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RESEARCH

The Effect of Sugar Beet (*Beta vulgaris* L.) Varieties Grown Under Semi-Arid Conditions in Turkey's Eastern Anatolia Region on Yield and Quality

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Abstract
Global climate change, which is increasingly evident today, leads to significant fluctuations in the yield and quality parameters of sugar beet varieties, particularly due to its direct impact on semi-arid regions. Therefore, the adaptation capacity of varieties especially in the semi-arid areas of eastern regions and their responses to drought and temperature stress are of critical importance. This study was conducted during the 2022–2023 growing seasons to evaluate the yield and quality performance of ten sugar beet varieties (Seranada, Lider, Mohican, Terronova, Aranka, Turbata, Bernache, Setenil, Tisserin, and Chevalier) within a continental agro-ecological zone characterized by high altitude and a semi-arid climate. The results revealed significant differences among the varieties in terms of all examined traits. The highest root yield was obtained from Chevalier (95.30 ton/ha) and Mohican (94.17 ton/ha), while Tisserin produced the lowest (71.34 ton/ha). In terms of sugar yield, Terronova ranked highest (16.18 ton/ha), whereas Tisserin (12.44 ton/ha) and Setenil (12.34 ton/ha) showed the lowest performances. The Lider variety recorded the highest sugar content (18.22%), indicating its potential as a quality-oriented genotype. Overall, Mohican and Terronova demonstrated the most favorable responses under semi-arid conditions. These findings underscore the importance of regional variety testing for identifying high-yielding and high-quality sugar beet genotypes, especially in environments affected by altitude, climate variability, and soil characteristics.

Keywords Adaptation · PCA · Root yield · Semi-arid conditions · Sugar beet · Sugar yield

Introduction

Due to increasing global warming in recent years, ensuring food security worldwide has been the primary scientific problem (Cassman, 2012). Global warming has started seriously threatening food production worldwide. Considering that the world population, which is increasing rapidly today (8 billion on average), will reach an average of 10 billion by 2050, it is inevitable that the demand for food will increase substantially due to population growth (Dorling, 2021). It is also clear that production needs to be increased by 60% on average to meet the food needs of the estimated population in 2050 (Le Mouël & Forslund, 2017). However, low yields in crop production in many global regions due to climate change and improper agricultural practices raise serious concerns about meeting the increasing demand for food (Field & Barros, 2014; Voss-Fels et al., 2019). Identifying suitable varieties to increase yield and quality potential under various growing conditions is an excellent advantage for food security's sustainability (Reynolds et al., 2021; Taleghani et al., 2024).

Sugar beet cultivation is of great importance to the food industry. Sugar beet is a strategic product due to its significant contribution to human nutrition, agricultural production, and industry, such as nutrition, feed additive in animal

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husbandry, coal industry, vegetable fertilizer, alcohol production, and yeast (Yetik & Candogan, 2022; Ayas, 2025). A herbaceous biennial plant with nearly 200 years of cultivation history in arid and semi-arid regions, sugar beet still holds many mysterious aspects as a sugar-producing treasure (Clouse et al., 2016). In addition to its contribution to farmers, the importance and production of sugar beet are increasing daily due to its economic contribution to many industrial sectors.

Sugar beet is very important in sugar production in our country and the world. According to 2022 data, Turkey ranks 5th in the world in terms of sugar beet production (269.9 million tons) (19.0 million tons) (FAOSTAT, 2025). According to 2023 data, global sugar production is estimated to reach 177.2 million tons, and consumption is 176.0 million tons. In total world sugar production (cane and beet sugar production), Turkey ranks 12th with a share of 1.83%, while in beet sugar production (3.3 million tons), it ranks 5th with 8.46%. Turkey produced 25.2 million tons of sugar beet from an average cultivation area of 362,815 ha, and the average sugar beet per hectare was 69.60 tons in Turkey, while it was 56.99 tons worldwide (Turkseker, 2025). Considering that the difference between world sugar production and consumption will reach 689 thousand tons, it is clear that Turkey is at a key point in closing the sugar deficit.

In recent years, systematic breeding programs of breeders and biotechnological methods of researchers have led to quantitative and qualitative performance improvement in sugar beet (Taleghani et al., 2022). This process has contributed significantly to the improvement of many important characteristics of sugar beet varieties, such as a genetic increase in sugar ratio from 8% to 18–20%, resistance of varieties to viral and fungal diseases, monogerm varieties, and resistance to shoot production (Taleghani et al., 2022, 2024; Hassani et al., 2023). The importance of such improvements to increase yield and quality in sugar beet production to meet future demand for sugar is evident. Although biotechnological methods can improve the genetic structure of seeds, the multifaceted nature of root yield, which is affected by genotype, environment, and their interaction, poses some difficulties in producing a stable crop (Sadeghzadeh et al., 2022). Differences between genotypes with the same genetic trait due to specific environmental conditions lead to phenotypic variations (Hassani et al., 2023). To obtain high yields in sugar beet cultivation, breeders must identify genotypes that consistently show superior characteristics under different climatic and environmental conditions by conducting extensive tests in various locations (Saremirad & Taleghani, 2022). This method helps select genotypes with broad adaptation and stability, thus increasing yield (Taleghani et al., 2023). In addition, high input costs are important factors that negatively affect farmers' profitability. Therefore, sugar beet producers must select varieties suitable for climate and environmental conditions for high yield and sugar ratio, directly impacting profitability (Yildiz et al., 2024).

Previous research has shown that the agronomic performance of sugar beet varieties can differ significantly across geographic regions, primarily due to variations in climate, soil composition, and cultivation practices. This variability underscores the critical role of genotype-environment interactions in shaping key traits such as root yield, sugar concentration, and processing quality. Consequently, region-specific variety trials are essential, especially in areas prone to abiotic stress factors like drought, temperature extremes, and low atmospheric humidity, which can severely constrain crop performance. Identifying genotypes that consistently exhibit high yield and quality under such conditions remains a strategic priority for ensuring the long-term sustainability of sugar beet production (Sefaoğlu, 2019; Erbil, 2020; Ertürk and Ağır, 2022; Ayaş, 2025).

Cultivating varieties with high yield potential under favorable climatic and environmental conditions results in obtaining high yields per unit area. Therefore, it is necessary to customize this type of research for each region and each variety. This study aimed to determine the adaptation balance of some sugar beet varieties to the agricultural and ecological conditions of a specific region. The study aimed to evaluate the interaction of the varieties over the years, to evaluate the yield and quality parameters, and to determine the high-performance variety or varieties suitable for the agricultural and ecological conditions of the region. The findings of this study are expected to contribute to the empirical literature and offer practical insights for future research on sugar beet cultivation within a continental agro-ecological zone characterized by high altitude and semi-arid climate.

Materials and Methods

Plant Materials

In this study, ten sugar beet varieties representing three genetic types *N*, *Z*, and *NZ* were evaluated. These types reflect varying combinations of root yield and sugar content potential. Detailed information regarding variety classification and sugar ratio levels is presented in Table 1.

Field Trials

Field trials were conducted during the 2022–2023 growing seasons in Üzümlü, a district of Erzincan province, located in the Upper Euphrates subregion of Eastern Anatolia,

Table 1 Some characteristics of beet varieties

Varieties	Type*	Sugar ratio
Seranada	NZ	High
Lider	NZ	High
Mohican	N	Moderate
Terronava	NZ	High
Aranka	N	Moderate
Turbata	N	Moderate
Bernache	NZ	High
Setenil	N	Moderate
Tisserin	N	Moderate
Chevalier	NZ	High

* Type of sugar beets: Z (Zucker) type-low root yield, high sugar ratio; N (Normal) type-moderate root yield and sugar ratio; NZ-hybrid type showing both high root yield and high sugar ratio. All varieties with high root yield, are resistant to rhizomania, and tolerant to cercospora

Türkiye. The experimental site lies at an altitude of 1324 m above sea level and is geographically situated at 39°40′15″ N latitude and 39°45′20″ E longitude.

Üzümlü is characterized by a continental climate, with cold winters and hot, dry summers. The study was carried out on an experimental field representative of the regional agro-ecological conditions. The physical and chemical properties of the soil at the trial site are presented in Table 2.

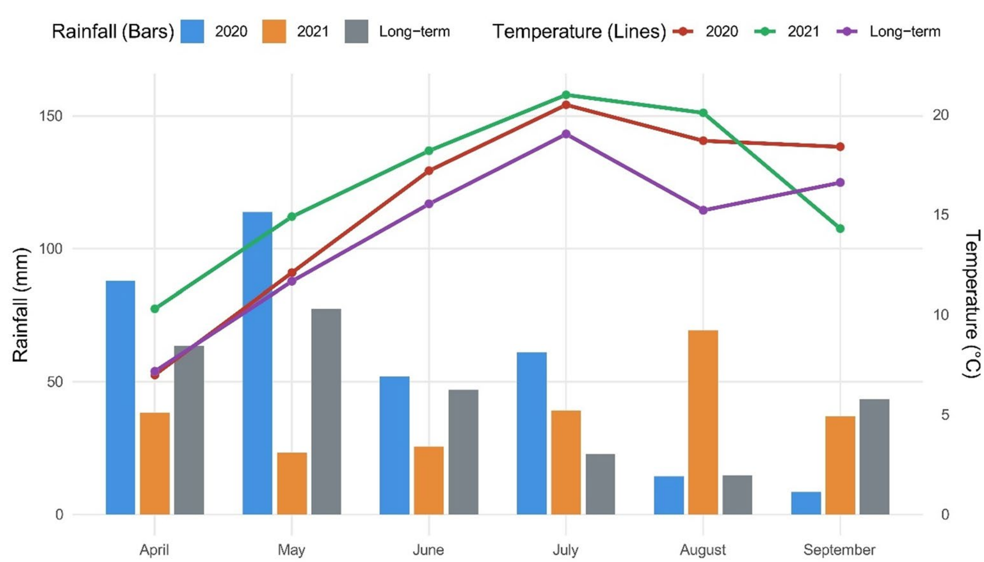
Meteorological data of the experimental area are given in Fig. 1. In the 2022 growing season, the total rainfall was 139.60 mm, and the average temperature was 19.83 °C. In the 2023 growing period, the total rainfall was 262.9 mm, and the average temperature was 18.98 °C.

The experiment used the "Randomized Block Experimental Design" with three replications. The experimental area was deep plowed before planting, then cultivated with a cultivator, and made ready for planting. Sowing was performed using a precision-adjusted seed drill on April 24, 2022, and May 1, 2023, at a depth of 2–3 cm. The seeds were sown in five rows, with an inter-row spacing of 20 cm. The spacing of 45 cm between the rows, and length of 4 m of each row were kept. Fertilizer was applied as pure 200 kg nitrogen (N) and 100 kg phosphorus (P) per hectare. In the experimental area, 55 kg Super Beet-S [13.18.15 + 2 (MgO) + 10 (SO3) + B] NPK compound fertilizer was applied as base fertilizer before planting, and 30 kg urea (46% N) fertilizer was applied as top fertilizer with the first hoe. In both years, hoeing was carried out when the sugar beet seedlings had 2–4 leaves, and a total of 3 hoeing operations were carried out according to the weed status in the plots. Irrigation was performed seven and six times in the growing period of 2022 and 2023, respectively. Harvesting for both trials was carried out on October 5th, 2022 and September 20th, 2023, respectively. After removing the edge effects from each plot, the sugar beets obtained from the harvest were sent to Erzincan Sugar Factory laboratory for ash ratio, α-amino nitrogen, digestion percentage, and polar sugar beet analysis.

Table 2 Characteristics of the trial soil

Years	Depth (cm)	Sturation (%)	Texture Classroom	pH	Salinity (%)	CaCO3 (%)	Organic Matter (%)	Available	
								P_2O_5 (kg/ha)	K_2O (kg/ha)
2022	0–30	69.3	Clay-Loamy	8.17	0.28	19.72	2.18	582.9	3514.4
2023	0–30	57.2	Clay-Loamy	7.28	0.24	1.58	1.94	66.2	596.1

Fig. 1 Rainfall and temperature data of the growth periods at the field sites in 2022 and 2023



Ash ratio (%): 5 g of sample was taken into a 100 ml solution flask and filled to 100 ml with distilled water. The conductivity of the resulting solution was then measured at 20 °C, and the ash percentage of the product was calculated using the formula below (Kavas & Leblebici, 2004).

$$\text{Ash}\,\% = (16.2 + 0.36 \times \text{D}) \times 10\text{-}4 \times (\text{C5-Cw}) \times \text{f}$$

D = dry matter concentration of the required solution.
C5 = conductivity of the required solution at 20 °C.
Cw = conductivity of water at 20 °C.
f = dilution factor, 5/m.

Alpha-amino nitrogen (mmol/100 g): It was measured using the Kubadinow-Weninger Method by looking at the absorption of the blue color formed by the α-amino nitrogen of copper nitrate/sodium acetate buffer in a spectrophotometer at 600 nm wavelength (Kavas & Leblebici, 2004).

Digestion (sugar content): The sugar content analysis was performed using the cold digestion method, with the beet pulp being ground into a paste. Average 26-gram samples were stirred for 2 min in 178.2 ml of lead acetate solution. The polar value was then read on the filter and the polymeter's 13 g/100 ml scale (Kavas & Leblebici, 2004).

Polar sugar ratio (%): Samples were pulverized using the cold digestion method. Average 26-gram samples were stirred in 178.2 ml of 0.3% aluminum sulfate solution for 2 min, then filtered and read on a polarimeter (Kavas & Leblebici, 2004).

Sugar yield (ton/ha): The beet yields in each plot were calculated by proportioning them to the sugar availability analyzed in the same plot (Sincik & Canigenis, 2016).

$$\text{Sugar Yield} = \frac{\text{Sugar content} \times \text{root yield}}{100}$$

Root yield (ton/ha): The beets in the harvest area of the plots were removed, the heads and leaves were cut, the soil was cleaned, and the plot yields were determined by weighing. Parcel yields were converted to hectares, and root yields were calculated.

Harvest Index (%): It was determined by proportioning the average stem weight values to the biomass weight values and multiplying by 100.

Data Analysis

The data obtained in the study were subjected to a mixed-model two-way ANOVA in Rstudio (version 2023.06.1 + 524) using the R package 'lme4' with year and replicate factors treated as fixed and random effects, respectively. Significant differences in mean values between genotypes or years were examined by Duncan's multiple comparison test (Steel & Torrie, 1980; Duzgunes et al., 1987).

Results and Discussion

Genotypic Varations and Year Effects on Each Trait

As shown in Table 3, there were significant variations among genotypes in all the studied traits. Root yield, harvest index, ash ratio and sugar yield were also found to significantly vary between years, indicating a significant environmental difference between 2022 and 2023. Interestingly, the performance of genotypes in all the traits was significantly affected by the genotype × year interactions, indicating the unstable performance of the same genotype between two years. Thus, year-specific recommendations are needed in selections for superior genotypes.

According to Fig. 2, significantly higher root yield (94.91 vs. 73.36 ton/ha), sugar yield (16.34 vs. 11.76 ton/ha), and harvest index (82.67% vs. 76.27%) were obtained in 2022 compared to 2023, while ash ratio was higher in 2023 (3.88%) than in 2022 (3.29%). These differences are likely due to dramatic changes in soil nutrient composition across years. For instance, soil $CaCO_3$ was 19.72% in 2022 compared to 1.58% in 2023; available phosphorus (P_2O_5) was 582.9 kg/ha in 2022 versus 66.2 kg/ha in 2023, and potassium (K_2O) levels were 3514.4 kg/ha in 2022 compared to 596.1 kg/ha in 2023 (Table 2). These soil-related differences may have significantly influenced plant growth and

Table 3 ANOVA table for the seven investigated traits (*: $p<0.05$, **: $p<0.01$, ***: $p<0.001$)

	Genotype	Year	Genotype × Year	Replicate (year)	Residual
Degree of freedom	9	1	9	-	-
	F value			Variance	
Root Yield	14.94***	224.14***	15.32***	2874	281,881
Harvest Index	6.44***	53.88***	20.10***	0.84	3
Ash Ratio	15.11***	28.37**	9.15***	0.01	0.08
Sugar Content	2.67*	2.69	4.75***	0.19	1.22
Sugar Ratio	4.63***	0.05	8.27***	0.08	0.6
α-amino N	8.69***	1.9	4.19***	0	0.0004
Sugar Yield	6.40***	175.95***	10.64***	0	17,875

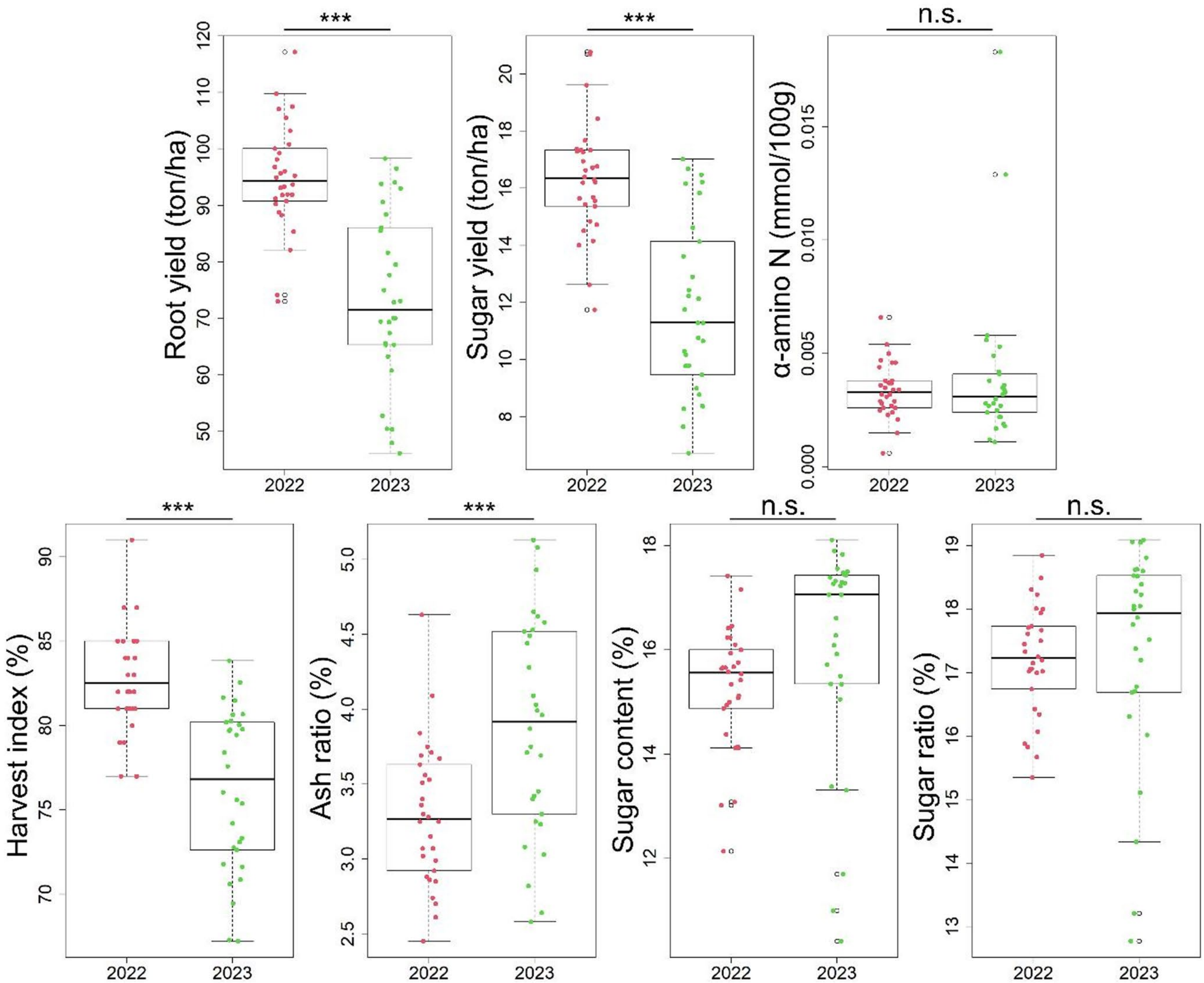


Fig. 2 The variation of the seven studied traits between 2022 and 2023. Significant differences between two yers are indicated by asterisks (t-test; ***: $p<0.001$, n.s.: not significant)

metabolic activity. Similarly, Ivanina et al. (2021) reported that altered fertilization regimes significantly affected sugar beet productivity. In addition, environmental fluctuations such as temperature and precipitation between years have also been shown to impact yield and quality components (Sefaoglu, 2019). Root yield, sugar yield, harvest index, and ash ratio all exhibited highly significant year-to-year changes ($p<0.001$), whereas sugar content, sugar ratio, and α-amino N did not show statistically significant differences (Fig. 2).

Among the genotypes, Chevalier (95.30 ton/ha) and Mohican (94.17 ton/ha) produced the highest root yields, while Tisserin had the lowest (71.34 ton/ha), as presented in Fig. 3. These findings confirm significant genotypic variation in root yield, consistent with previous studies (Sahiner & Ismail, 2020; Erturk & Agır, 2022; Baran & Yalinkilic, 2025). Such varietal differences may arise from the combined effects of genetic background, agronomic management, and environmental interactions (Gul & Kara, 2015; Sefaoglu et al., 2021).

Sugar ratio did not significantly vary between years, with similar averages recorded in 2022 (17.20%) and 2023 (17.26%) (Fig. 2). Across genotypes, sugar ratio ranged from 16.34% to 18.22%, with the highest value recorded for Lider (18.22%) and the lowest for Chevalier, Bernache, and Setenil (16.54%, 16.46%, and 16.34%, respectively). These results are within the range reported by prior studies: Mohammadian et al. (2008) (13.99–16.31%), Ada and Akınerdem (2011) (16.39–19.30%), and Baran and Yalinkilic (2025) (16.68–19.04%). The genotype × year interaction for sugar ratio was significant, indicating that

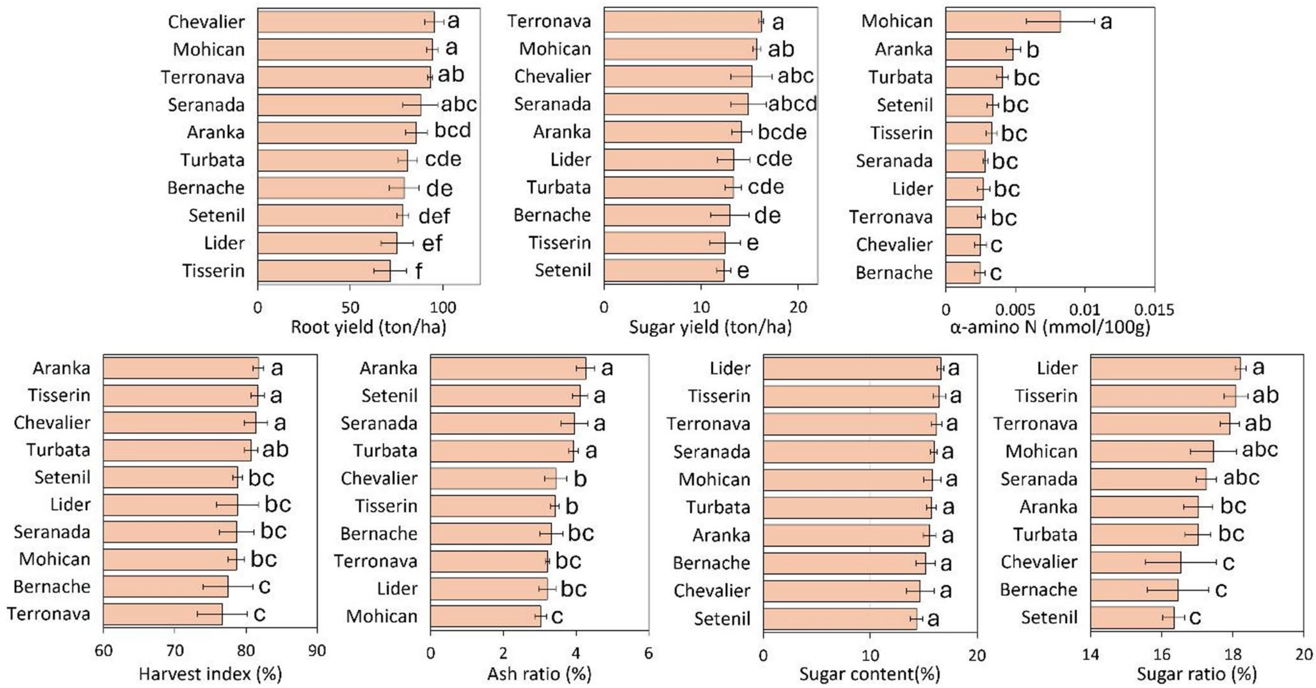


Fig. 3 Two-year average values of each traits among genotypes. Values followed by the same letter do not differ sigificantly (Duncan's test, at $p<0.05$)

varietal response to sugar accumulation is dependent on environmental conditions (Xie et al., 2022).

Sugar content remained statistically stable across years (15.28% in 2022 and 16.03% in 2023), suggesting that it may be less sensitive to environmental variation (Fig. 2). However, genotype × year interaction was significant (Table 3). This reflects the combined effects of genetic potential and physiological response to year-specific environmental factors (Okut & Yildirim, 2004; Kenter et al., 2006).

Sugar yield, unlike sugar content, was significantly influenced by both year and genotype. A higher average sugar yield was obtained in 2022 (15.28 ton/ha) than in 2023 (16.03 ton/ha). Among genotypes, Terronova had the highest sugar yield (16.18 ton/ha), while Setenil and Tisserin recorded the lowest (12.34 and 12.44 ton/ha). These differences further highlight the role of genetic background in sugar accumulation and translocation, which is well-supported by earlier studies (Tosun et al., 2019; Erturk & Agir, 2022; Yagmur & Yasar, 2023; Zhang et al., 2025). The fact that Seranada and Chevalier outperformed Mohican and Terronova in 2022, while the reverse occurred in 2023, further supports the significance of the genotype × year interaction (Fig. 3).

Harvest index also showed significant variation between years (82.67% in 2022 vs. 76.27% in 2023). Among varieties, Aranka, Tisserin, and Chevalier exhibited the highest harvest indices (81.75%, 81.60%, and 81.42%, respectively), while Terronova and Bernache had the lowest. This indicates that genetic differences influence how effectively photosynthates are allocated to harvestable organs (Yavas & Ilker, 2020). A significant genotype × year interaction was also observed for this trait, likely reflecting differences in genotype adaptability to annual climatic variations (Raza et al., 2019; Swarup et al., 2021).

Although α-amino N content did not significantly differ between years (0.00034 mmol/100 g in 2022 vs. 0.00039 mmol/100 g in 2023), there were considerable genotypic differences. Mohican had the highest α-amino N value (0.00082 mmol/100 g), while Bernache and Chevalier recorded the lowest (0.00024 and 0.00025 mmol/100 g). Since α-amino N increases molasses loss, high values negatively affect sugar yield (Alotaibi et al., 2011). The significant genotype × year interaction indicates that α-amino N accumulation is influenced by environmental factors such as temperature and soil properties. Previous studies (Dirim et al., 2024; Ustuner & Ozturk, 2018; Piskin & Inal, 2014; Demirel & Akinerdem, 2016) reported considerably higher α-amino N values than those observed here, supporting the suitability of the tested genotypes for processing.

Finally, ash ratio is a critical trait for sugar processing efficiency-differed significantly between years, genotypes, and their interaction. The 2023 season resulted in higher ash accumulation (3.88%) than 2022 (3.29%). Genotypically, Aranka (4.27%), Setenil (4.11%), and Seranada (3.96%) showed the highest values, whereas Mohican had the lowest (3.03%). Ash ratio is known to be influenced by both mineral uptake efficiency and environmental conditions such as moisture and soil composition (Djordjević et al., 2021; Baryga et al., 2020). The observed year × genotype interaction suggests that varieties differ in their sensitivity to these factors. While our results are consistent with those of Yagmur and Yasar (2023), the values reported were higher than those found by Mohamed et al. (2023) and El-Geddawy et al. (2023).

Multivariate Analysis of Genotypic Performance

The hierarchical clustering heatmaps for 2022 and 2023 reveal considerable genotypic variation and clear genotype × environment interactions among the ten sugar beet cultivars evaluated. In 2022, Chevalier, Seranada, and Bernache were grouped together, characterized by lower ash ratio and α-amino N traits. In contrast, Mohican, Setenil, and Turbata formed a distinct cluster with higher ash and α-amino N values and relatively lower sugar content and sugar ratio, indicating their potential as quality-oriented genotypes. Terronova and Tisserin displayed balanced profiles, suggesting suitability for dual-purpose breeding. In 2023, shifts in clustering patterns highlighted environmental influence. Terronova and Mohican maintained strong associations with root yield, sugar yield, and harvest index, emerging as high-yielding genotypes. Meanwhile, Bernache, Chevalier, and Setenil clustered with lower trait values, reflecting a decline in quality-related traits. Lider, Tisserin, Seranada, and Turbata showed more stable, intermediate values, suggesting moderate adaptability (Fig. 4).

Figure 5 presents the biplot analysis of principal component analysis (PCA) based on yield and quality-related traits of ten sugar beet genotypes under semi-arid conditions. The first two principal components, PC1 and PC2, explained 42.73% and 31.42% of the total variation, respectively. The biplot revealed distinct groupings among traits. Root yield, sugar yield, and harvest index were closely aligned, indicating a strong positive correlation among these yield-related traits. On the other hand, sugar content, sugar ratio, and α-amino N vectors formed another group, showing strong mutual associations. Ash ratio appeared in the opposite direction of the yield traits, suggesting a negative relationship. These vector relationships are consistent with earlier findings where yield and quality parameters often show

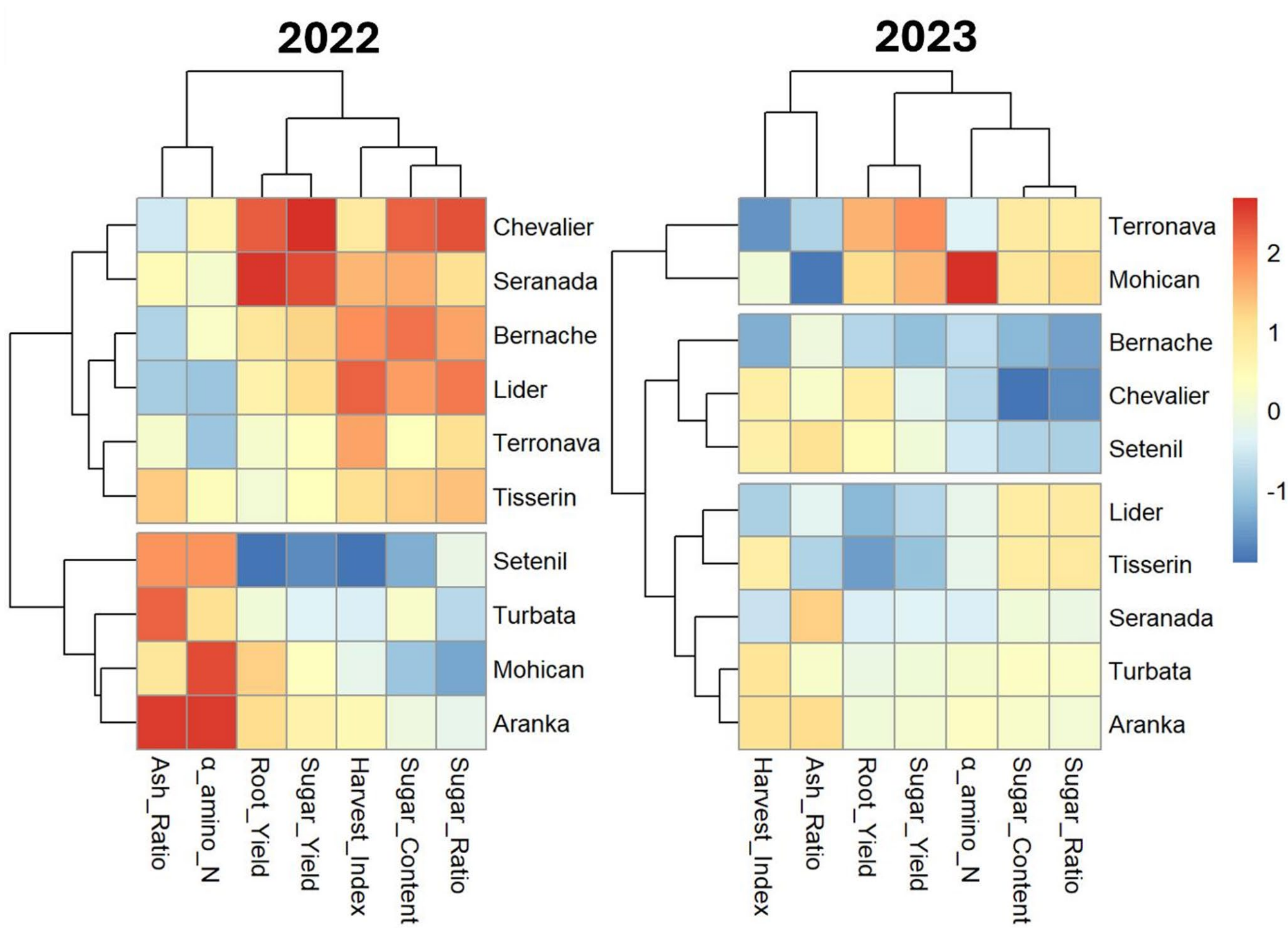


Fig. 4 Hierarchical clustering heatmaps showing the variation in yield and quality traits among ten sugar beet varieties across 2022 and 2023

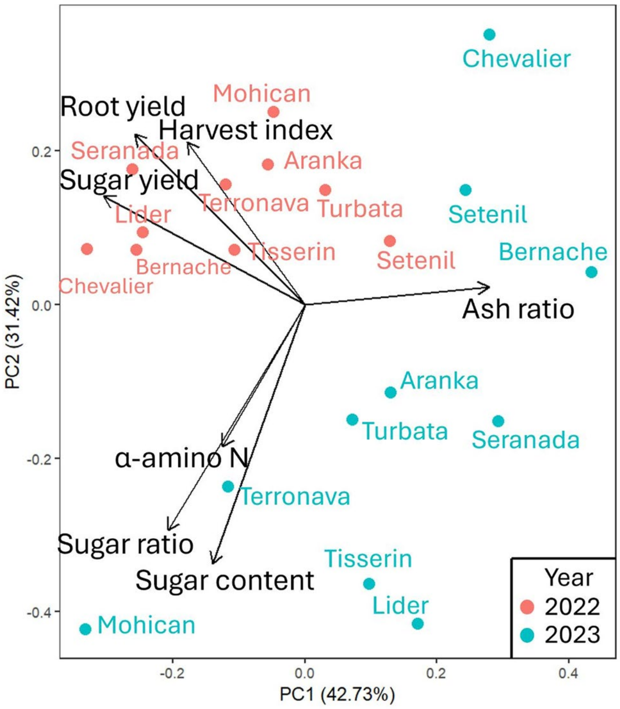


Fig. 5 Principal component analysis (PCA) biplot illustrating relationships among sugar beet varieties and seven agronomic traits across two years

trade-offs under stress conditions (Mehari et al., 2015; Seify et al., 2023).

The distribution of genotypes in the biplot revealed significant genotypic variation. Genotypes such as Terronova, Mohican, and Seranada (mostly in 2022) were positively associated with high root and sugar yield traits, positioning them as promising candidates for yield improvement. Mohican (2023), located in the direction of sugar content and sugar ratio vectors, stood out as a potential high-quality genotype. Tisserin and Lider also showed strong associations with sugar content traits, supporting their classification as quality-focused genotypes. In contrast, Chevalier (2023) aligned closely with ash ratio, indicating high ash accumulation, which is generally undesirable. Bernache (2022) and Chevalier (2022) were positioned far from major positive traits, indicating poor overall performance. The clear year-to-year shifts in genotypic positioning suggest strong genotype × environment interaction, as also noted in industrial crops studies (Coban et al., 2024). Overall, PCA effectively distinguished genotypes based on trait combinations, highlighting its utility in selection strategies.

Recommendations for Genotype Selection and Breeding Implications

Based on the multi-trait evaluation across two growing seasons, Terronova and Mohican emerged as promising candidates for high root and sugar yield performance, while Lider demonstrated stable superiority in sugar content and sugar ratio. Although some genotypes such as Chevalier and Seranada performed well in specific years, their sensitivity to environmental variation suggests limited adaptability. The significant genotype × year interactions detected for all traits underscore the importance of multi-environment trials in genotype evaluation. Therefore, selection programs should prioritize both mean performance and trait stability, especially under variable semi-arid conditions. Furthermore, genotypes like Mohican, which combine acceptable yield with low α-amino N and ash ratio, are particularly valuable for improving processing quality. These findings provide a useful foundation for targeted breeding strategies aimed at developing dual-purpose sugar beet varieties with high yield potential and improved industrial quality under diverse agro-environmental conditions.

Conclusion

This study aimed to evaluate and compare the yield and quality performances of ten sugar beet varieties cultivated under semi-arid conditions in Eastern Turkey. The results demonstrated that climatic and environmental differences between the experimental years significantly influenced the measured parameters. Accordingly, the effects of year, variety, and their interaction (year × variety) were statistically significant for many traits. Overall, the data obtained in 2022 outperformed those of 2023, particularly in terms of root and sugar yield, where Chevalier (95.30 and 15.20 ton/ha), Mohican (94.17 and 15.73 ton/ha), and Terronova (93.15 and 16.18 ton/ha) were among the best-performing varieties. In contrast, regarding sugar ratio and sugar content, Lider (18.22% and 16.59%) and Tisserin (18.08% and 16.46%) gave the most favorable results.

In general, it was evident that both genetic variation and environmental conditions played decisive roles in determining yield and quality traits. Key processing-related parameters such as α-amino N and ash ratio were significantly affected by year and variety interactions, highlighting the importance of selecting varieties that are best suited to specific environmental conditions. Notably, Mohican and Terronova stood out as the most promising genotypes for both yield and quality performance under semi-arid conditions like those in Erzincan. Additionally, Lider consistently produced the highest sugar content.

These findings emphasize the relevance of genotype-environment interaction studies in identifying high-performing and quality-stable sugar beet varieties, especially for regions where altitude, soil characteristics, and climatic variability pose significant agronomic challenges.

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Author Contributions Ikram Bagcı: Conceptualization; Data Curation, Funding Acquisition; Investigation, Resources; Validation. Volkan Gul: Conceptualization; Funding Acquisition, Methodology; Project Administration, Resources, Supervision; Validation, Writing-Original Draft Preparation; Visualization, Writing-Reviewing and Editing. Fırat Sefaoglu: Conceptualization; Formal Analysis, Methodology; Software, Project Administration; Validation, Visualization; Writing-Original Draft Preparation; Writing-Reviewing and Editing. Yuzhou Lan: Formal Analysis; Visualization; Statistical Validation; Writing – Reviewing and Editing. Furkan Çoban: Data Curation; Formal Analysis; Visualization; Language Editing; Writing – Reviewing and Editing.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

Ada, R., & Akınerdem, F. (2011). Determination of the yield, qualityand losses of mechanized harvesting of sugar beet (*Beta vulgaris saccharifera* L.) harvested different dates. *Selcuk Journal of Agriculture and Food Sciences*, *25*(1), 17–25.

Alotaibi, F., Bamagoos, A. A., Ismaeil, F. M., Zhang, W., Ada, R., & Akınerdem, F. (2011). Determination of the yield, qualityand losses of mechanized harvesting of sugar beet (*Beta vulgaris saccharifera* L.) harvested different dates. *Selcuk Journal of Agriculture and Food Sciences*, *25*(1), 17–25.

Ayas, S. (2025). Effects of different irrigation and fertilization levels on the yield and quality of wet sugar beet pulp used as animal feed. *Sugar Tech*, *26*(5), 1448–1462. https://doi.org/10.1007/s12355-024-01490-1

Baran, N., & Yalinkilic, N. A. (2025). Determination of yield and quality characteristics of some sugar beet (*Beta vulgaris* L.) varieties by different analytical methods. *International Journal of Agriculture Environment and Food Sciences*, *9*(1), 157–165. https://doi.org/10.31015/2025.1.18

Baryga, A., Połeć, B., & Klasa, A. (2020). Quality of sugar beets under the effects of digestate application to the soil. *Processes*, *8*(11), 1402. https://doi.org/10.3390/pr8111402

Cassman, K. G. (2012). What do we need to know about global food security? *Global Food Security*, *1*(2), 81–82. https://doi.org/10.1016/j.gfs.2012.12.001

Clouse, J. W., Adhikary, D., Page, J. T., Ramaraj, T., Deyholos, M. K., Udall, J. A., Fairbanks, D. J., Jellen, E. N., & Maughan, P. J. (2016). The Amaranth genome: genome, transcriptome, and physical map assembly. *The Plant Genome*, *9*(1), 1–14. https://doi.org/10.3835/plantgenome2015.07.0062

Coban, F., Ozer, H., & Lan, Y. (2024). Genetic and environmental influences on fatty acid composition in different Fenugreek genotypes. *Industrial Crops and Products*, *222*, 119774. https://doi.org/10.1016/j.indcrop.2024.119774

Demirel, D., & Akınerdem, F. (2016). The effect of storage duration on the yield and quality of sugar beet, harvested and storaged in field different times. *Selcuk Journal of Agriculture and Food Sciences*, *3*(2), 143–156.

Dirim, E., Say, A., & Arslan, M. (2024). Assessment of genetic diversity, yield and quality performance of O-Type sugar beet (*Beta vulgaris* L.) breeding lines. *Genetic Resources and Crop Evolution*, *71*(4), 1605–1614. https://doi.org/10.1007/s10722-023-01721-6

Djordjević, M., Šereš, Z., Maravić, N., Šćiban, M., Šoronja-Simović, D., & Djordjević, M. (2021). Modified sugar beet pulp and cellulose-based adsorbents as molasses quality enhancers: Assessing the treatment conditions. *Lwt*, *150*, 111988. https://doi.org/10.1016/j.lwt.2021.111988

Dorling, D. (2021). World population prospects at the UN: Our numbers are not our problem? The struggle for social sustainability (pp. 129–154). *Policy Press*. https://doi.org/10.51952/9781447356127.ch007

Duzgunes, N., Allen, T. M., Fedor, J., & Papahadjopoulos, D. (1987). Lipid mixing during membrane aggregation and fusion: Why fusion assays disagree. *Biochemistry*, *26*(25), 8435–8442.

El-Geddawy, M. A., Mustafa, O. A., El-Syiad, S. I., & Mohamed, E. S. G. I. (2023). The potential impact of the quality of sugar beet roots (*Beta vulgaris* L.) on sugar loss in the beet molasses. *Assiut Journal of Agricultural Sciences*, *54*(4), 108–122. https://doi.org/10.21608/ajas.2023.232654.1289

Erbil, E. (2020). Determination of yield and quality characteristics of some sugar beet (*Beta vulgaris saccharifera* L.) cultivars winter grown in Şanlıurfa conditions. *Agricultural Engineering*, *371*, 41–50. https://doi.org/10.33724/zm.718438

Erturk, E., & Agır, H. B. (2022). Yield and quality characteristics, and profitability of some winter–summer sugar beet varieties in Kahramanmaraş conditions. *Sugar Tech*, *24*(5), 1461–1469. https://doi.org/10.1007/s12355-021-01049-4

FAOSTAT. (2025, June 25). *Food and Agriculture Organization of the United Nations*. https://www.fao.org/faostat/en/#data/QV

Field, C. B., & Barros, V. R. (2014). *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects, eds, 1132*. Cambridge University Press.

Hassani, M., Mahmoudi, S. B., Saremirad, A., & Taleghani, D. (2023). Genotype by environment and genotype by yield* trait interactions in sugar beet: Analyzing yield stability and determining key traits association. *Scientific Reports*, *13*(1), 23111. https://doi.org/10.1038/s41598-023-51061-9

Ivanina, V., Shapovalenko, R., Strilets, O., & Senchuk, S. (2021). Sugar beet fertilisation for sustainable yield under climate change conditions. *Zemdirbyste-Agriculture*, *108*(4), 355–362. https://doi.org/10.13080/z-a.2021.108.045

Kara, K. (2015). Effects of different nitrogen doses on Yıeld and Qualıty Traıts of common sunflower (*Helianthus annuus* L). *Turk Journal Field Crops*, *20*(2), 159–165.

Kavas, M. F., & Leblebici, M. J. (2004). *Quality and operation control laboratories Handbook, Türkiye sugar factories inc*. General Directorate.

Kenter, C., Hoffmann, C. M., & Märländer, B. (2006). Effects of weather variables on sugar beet yield development (*Beta vulgaris* L). *European Journal of Agronomy*, *24*(1), 62–69.

Le Mouël, C., & Forslund, A. (2017). How can we feed the world in 2050? A review of the responses from global scenario studies. *European Review of Agricultural Economics*, *44*(4), 541–591. https://doi.org/10.1093/erae/jbx006

Mehari, M., Tesfay, M., Yirga, H., Mesele, A., Abebe, T., Workineh, A., & Amare, B. (2015). GGE biplot analysis of genotype-by-environment interaction and grain yield stability of bread wheat genotypes in South Tigray, Ethiopia. *Communications in Biometry and Crop Science*, *10*(1), 17–26.

Mohamed, E. S. G., El-Syiad, S. I., Farghly, O. A., & El-Geddawy, M. A. (2023). Evaluation of sugar losses in beet molasses as affected by the quality of sugar beet roots. *Egyptian Sugar Journal*, *20*, 24–33. https://doi.org/10.21608/esugj.2023.190390.1034

Mohammadian, R., Sadeghian, S. Y., Rahimian, H., & Moghadam, M. (2008). Reduced water consumption of dormant-seeded sugar beet in a semiarid climate. *Agricultural Water Management*, *95*(5), 545–552. https://doi.org/10.1016/j.agwat.2007.12.004

Okut, N., & Yildirim, B. (2004). The effects of planting time and species on yield, yield Components, and quality of sugar beet (*Beta vulgaris var. Saccharifera* L.) in Van condition. *Yuzuncu Yıl University Journal of Agricultural Sciences*, *14*(2), 149–158.

Piskin, A., & Inal, A. (2014). The effect of potassium on yield and quality of sugar beet (*Beta vulgaris* L.) in drip irrigation. *Selcuk Journal of Agriculture and Food Sciences*, *1*(2), 67–73.

Raza, A., Razzaq, A., Mehmood, S. S., Zou, X., Zhang, X., Lv, Y., & Xu, J. (2019). Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. *Plants*, *8*(2), 34. https://doi.org/10.3390/plants8020034

Reynolds, M., Atkin, O. K., Bennett, M., Cooper, M., Dodd, I. C., Foulkes, M. J., Frohberg, C., Hammer, G., Henderson, I. R., Huang, B., Korzun, V., McCouch, S. R., Messina, C. D., Pogson, B. J., Slafer, G. A., Taylor, N. L., & Wittich, P. E. (2021). Addressing research bottlenecks to crop productivity. *Trends in Plant Science*, *26*(6), 607–630. https://doi.org/10.1016/j.tplants.2021.03.011

Sadeghzadeh, H. S., Hosseınpour, M., Jalılıan, A., Ahmadı, M., Azızı, H., Hamidi, H., Hamdi, F., & Matloubi, A. F. (2022). Evaluation of white sugar yield stability of some commercially released sugar beet cultivars in Iran from 2011–2020. *Seed and Plant*, *38*(3), 339–364. https://doi.org/10.22092/SPJ.2023.362024.1305

Sahiner, A., & Ismail, D. (2020). The determination of yield and quality properties of some sugar beet (*Beta vulgaris* L.) varieties in Kirsehir ecological condition. *Manas Journal of Agriculture Veterinary and Life Sciences*, *10*(2), 71–75.

Saremirad, A., & Taleghani, D. (2022). Utilization of univariate parametric and non-parametric methods in the stability analysis of sugar yield in sugar beet (*Beta vulgaris* L.) hybrids. *Journal of Crop Breeding*, *14*(43), 49–63. https://doi.org/10.52547/jcb.14.43.49

Sefaoglu, F. (2019). Evaluation of yield and yield components of some sugar beet varieties (*Beta vulgaris* L.) in Erzurum ecological conditions. *Feb-Fresenius Environmental Bulletin*, *28*, 4903–4908.

Sefaoglu, F., Ozturk, H., Ozturk, E., Sezek, M., Toktay, Z., & Polat, T. (2021). Effect of organic and inorganic fertilizers or their combinations on yield and quality components of oilseed sunflower in a semi-arid environment. *Turk J Field Crops*, *26*(1), 88–95.

Seify, S. M., Madani, H., Pourdad, S. S., Nour-Mohammadi, G., & Changizi, M. (2023). Impact of deficit irrigation on the physiological and agronomic traits of 24 safflower (*Carthamus tinctorius* L.) genotypes grown in Iran. *Oilseeds and Fats Crops and Lipids (OCL)*, *30*, 27.

Sincik, M., & Canigenis, T. (2016). The effect of different nitrogen rates on root yield and quality of N and NZ type sugar beet verieties. *Open Access Journal of Agricultural Research*, *1*(1), 2474–8846.

Steel, R. G. D., & Torrie, J. H. (1980). *Principles and procedures of statistics: a biometrical approach* (2nd ed.). McGraw-Hill.

Swarup, S., Cargill, E. J., Crosby, K., Flagel, L., Kniskern, J., & Glenn, K. C. (2021). Genetic diversity is indispensable for plant breeding to improve crops. *Crop Science*, *61*(2), 839–852. https://doi.org/10.1002/csc2.20377

Taleghani, D., Rajabi, A., Hemayati, S. S., & Saremirad, A. (2022). Improvement and selection for drought-tolerant sugar beet (*Beta vulgaris* L.) pollinator lines. *Results in Engineering*, *13*, 100367. https://doi.org/10.1016/j.rineng.2022.100367

Taleghani, D., Rajabi, A., Saremirad, A., & Fasahat, P. (2023). Stability analysis and selection of sugar beet (*Beta vulgaris* L.) genotypes using AMMI, BLUP, GGE biplot and MTSI. *Scientific Reports*, *13*(1), 10019. https://doi.org/10.1038/s41598-023-37217-7

Taleghani, D., Rajabi, A., Saremirad, A., & Darabi, S. (2024). Estimation of gene action and genetic parameters of some quantitative and qualitative characteristics of sugar beet (*Beta vulgaris* L.) by line×tester analysis. *Crop Breed*, *15*, 201–212. https://doi.org/10.61186/jcb.15.48.201

Tosun, B., Karadogan, T., & Sanlı, A. (2019). Determination of yield and some quality traits of varied types of sugarbeet (*Beta vulgaris var. Saccharifera* L.) cultivars harvested at different times. *Süleyman Demirel University Journal of Natural and Applied Sciences*, *23*, 1–8. https://doi.org/10.19113/sdufenbed.430348

Turkseker (2025, June 25). 2023 Industry Report. https://www.turkseker.gov.tr/data/dokumanlar/Sektor_Raporu_2023.pdf

Ustuner, T., & Ozturk, E. (2018). Effect of dodder (*Cuscuta Campestris Yunc*.) on yield and quality in sugar beet (*Beta vulgaris* L.) cultivation. *Plant Protection Bulletin*, *58*(1), 32–40. https://doi.org/10.16955/bitkorb.360142

Voss-Fels, K. P., Stahl, A., & Hickey, L. T. (2019). Q&A: Modern crop breeding for future food security. *BMC Biology*, *17*(1), 18. https://doi.org/10.1186/s12915-019-0638-4

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

Yagmur, H., & Yasar, M. (2023). Investigation of yield and quality parameters of some sugar beet varieties in Muş ecological conditions. *International Journal of Agriculture Environment and Food Sciences*, *7*(2), 436–447. https://doi.org/10.31015/jaefs.2023.2.22

Yavas, I., & Ilker, E. (2020). Changes in photosynthesis and phytohormone levels in plants exposed to environmental stress conditions. *Journal of Bahri Dagdas Crop Research*, *9*(2), 295–311.

Yetik, A. K., & Candogan, B. N. (2022). Optimisation of irrigation strategy in sugar beet farming based on yield, quality, and water productivity. *Plant Soil and Environment*, *68*(8), 358–365. https://doi.org/10.17221/234/2022-PSE

Yildiz, U., Ozturk, E., Sefaoglu, F., Gul, V., & Toktay, Z. (2024). The effect of different storage duration periods after harvesting in a semi-arid environment on the quality components in sugar beet. *Turkish Journal of Field Crops*, *29*(2), 218–225. https://doi.org/10.17557/tjfc.1523530

Zhang, B., Chang, Y., Li, G., Zhang, S., Zhang, P., Wang, Z., & Kong, D. (2025). The effect of irrigation and fertilization reduction on yield, quality, and resource use efficiency of drip-fertilized sugar beet (*Beta vulgaris* L.) in Northern China. *Plants*, *14*(4), 536. https://doi.org/10.3390/plants14040536