{-1}) was found in the N_1 treatment (300 kg of nitrogen, 50% during planting and 50% at the 6-8 leaf stage) in Khoy (Table 4). A comparison of the four levels of boron across the two regions revealed that treatment B_2 (soil application of boron) resulted in the highest root boron concentration of 12.39 mg kg^{-1} in Naqadeh, whereas the lowest value in Khoy for the same treatment was 6.94 mg kg^{-1} (Figure 2). All three boron levels (B_1, B_2, and B_3) significantly increased the root boron content at both locations, and there was no statistically significant difference among them (Figure 2). Boron contributes to plant processes by participating in enzyme reactions, enhancing membrane strength and function, regulating stomatal opening and closing, supporting cell division in meristem tissues, and maintaining plant water content. These actions can increase photosynthetic efficiency and allocation of assimilates for sugar metabolism in plants, including sugar beet (Zarski et al., 2020). Additionally, boron plays a vital role in chloroplast formation, cell wall modifications, and overall plant metabolism, growth, and yield quality (Kernchen, 2010). Specifically, it helps maintain the balance between sugar and starch; facilitates the transport of sugars and carbohydrates; supports cell division, nitrogen metabolism, and protein synthesis; and is crucial for cell membrane functionality and potassium transport, thereby contributing to the regulation of the internal water balance.

Sugar content

The interaction effect of location, nitrogen, and boron on sugar content was significant (Table 3). Regardless of the boron level, the highest percentage of root sugar was observed in the N_1

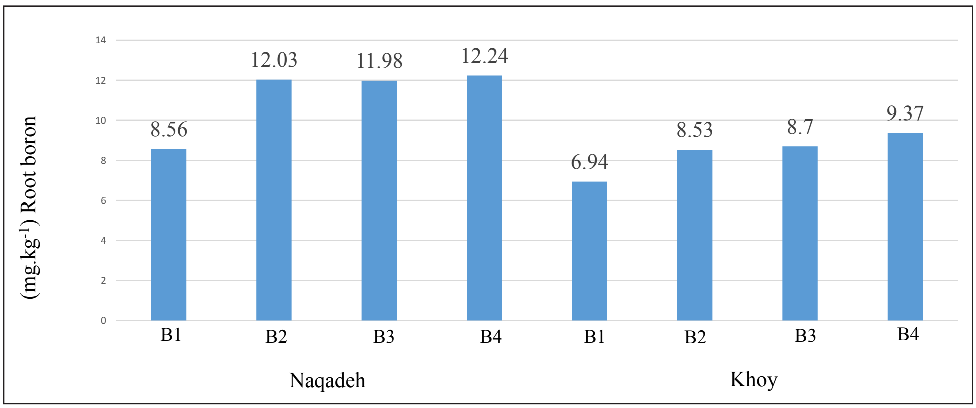

Figure 2. Comparison of the mean interaction of "boron * location" on root boron

treatment, while increasing the nitrogen content led to a decrease in the sugar percentage. Among the four nitrogen levels, treatment B_4 was the most effective at increasing the sugar percentage (Table 6). The mean comparison indicated that the maximum sugar content was 21.4% in Naqadeh under the N1 treatment (300 kg ha^{-1} of urea, with 50% applied at planting and 50% at the 6-8 leaf stage) combined with boron foliar application at the 8-12 and 16-20 leaf stages (treatment B_4). Conversely, the lowest sugar content (11.90%) occurred in Khoy under the same nitrogen treatment (N_1) but without boron application (Table 5). At both locations, as the nitrogen content increased from N_1 (300 kg ha^{-1}) to N_4 (450 kg ha^{-1}), the root sugar content tended to decrease (Table 4). This finding suggests that high nitrogen application, particularly toward the end of the growing season, negatively impacts root sugar levels. Treatment B_4 (boron foliar application during the 8-12 and 16-20 leaf stages) consistently resulted in the highest sugar percentage, even at relatively low nitrogen levels, whereas all four nitrogen levels with soil-applied boron (B_2) presented no significant differences (Table 5). Considering that boron increases the speed of the transfer of sugars produced by photosynthesis in mature leaves to the growing roots of sugar beet, its combined use with nitrogen can increase the percentage of root dry matter. In sugar beet, a high amount of root sugar is obtained when the amount of dry matter produced in the root is high (Draycott, 2003). It has been demonstrated that the quality of sugar beet can be increased by increasing the sugar content and reducing nonsugar substances. With increasing impurities, the crystallization of sucrose is prevented, and the ability to extract sugars decreases (Last et al., 2020). Research by Kristek et al. (2006) indicated that fertilizers containing low-consumption elements, particularly boron, can lead to a 10.8% increase in sugar content. Furthermore, the root yield and sucrose percentage significantly influence overall sugar beet yield (Ouda Sohier, 2005). Some studies have linked increased metabolic activities, particularly those leading to sucrose synthesis, to the effects of boron (Ebrahimipak & Mostashari, 2012). The results indicated that foliar boron application was more effective than soil boron application at increasing the root sugar content (Table 4), likely due to easier access by the plant. Thus, for optimal sugar beet cultivation, adequate boron application is essential. Researchers have consistently linked increased metabolic activity, especially in sucrose synthesis, to the beneficial effects of boron (Ebrahimipak & Mostashari, 2012; Kristek et al., 2006).

Pure sugar yield

The interaction effects of location and nitrogen, as well as those of nitrogen and boron, on the pure sugar yield were significant (Table 3). In terms of location, root yields were consistently higher in Naqadeh than Khoy, leading to a corresponding increase in the pure sugar yield. The maximum pure sugar yield recorded was 1570.82 grams per square meter, which was associated with treatment N_3 (450 kg ha^{-1} of urea, applied 50% at planting and 50% at the 6-8 leaf stage). Conversely, the lowest yield of pure sugar, at 741.81 grams per square meter, was observed in treatment N_4 (450 kg ha^{-1} of urea, with 50% applied during planting and 50% at the 8-12-leaf stage) in Khoy (Table 4). In terms of the interaction between nitrogen and boron, the highest pure sugar yield was achieved with the N_1B_4 treatment, yielding 1228.83 grams per square meter, which represented a 23% increase when compared with the same nitrogen level without boron (Table 5). Across all four nitrogen levels, the yield of pure sugar in Naqadeh consistently surpassed that in Khoy, likely due to the higher root yield in Naqadeh. Research indicates that the application of urea and animal manure can negatively affect the percentage of pure sugar (Lehrsch et al., 2014). Excessive nitrogen fertilizer use has been associated with increased potassium and harmful nitrogen levels in roots, ultimately decreasing the percentage of pure sugar in sugar beets (Ahmadpour Dehkordi & Tadayon, 2013). The results further demonstrated that the highest yields of both pure sugar and gross sugar were observed in the N_1B_4 treatment, with values of 1228.83 grams per square meter for pure sugar and 1353.2 grams per square meter for gross sugar (Table 5). These findings underscore the importance of balancing nitrogen and boron applications to optimize sugar beet yield and quality.

Sugar productivity percentage

The simple effect of nitrogen on the sugar productivity coefficient was significant, whereas the other interaction effects were not significant for this trait (Table 3). The order of sugar productivity across nitrogen treatments was as follows: $N_1 > N_3 > N_2 > N_4$. Notably, the first level of boron (B_1, nonuse) had the most significant effect on increasing the percentage of sugar productivity and was classified into the first statistical group (Table 4). The percentage of sugar productivity is calculated by dividing the sugar produced by the sugar beet weight in kilogram. This percentage is influenced by the levels of harmful sodium, potassium, and nitrogen salts present in the root. Research has indicated that the application of low-use elements is crucial for various processes, including the transport of sugar substances, the regulation of cell metabolism, and the balance of potassium and calcium in plants. These factors positively contribute to the production and accumulation of sugar in beets (Hassanzadeh Azar et al., 2009). Several studies have concluded that insufficient nitrogen fertilization can lead to a decrease in root tonnage, whereas excessive nitrogen application can result in a decreased sucrose concentration and a decreased purity percentage (Abdel et al., 2019). Additionally, boron plays a vital role in plant growth and various morphophysiological processes by significantly increasing the activity of antioxidant enzymes and reducing reactive oxygen species (ROS) accumulation in plant cells, which helps mitigate oxidative stress (Semida et al., 2014).

Overall, these findings underscore the importance of optimizing nitrogen and boron applications to maximize sugar productivity in sugar beet cultivation.

Conclusion

The results of this study indicate that the application of nitrogen and boron significantly

Table 5. Comparison of the mean effect of nitrogen × boron on some physiological characteristics of sugar beet

(Nitrogen)	(Boron)	(Root yield)	(Root sugar)	(Pure sugar yield)
		($g.m^{-2}$)	(%)	($g.m^{-2}$)
N_1	B_1	6035.65g	17.82dc	997.34f
	B_2	6092.12g	18.79b	1064.35e
	B_3	6550.82f	18.07c	1093.10de
	B_4	6909.27de	19.31a	1228.83a
N_2	B_1	6632.22ef	16.66e	993.00f
	B_2	6844.17def	17.71c	1099.26de
	B_3	6871.72de	17.17d	1069.97e
	B_4	7073.85d	18.12c	1169.76bc
N_3	B_1	7702.05c	15.46fg	1095.95de
	B_2	7815.35c	16.52e	1196.50ab
	B_3	7889.42bc	15.89f	1161.69bc
	B_4	7908.67bc	16.37e	1202.93ab
N_4	B_1	8183.60ab	14.68i	1084.92de
	B_2	8165.92ab	15.26gh	1132.20cd
	B_3	8479.22a	14.84hi	1133.82cd
	B_4	8417.30a	15.32g	1164.71bc

Means in a column of each treatment followed by the same letter are not significantly different at $P \leq 0.05$

enhances both root yield and pure sugar yield in sugar beet cultivation. As the amount of root impurities increased, the percentage of root sugar decreased. The yields of both pure sugar and gross sugar are influenced by the root yield and sugar percentage, which are maximized with relatively high nitrogen levels (N_4) and foliar application of boron during the critical growth stages of 8-12 and 16-20 leaves (B_4). Comparative analysis of the two experimental locations revealed that Naqadeh consistently outperformed Khoy across all the treatments, with the yield of pure sugar being greater at every nitrogen level in Naqadeh. This difference can be attributed to the greater root yield observed in Naqadeh, which subsequently increased the pure sugar yield. Furthermore, regardless of the nitrogen level, applying boron at the fourth level (B_4) significantly improved the pure sugar yield. The highest yield of pure sugar was recorded in the N_1B_4 treatment, reaching 1228.83 gr m^{-2}. Notably, as nitrogen application increased from N_1 (300 kg ha^{-1}) to N_4 (450 kg ha^{-1}), a decrease in the root sugar percentage was noted. The application of boron, especially in the later stages of growth, effectively increased both the boron content and the root sugar content. Thus, on the basis of the findings of this study, the N_1B_4 treatment is recommended for optimal results, with this treatment involving the consumption of 300 kg of urea per hectare (50% at planting and 50% at the 6-8 leaf stage) in conjunction with foliar application of boric acid at the 8-12 and 16-20 leaf stages. This combination is expected to maximize both root yield and sugar productivity in sugar beet cultivation.

Resumen

H. Azaryar, F. Jalili, J. Khalili Mahalleh, A. Nasrollahzadeh Asl, y M. Roshdi. 2024. Efectos del Nitrógeno y el Boro en el Rendimiento y las Características Bioquímicas de la Remolacha Azucarera (*Beta vulgaris* L.). Int. J. Agric. Nat. Resour. 176-188. Se realizó un experimento para revelar cómo afectan los fertilizantes nitrogenados y borónicos al rendimiento y la calidad de la remolacha azucarera. Se utilizó un diseño de parcelas divididas con bloques aleatorios, y el experimento se repitió tres veces en dos zonas del noroeste de Irán (Khoy y Naqadeh) entre 2019 y 2020. En la parcela principal se utilizó fertilizante nitrogenado en cuatro niveles: N_1 (300 kg ha^{-1} de urea con 50% de consumo en la siembra y 50% en la etapa de 6-8 hojas), N_2 (300 kg ha^{-1} de urea con 50% de consumo en la siembra y 50% en la etapa de 8-12 hojas), N_3 (1,5 veces el de N1), N_4 (1,5 veces el de N_2), y se utilizó fertilizante de boro como subagente en cuatro niveles: B_1 (sin boro, utilizado como control), B_2 (boro utilizado como ácido bórico a razón de 20 kg ha^{-1}), B_3 (pulverización foliar con Boroplus, un fertilizante líquido con un 10% de boro, utilizado en los estadios de 6-8 hojas y 8-12 hojas), y B_4 (pulverización foliar con Boroplus en los estadios de 12-8 y 16-20 hojas). Los resultados revelaron que, a medida que se aplicaba más nitrógeno y boro, aumentaba el peso seco de las hojas, el rendimiento radicular, el contenido de azúcar y el rendimiento de azúcar puro. Sin embargo, el porcentaje de azúcar en las raíces disminuía a medida que se añadía más nitrógeno. Por lo tanto, el rendimiento máximo de raíces se alcanzó en el tratamiento N_4, y el porcentaje máximo de azúcar (21,4%) se alcanzó en el tratamiento B_4, que representaba el nivel mínimo de nitrógeno. El rendimiento máximo de azúcar puro (1228,8 g m^{-2}) se alcanzó en los tratamientos N_1B_4. Por lo tanto, el nitrógeno y el boro deben aplicarse después del tratamiento N_1B_2 para la plantación de remolacha azucarera.

Palabras clave: Fertilizante, porcentaje de azúcar, rendimiento de raíces.

References

Abbas, F. E., Al-Jbawi, H., Al-Deen, S. & Alisha, J. (2020). Sugar beet (*Beta Vulgaris* Var Crassa) yield and quality attributes as affected by nitrogen fertilization and foliar boron application. *Journal of Earth and Environmental Sciences Research*, *2*(4), 1-6. https://doi.Org/ 10.47363/JEESR/2020(2)131

Afshar, R. K., Nilahyane, C. Chen, H. He, W. B., Iversen, W. M. (2019). Impact of conservation tillage and nitrogen on sugar beet yield and quality. *Soil and Tillage Research*, *191*, 216-223. https://doi.org/10.1016/j.still.2019.03.017

Ahmadpour Dehkordi, A. & Tadayon, M. R. (2013). The effect of urban wastewater and different types of fertilizers on quantitative and qualitative traits of sugar beet (*Beta vulgaris* L.). *Journal of Science and Technology of Agriculture and Natural Resource*, *8*(2), 117-97. (In Persian). http://dx.doi.org/10.18869/acadpub.jstnar.19.73.59

Armin, M. & Asgharipour, M. (2012). Effect of time and concentration of boron foliar application on yield and quality of sugar beet. *American-Eurasian Journal of Agricultural and Environmental Sciences*, *12*(4), 444-448. http://dx.doi.org/10.3923/ajps.2011.307.311

Baker, A. V. & Pilbeam, D. J. (2007). Hand book of plant nutrition. Boron by Umesh C. Gupta, pp.241-278.

Camacho-Cristobal, J. J., Herrera-Rodriguez, M. B., Beato, V. M., Rexach, J., Navarro, M. T., Gochicoa, M., Maldonado J. & Gonzalez-Fontes, A. (2008). The expression of several cell wall-related genes in Arabidopsis roots in down-regulate under boron deficiency. *Environmental and Experimental Botany*, *63*(1-3), 351-358. https://doi.org/10.1016/j.envexpbot.2007.12.004

Chandan, K., Mahapatra, T. & Kumar, P. (2020). Nutrient management in sugar beet: a review. *Pakistan Sugar Journal*, *35*, 31-44. http://dx.doi.org/10.35380/sugar.035.02.0160

Dutton, J. & Bowler, G. (1984). Money is still being wasted on nitrogen fertilizer. *British Sugar Beet Review*, *2*, 75-77. http://dx.doi.org/10.22092/jsb.2016.107054

Draycott, A. P. & Christenson, D. R. (2003). Nutrients for sugar beet production, soil plant relationship, CABI Publishing, pp. 1-105. http://dx.doi.org/10.1111/j.1365-2389. 2004.0635k.x

Ebrahimipak, N. A. & Mostashari, M. (2012). Evaluation of irrigation water management and boron fertilizer to increase water use efficiency of sugar beet. *Water and Irrigation Management*, *2*(2), 53-67. http://dx.doi.org/10.22059/JWIM.2013.30340

Emami, A. (1996). Methods of plant degradation, Soil and Water Research Institute. Technical Report. No. 982. Tehran. Iran (In Persian). https://doi.org/10.22059/ijswr.2023.363792.669555

FAO. (2022). World food and agriculture: Statistical pocketbook. License: CC BY-NC-SA 3.0 IGO. FAO, Rome, 262p. http://www.fao.org/economic/ess/ess-publications/ess-earbook/en/

Gaderi.J., Tehrani, M. M., Hamedi, F. & Haidari, K. (2020). Effect of municipal solid waste most and chemical fertilizers on quality and quantity of sugar beet yield and concentration of some nutrients in soil. *Journal of Soil research (Water and Soil)*, *34*(1),47-60 (In Persian). https://doi.org/10.22092/IJSR.2020.122138

Helal, F. A., Taalab, A. S. & Safaa, A. M. (2009). Influence of nitrogen and boron nutrition on nutrient balance and sugar beet yield grown in calcareous soil, *Ozian Journal of Applied Sciences*, *2*(1),1-10.

Jovzi, M. & Zare Abyaneh, H. (2015). Effect of N-fertilizer levels and deficit irrigation on qualitative and quantitative yield of sugar beet. *Journal of Sugar Beet*, *31*(2), 141-156. (In Persian, abstract in English). https://doi.org/10.22092/JSB.2016.105601

Kabu, M. & Akosman, M. S. (2019). Biological effects of boron. *Reviews of Environmental Contamination and Toxicology*, *225*, 57-75. https://doi.org/10.1007/978-1-4614-6470-9_2

Kandil, E. E., Abdelsalam, N. R. & El-Aziz, A. A. (2020). Efficacy of nano fertilizer, fulvic acid and boron fertilizer on sugar beet (*Beta vulgaris* L.) yield and quality. *Sugar Technology*, *22*, 782-791. https://doi.org/10.1007/s12355-020-00837-8

Kristek, A., Biserka, A. & Kristek, S. (2006). Effect of the foliar boron fertilization on sugar beet root yield and quality. *Agriculture Scientific and professional Review*, *12*(1), 22-26. https://doi.org/10.17557/.90799

Kernchen W. (2010). Instruction for Installation and

Operation. Betalyzer, Dr Wolfgang Kernchen, GmBH, Germany. 14p. https://doi.org/10.22069/EJCP.2022.19768.2477

Last, P. J., Draycot, A. P., Messam, A. B. & Webb, D. J. (2020). Effects of nitrogen fertilizer and irrigation on sugar beet at Brooms Barn. 1973-8. *Journal of Agriculture Science Cambridge*, *101*, 185-205. https://doi.org/10.1017/s0021859600036509

Lehrsch, G. A., Brown, B., Lentz, R. D., Johnson Mayard, J. L. & Leytem, B. (2014). Sugar beet yield and quality when substituting compost or manure for conventional nitrogen fertilizer. Agronomy Journal, *107*(1), 221-231. https://doi.org/10.2134/agronj13.0462

Mahapatra, C. K., Bhadra, T. & Paul, S. K. (2020). Nutrient management in sugar beet: a review. *Pakistan Sugar Journal*, *35*(2). 14. .https://doi.org/10.1007/978-981-19-2730-0_13

Mahfouz H, Ali AM. M., Megawer, E. A., Mahmoud, A. S. (2015). Response of growth parameters, forage quality and yield of dual-purpose sorghum to regrowth and different levels of FYM and N fertilizers in new reclaimed soil. *International Journal Current Microbiology and Applied Science*, *4*(11), 762-782.

Noshad, H., Mohamadian, R. & Hamdi, F. (2014). Effect of organic fertilizer content of amino acids on nitrogen efficiency and quality and quantity traits of sugar beet. *Journal of sugar beet*, *30*(2), 167-181. https://doi.org/10.22092/JSB.2015.11551

Ouda Sohier, M. M. 2005. Yield and quality of sugar beet as affected by planting density and nitrogen fertilizer levels in the newly reclaimed soil. Sugar Crop Research Egypt.

Rahimi, A., Dolati, B. Heidarzadeh, S. (2017). The effect of foliar application of some microelements on the quantitative and qualitative characteristics of sugar beet cultivar Latitia. *Applied soil research*, *5*(2), 108-121 (In persian).

Reinefeld, E., Emmerich, A., Baumgarten, G., Winner, C. & Bei, U. (1974). Zur Voraussage des Melassezuckers aus Rübenanalysen. *Zucker*, *27*, 2-15. https://doi.org/10.1007/BF00043365

Semida, W. M., Abd El-Mageed, T. A. & Howladar, S. M. (2014). A novel organo-mineral fertilizer can alleviate negative effects of salinity stress for eggplant production on reclaimed saline calcareous soil. *Acta Horticuture*, *1034*, 493-499. https://doi.org/10.17660/ActaHortic.2014.1034.61

Shukla, A. K., Behera, S. K., Pakhre, A. & Chaudhary, S. K. (2018). Micronutrients in soils, plants, animals and humans. *Indian Journal of Fertilizers*, *14*(3), 30-54. https://doi.org/10.3390/su13169136

Seyed Esmailzadeh, S. N. (2011). *Effect of macro and microelements on quality and quantity yield of sugar beet*, M.Sc. thesis faculty of agriculture, IAU Mahabad branch.

Tlili, A., Dridi, I., Fatnassi, S., Hamrouni, H. & Gueddari, M. (2018). Effects of Boron Distribution on Sugar Beet Crop Yield in Two Soils of Dour Ismail Irrigated Perimeter (Béja-Goubellat, Northwest Tunisia). In: Kallel, A., Ksibi, M., Ben Dhia, H., Khélifi, N. (eds) *Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions*. EMCEI 2017. Advances in Science, Technology & Innovation. Springer, Cham. https://doi.org/10.1007/978-3-319-70548-4_131

Yarnia, M., Farajzadeh, E., Rezaei, F. and Nobari, N. 2009. Effect of application method of micronutrient on yield of sugar beet varieties monogerm Rasoul. *Journal of Agriculture. Science and Research*, 10, 31-46. (In Persian). https://doi.org/10.22055/agen.2019.26649.1444

Zarski, J., Tomaszewska, R. K. & Dudek, S. (2020). Impact of irrigation and fertigation on the yield and quality of sugar beet (*Beta vulgaris* L.) in a moderate climate. *Agronomy*, *10*, 166-173. https://doi.org/10.3390/agronomy10020166

Zewail, R. M. Y., El-Gmal, I. S., Khaitov, B. & El-Dosouky, S. A. (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

Zhang, D., Zhao, H., Shi, L. & Xu, F. (2014). Physiological and genetic responses to boron deficiency in Brassica napus: A review. *Soil Science and Plant Nutrition*, *60*(3), 304-313. https://doi.org/10.1080/00380768.2014.893537