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ANALYSIS OF VARIATION IN SOME MORPHOLOGIC AND YIELD RELATED TRAITS IN SOME SUGAR BEET GENOTYPES

Naser SABAGHNIA[1], Keiwan FOTOUHI[2], Masoumeh RAHIMPOUR[1], Hamid HATAMI MALEKI[1]

[1]University of Maragheh, Faculty of Agriculture, Department of Plant Production and Genetics, P.O. Box 55181-83111, Maragheh, Iran
[2]West Azarbaijan Agricultural and Natural Resources Research and Education Centre, Urmia, Iran

Corresponding author emails: sabaghnia@maragheh.ac.ir, sabaghnia@yahoo.com

Abstract

This research aimed to evaluate sugar beet (Beta vulgaris L.) genotypes in the cold semi-arid environment of northwestern Iran. Twenty sugar beet genotypes underwent assessment for yield performance and various quality traits. Parameters such as sugar content (SC), potassium amount (K), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), sodium content (NA), molasses sugar (MS), white sugar content (WSC), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY) were measured. The coefficient of variation ranged from 1.56% in ECS to 43.59% in RY. Factor analysis revealed that the first seven eigenvalues extracted explained 89% of the variation. Plotting the first three factors showed positive associations, such as CC with PH; ECS and SC with WSC; and PW, PL, LL, GU, and TS with AN. The three-dimensional biplot indicated that G4 exhibited high PH, CC, PW, PL, LL, and AN, while G3 showed high K, RY, MS, PNH, SD, and NA traits. Additionally, G11 demonstrated high ESC, SC, and WSC. The traits clustered into five groups, with the genotypes categorized into two clusters. Cluster-II (G3, G8, G18, and G19) emerged as the best group due to high root yield. To achieve higher yield, factors like growth uniformity, stem diameter, and tuber size must be considered, along with plant number at harvesting in sugar beet.

***Key words**: clustering, factor analysis, root yield, variation.*

INTRODUCTION

Milk Sugar beet is a crop cultivated worldwide for its economic significance in sugar production. The evaluation of various traits in sugar beet plays a crucial role in understanding the complex interplay between genotypes and their corresponding characteristics. This multifaceted assessment not only provides insights into the crop's adaptability to diverse environments but also serves as a foundation for genetic improvement programs. The optimization of traits such as root yield, sugar content, and morphological characteristics has become paramount for enhancing the crop's overall performance and economic viability (Fasahat et al., 2021). To achieve this, researchers employ advanced methodologies such as multivariate factor analysis and clustering techniques, which enable a holistic interpretation of the genotype-trait interactions. As sugar beet production expands beyond traditional regions, the evaluation of imported cultivars becomes imperative. The adaptability and performance of these cultivars in new environments, such as those in Iran, require cautious scrutiny so, understanding the correlations between traits like root yield, inorganic compound levels, and organic compounds is essential for optimizing sugar beet cultivation practices (Jalilian et al., 2017).

Sugar beet is cultivated on approximately 90 thousand hectares in Iran, yielding 5 million tons of roots. This crop plays a significant role in meeting 12% of the world's sugar demand and is predominantly distributed in Mediterranean regions. Understanding the genetic variation structure of morphological traits is crucial for breeding programs, especially in limited genetic base situations. The production of sugar beet holds economic importance, serving as a key raw material for sugar production in temperate climatic regions. In 2022, global sugar beet production reached 261 million tons across 20 million hectares, according to the FAOSTAT database. Although the harvesting area has decreased in the past three decades, the total root yield has remained relatively stable, thanks to the adoption of modern cultivars causing to increased yields. Notably, a significant portion of the world's sugar beet (approximately 53%) is produced by major players like the Russian Federation, France, the United States, and Germany. In Asia, China, Iran, and Japan are the leading producers (FAOSTAT, 2022). The cultivation of sugar beet in developing countries holds the potential for profitability among local producers. This expansion can diversify their income streams by encouraging the cultivation of another cash crop, so it contributes to the supply of raw materials for local factories (Abou-Elwafa et al., 2020).

Modern agriculture has led to a significant reduction in crop diversity. Out of approximately 30,000 identified edible plant species, only 30 have become the primary food sources for people worldwide. Maintaining genetic diversity in morphological characteristics is crucial for successful plant breeding. Without a sufficient amount of variability in plant material, progress in genetic improvement programs becomes unfeasible. It is therefore essential to ensure the preservation of an ample amount of variability so, the common practice of selecting the most favourable genotypes poses a risk of increasing genetic erosion (Singer et al., 2021). To address this concern, the evaluation of variability in plant materials has been employed. Breeders aim to maintain enough variability by investigating morphological traits and designing crossbreeding strategies. The study of morphological traits, although not necessarily unique to specific collection regions, can be observed simultaneously in distant germplasms. Recognizing genetic variation in plant materials and heritable traits is instrumental in making effective selections within plant breeding programs.

Several procedures utilizing morphological traits have been employed to analysing genetic variation and support the managing of germplasm. This approach aids in maintaining genetic diversity and ensuring the sustainability of plant breeding efforts (Salgotra & Chauhan, 2023). Sugar beet breeding heavily relies on the amount of genetic variation and the extent to which desirable traits can be transmitted. The primary goal of most genetic improvement programs for sugar beet is to develop cultivars that maximize yield while minimizing economic and environmental costs. Depending on environmental conditions, additional goals may include optimizing sugar yield, sugar extraction quality, seed germination potential, resistance to stem loss, and, notably, resistance to diseases - all of which are quantitative traits (McGrath & Panella, 2018). Improving quantitative traits involves intricate breeding programs compared to qualitative traits. Heritability plays a crucial role in predicting breeding outcomes, indicating the reliability of a phenotype as a guide to its breeding value. In a study by Nasri et al. (2012), a multiple regression model identified root dry weight, total fresh weight, leaf fresh weight, and ring fresh weight as the most influential traits for sugar beet, explaining about 99% of root yield variation. Leaf fresh weight was highlighted for its highest direct positive effect on root yield performance. Another study by Nabizadeh & Fotohi (2018) examined sugar beet genotypes under Rhizoctonia stress, clustering them into three groups and reported the second cluster stood out with superior scores in yellowness, uniformity, growth, number of healthy plants, root yield, percentage of gross sugar, percentage of pure sugar, extraction percentage, and yield of pure sugar. Quantitative traits pose challenges in selection programs because heritable variations are often obscured by non-heritable variations.

Heritability estimates become more useful when combined with genetic advance values expressed as a percentage of the mean (de Los Campos et al., 2015). Additionally, understanding how much of variation in individual plant characteristics is transmitted to the next generation is crucial for expediting population screening in breeding programs. The goal of this investigation study was to determine cultivars with high root yield and sugar yield.

MATERIALS AND METHODS

Trial

In this study, 20 sugar beet genotypes (Table 1) were investigated at Miandoab Agricultural Research Station (36°57′ N, 46°06′ E) situated in West Azarbaijan Province, Iran, at an altitude of 1314 meters. The location experienced an average annual rainfall of 290 mm, with minimum and maximum temperatures recorded at 5 and 20°C, respectively. Following routine tillage operations, the plant materials were sown in a randomized complete block design on eight-meter-long rows, with a 60 cm spacing between rows in six blocks.

Table 1. The pedigree of studied sugar beet genotypes

	Pedigree		Pedigree
1	(7112×SB36)×SB34-P.1	11	(7112×SB36)×31285-P1
2	(7112×SB36)×SB34-P.6	12	(7112×SB36)×31285-P5
3	(7112×SB36)×89003-P.5	13	(7112×SB36)×31285-P6
4	(7112×SB36)×89016-P.2	14	(7112×SB36)×31285-P10
5	(7112×SB36)×89016-P.3	15	(7112×SB36)×31285-P11
6	(7112×SB36)×89016-P.4	16	SBSI-1
7	(7112×SB36)×89029-P.1	17	SBSI-19
8	(7112×SB36)×89053-P.2	18	F-20704
9	(7112×SB36)×31283-P.6	19	F-20707
10	(7112×SB36)×31283-P.9	20	SBSI-4

Seeds were planted along the row at a distance of 17 cm and a depth of 3 to 4 cm. Initial seed placement on the rows exceeded the final desired density, and subsequent thinning occurred at the 2-4 leaf stage. Fertilizers, comprising 200 kg ha^{-1} of $(NH_4)_3PO_4$ and 250 kg ha^{-1} of nitrogen in urea form (half at planting time + half as top-dressing in the 4-6 leaf stage), were applied. Plant irrigation was conducted based on water requirements, and controlled using volumetric meters and related connections for all plots. Weed control in the field involved manual weeding at various stages and the application of herbicides.

Traits

Harvesting took place in late October, involving the counting and weighing in obtained roots of the plots. Subsequently, the roots were transferred to the laboratory, and various traits, including sugar content (SC), potassium amount (K), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), white sugar content (WSC), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), sodium content (NA), molasses sugar (MS), plant number at harvesting (PNH), and root yield (RY), were measured according to standard protocols.

Statistical analysis

The normal distribution of the data was assessed using the Ryan-Joiner goodness-of-fit test. Factor analysis was employed to decrease the associated traits to a restricted number of factors, and the extracted factor loadings were rotated using the varimax orthogonal method to better understand the data structure. Eigenvalues greater than unity were utilized for integration. To visually represent the associations among traits, the scores of the first three factors were plotted in a three-dimensional graph. For a simultaneous presentation of genotypes and traits in a single graph, a three-dimensional scatter plot was generated, creating a biplot graph that incorporates both genotype and trait signs. This biplot graph serves to illustrate the pattern of the data. In the final step, genotypes and traits were clustered based on their distances from each other using the Squared Euclidean Distance measure. The clustering was carried out through Ward's minimum variance clustering procedure.

The determination of the number of final clusters was verified using the lambda statistic of multivariate analysis of variance as the cutoff point. This comprehensive approach allowed for a thorough analysis and visualization of the relationships between genotypes and traits in the study.

RESULTS AND DISCUSSIONS

Descriptive statistics

The coefficient of variation (CV) for sugar beet characteristics ranged from 1.56% in the extraction coefficient of sugar (ECS) to 43.59% in root yield (RY), as indicated in Table 2. The table presents descriptive indices such as Mean, Min, Max, Range, and CV. Notably, plant number at harvesting (PNH) and sodium content (NA) exhibited high CV values, while sugar content (SC), potassium amount (K), white sugar content (WSC), ECS, and molasses sugar (MS) had low CV values (Table 2). The CV values for the remaining characteristics were relatively moderate. These findings align closely with the report of Romano et al. (2013), who identified a higher CV for sugar beet root (approximately 40%), indicating significant variation in root yield. Other sugar beet breeders, such as Hassani et al. (2018) and Bojović et al. (2019), have reported similar results, suggesting that traits interact with environmental factors and undergo gene expression processes.

Table 2. Some descriptive indices sugar beet traits

Traits†	Mean	Range	Min	Max	CV
SC	18.63	4.10	16.85	20.95	4.20
Na	1.18	1.37	0.68	2.05	25.45
K	5.14	1.74	4.24	5.98	6.15
AN	1.27	0.81	0.94	1.75	15.61
ALC	5.08	2.60	3.80	6.40	12.32
WSC	16.05	4.16	14.08	18.24	5.56
ECS	86.13	5.40	83.55	88.95	1.56
MS	1.98	0.84	1.56	2.40	8.72
GU	4.68	4.00	1.00	5.00	15.79
PNH	26.85	43.00	7.00	50.00	34.18
RY	24.05	55.73	3.65	59.38	43.59
CC	50.66	44.00	19.33	63.33	17.25
PH	45.86	50.34	15.66	66.00	21.82
PL	9.90	7.84	6.91	14.75	15.41
PW	18.24	19.59	11.91	31.50	18.49
LL	22.36	21.67	10.91	32.58	19.11
SD	9.23	5.74	6.32	12.06	13.21
TS	31.23	19.40	21.00	40.40	10.51

†Traits are: sugar content (SC), sodium content (NA), potassium amount (K), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), white sugar content (WSC), extraction coefficient of sugar (ECS), molasses sugar (MS), plant number at harvesting (PNH) and root yield (RY).

The impact of environmental factors varies with the traits assessed in the plant materials. This emphasizes the complex interplay between genetic and environmental influences on sugar beet traits.

Numerical factor analysis

The factor analysis revealed the extraction of the first seven eigenvalues (Table 3), employing the Varimax rotation method with Kaiser normalization. Communalities were examined to determine the proportion of each trait's variability explained by the extracted factors.

The first factor (F1), explaining about 30% of the variation, demonstrated a reverse correlation with sugar-related properties such as SC, WSC, and ECS, suggesting a focus on sugar and its extraction.

This factor can appropriately be named the sugar factor. The second factor (F2), explaining 14% of the variation, exhibited a negative correlation with potassium (K) and molasses sugar (MS) traits, leading to its designation as the molasses factor.

Table 3. The varimax rotated scores of factor analysis for sugar beet traits

Traits	F1	F2	F3	F4	F5	F6	F7	Communality
SC	-0.97	0.10	0.09	-0.13	0.01	0.01	-0.02	0.96
Na	0.46	-0.17	-0.14	-0.01	0.11	-0.06	0.01	0.78
K	0.17	-0.96	0.08	0.06	-0.08	0.15	0.01	0.94
AN	0.25	-0.35	-0.84	0.13	0.08	0.15	0.06	0.93
ALC	-0.05	-0.20	0.95	-0.12	-0.08	-0.13	-0.08	0.91
WSC	-0.94	0.25	0.10	-0.12	0.00	-0.02	-0.02	0.98
ECS	-0.70	0.60	0.12	-0.07	0.01	-0.07	-0.01	1.00
MS	0.39	-0.79	-0.11	0.05	0.02	0.09	0.01	0.98
GU	-0.14	0.07	0.09	0.21	0.22	-0.22	-0.01	0.88
PNH	-0.19	0.10	-0.10	-0.05	0.72	-0.15	-0.49	0.87
RY	0.11	0.02	-0.10	-0.13	0.93	0.09	0.03	0.82
CC	0.18	0.06	-0.11	0.85	-0.18	0.17	0.19	0.85
PH	0.18	-0.26	-0.21	0.80	-0.03	0.14	0.12	0.86
PL	0.15	-0.29	-0.09	0.18	-0.10	0.59	-0.23	0.92
PW	-0.02	-0.16	-0.22	0.17	0.05	0.93	0.06	0.83
LL	0.12	0.09	-0.05	0.19	0.01	0.03	-0.06	0.85
SD	0.01	-0.01	0.13	-0.19	0.08	0.01	-0.95	0.78
TS	0.04	0.13	0.05	0.09	0.20	0.14	-0.21	0.84
Eigenvalue	5.46	2.56	2.30	1.82	1.69	1.20	0.95	15.98
Proportion	0.30	0.14	0.13	0.10	0.09	0.07	0.05	---
Cumulative	0.30	0.45	0.57	0.67	0.77	0.84	0.89	0.89

Traits are: sugar content (SC), white sugar content (WSC), potassium amount (K), sodium content (NA), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), molasses sugar (MS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY).

The third factor (F3), contributing 13% to the variation, displayed a high negative score for alpha-amino nitrogen (AN) and a high positive score for the alkalinity coefficient (ALC). This factor can be denoted as the inhibitor of crystallized sucrose. The fourth factor (F4), contributing about 10% to the variability, showed a positive association with canopy cover (CC) and plant height (PH), followed by growth uniformity (GU) and lamina length (LL). Consequently, this factor can be termed the morphologic growth factor. The fifth factor (F5), accounting for approximately 9% of the variance, exhibited high scores for yield traits, plant number at harvesting (PNH), and root yield (RY), followed by tuber size (TS). This factor is aptly named the yield factor. The sixth factor (F6), contributing about 7% to the variation, displayed a positive association with petiole length (PL) and petiole width (PW), leading to its designation as the petiole factor.

The seventh factor (F7), accounting for approximately 5% of the variance, displayed high scores for stem diameter (SD) and PNH, resulting in its apt naming as the plant factor. Considering communalities, it can be inferred that the extracted factors describe the major portion of each trait's variability. Hu et al. (2019) conducted a similar analysis on fourteen sugar beet genotypes using principal components analysis, reporting a 92% contribution of the first four components, which categorized genotypes into four groups regarding quality.

Graphic factor analysis

The first three factors, as described in Table 3, collectively explained 57% of the variation. The associations among these factors can be understood by examining the distances of characteristics. The distance from the center of the plot indicates the bias of association, and the cosine of the characteristics' angle indicates the association coefficient. In Figure 1, canopy cover (CC) and plant height (PH) were positively associated and provided relatively similar information about the response of sugar beet genotypes. Additionally, the extraction coefficient of sugar (ECS), sugar content (SC), and white sugar content (WSC), as well as petiole width (PW), petiole length (PL), lamina length (LL), growth uniformity (GU), tuber size (TS), and alpha-amino nitrogen (AN), were positively associated. Potassium (K), root yield (RY), plant number at harvesting (PNH), stem diameter (SD), sodium content (NA), and molasses sugar (MS) were positively associated with each other due to the close angles among their signs (cos 0° = +1).

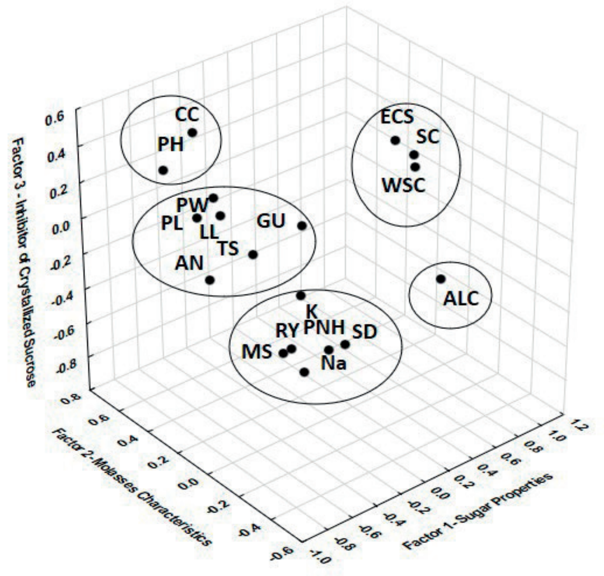

Figure 1. Three-dimensional plot of first three factors in sugar beet traits

Traits are: sugar content (SC), white sugar content (WSC), potassium amount (K), sodium content (NA), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), molasses sugar (MS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY).

In the study by Kiymaz & Ertek (2015), significant associations among sodium (Na), alpha-amino nitrogen, and root dry matter of sugar beet were observed. Right angles between lines represent no association (cos 90° = 0), such as alkalinity coefficient (ALC) with CC and PH. Opposite angles between lines represent negative associations (cos 180° = -1), like the group comprising ECS, SC, and WSC with the group comprising K, RY, PNH, SD, NA, and MS.

For a simultaneous assessment of genotypes and traits, a biplot - a scatter plot that benefits both genotypes and traits to display data patterns - was generated (Figure 2).

It showed that G4 produced high amounts of PH, CC, PW, PL, LL, and AN, while G3 exhibited high magnitudes of K, RY, MS, PNH, SD, and NA traits. G11 produced high amounts of ECS, SC, and WSC, suggesting that using G3 could result in obtaining higher yield, while G11 may generate sugar properties. A study by Abbasi et al. (2015) which evaluated 13 morphological characteristics of sugar beet in 168 genotypes, found similar associations for RY, PNH, AN, NA, MS, and K. Notably, this research identified a relation between SC and WSC, supporting the report of Tsialtas & Maslaris (2013), who found similar results in sugar beet.

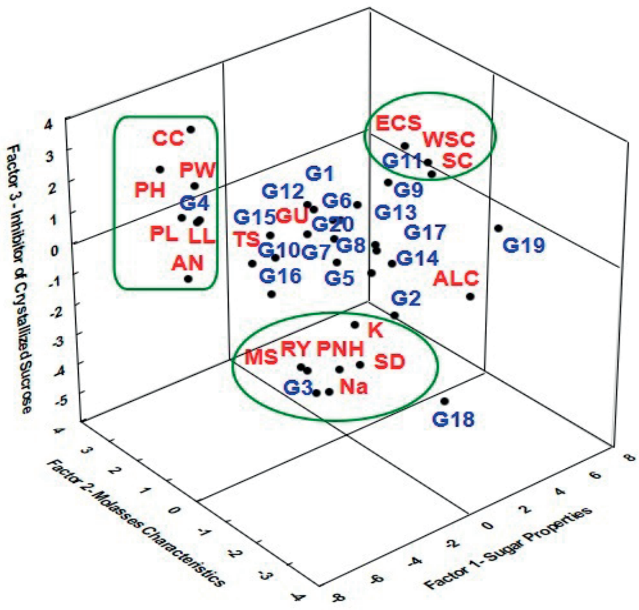

Figure 2. Three-dimensional biplot of first three factors for traits of sugar beet genotypes

Traits are: sugar content (SC), white sugar content (WSC), potassium amount (K), sodium content (NA), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), molasses sugar (MS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY).

Cluster analysis

To validate the obtained results of factor analysis, the cluster analysis was applied to group traits (Figure 3) and genotypes (Figure 4). The eighteen measured traits of sugar beet were grouped into five clusters, confirming the significance of Wilks' lambda obtained from MANOVA ($\lambda=0.0062$, $p<0.01$). I

n the dendrogram of Figure 3, Cluster-I comprised ECS, SC, and WSC traits, aligning with the results of Figure 1 or Figure 2. Cluster-II contained ALC, and Cluster-III included GU, PNH, RY, SD, and TS, indicating the importance of growth uniformity, stem diameter, and tuber size to achieve high root yield. Cluster-IV encompassed NA, AN, K, and MS traits, while Cluster-V included CC, PH, LL, PL, and PW traits.

Although, it is expected that most results of factor analysis and clustering align, some minor inconsistencies may arise because factor analysis typically describes less than 100% of the total variability.

In this study, the first three factors explained 56% of the variance, leaving 44% for the other factors. However, the overall results were in agreement with the clustering method, which utilized 100% of the variance.

Genotypes were categorized into two main clusters, verified by Wilks' lambda in MANOVA ($\lambda=0.0054$, $p<0.01$).

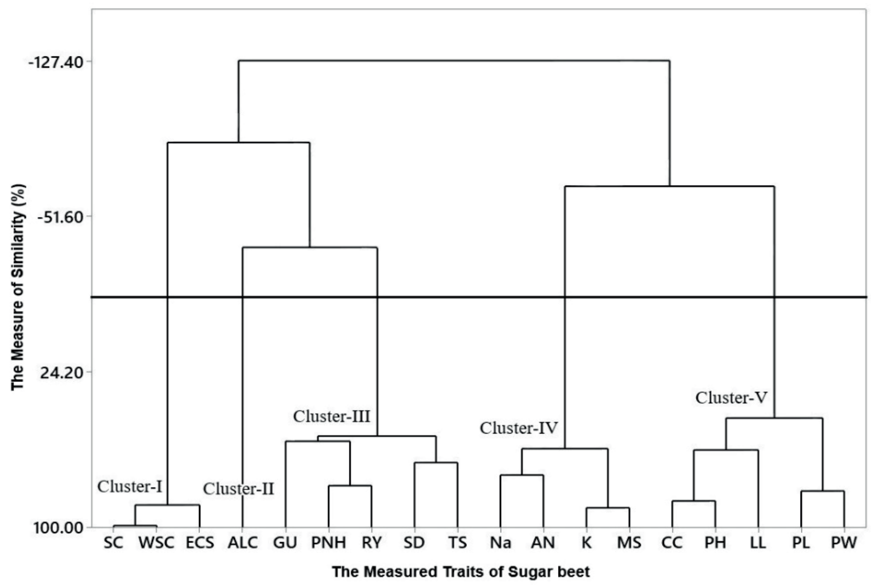

Figure 3. Tree plot of cluster analysis for measured traits of sugar beet

Traits are: sugar content (SC), white sugar content (WSC), potassium amount (K), sodium content (NA), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), molasses sugar (MS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY).

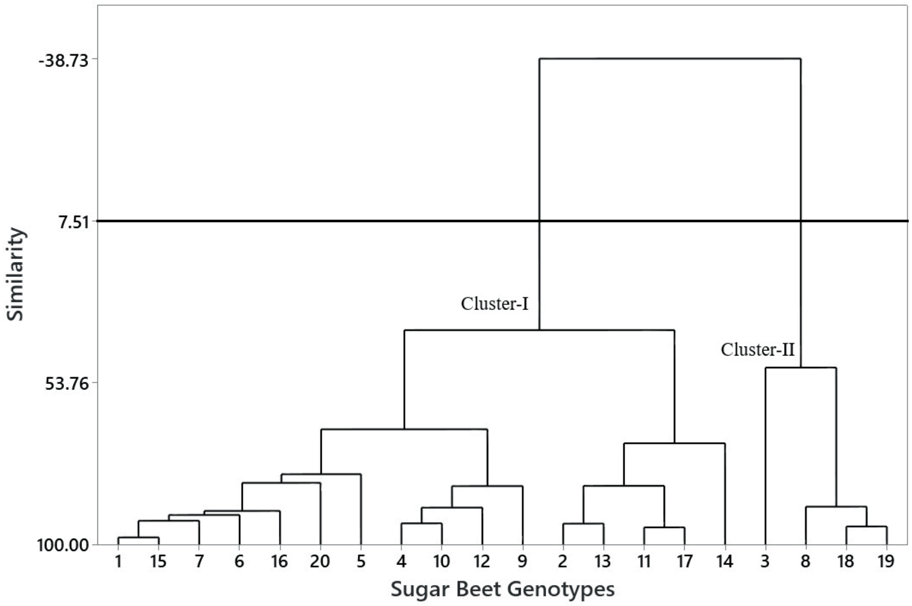

Figure 4. Tree plot of cluster analysis for twenty genotypes of sugar beet

In the dendrogram of Figure 4, Cluster-II included G3, G8, G18, and G19, forming the best group due to high root yield and plant number at harvesting (PNH). Cluster-I comprised the remaining genotypes with lower RY and PNH (Table 4).

Table 4. Means of sugar beet traits for two main clusters

Traits	Cluster-I	Cluster-II
SC	18.60	18.76
Na	1.18	1.17
K	5.14	5.12
AN	1.27	1.23
ALC	5.05	5.17
WSC	16.02	16.19
ECS	86.09	86.29
MS	1.98	1.96
GU	4.65	4.79
PNH	25.96	30.42
RY	23.40	26.63
CC	51.40	47.74
PH	46.93	41.56
PL	10.01	9.46
PW	18.46	17.37
LL	22.57	21.52
SD	9.12	9.65
TS	31.15	31.56

Traits are: sugar content (SC), white sugar content (WSC), potassium amount (K), sodium content (NA), alpha-amino nitrogen (AN), alkalinity coefficient (ALC), extraction coefficient of sugar (ECS), molasses sugar (MS), growth uniformity (GU), canopy cover (CC), plant height (cm) (PH), petiole length (PL), petiole width (PW), lamina length (LL), stem diameter (SD), tuber size (TS), plant number at harvesting (PNH), and root yield (RY).

Additionally, Cluster-I exhibited high values of CC and PH, while Cluster-II had lower values of these traits. Differences in AN, PL, PW, and LL were observed (higher in Cluster-I), as well as in ALC, GU, and SD (higher in Cluster-II). Unlike traits, the clustering of genotypes did not entirely corroborate the results of factor analysis in Figure 2. However, G3 and G18 in Cluster-II were identified as the best in most economic traits.

Sugar beet production is primarily concentrated in Europe, with lesser contributions from other regions like Asia. However, many improved sugar beet cultivars used in Iran are imported from the European countries. These cultivars are renowned for their high root yield and sucrose content, but their adaptability to the Iranian environment is not well-established. Assessment of these imported cultivars in Iran is crucial for providing the necessary materials for the genetic improvement of sugar beet (Hasanvandi et al., 2022). In this study, both used statistical methods, factor analysis and clustering, were employed to categorize sugar beet genotypes into clusters, revealing potential genetic relationships. The assessment of various traits in sugar beet indicated that potassium and sodium are related to root yield, while alpha-nitrogen is less associated with root yield. In terms of sugar production, potassium and sodium, as inorganic compounds, and alpha-nitrogen, as an organic compound, are non-sugar contents.

Lower content of these non-sugar compounds results in reduced ash content and waste, leading to lower production costs (Ghaffari et al., 2022). Considering food usage, genotypes with high potassium and low sodium contents could be beneficial for individuals with hypertension. However, the exact mechanism is not covered in this study and require further investigation to identify differences among sugar beet genotypes. The application of factor analysis and clustering tools simplifies the evaluation of genotypes and traits. Combining these tools can be valuable for selecting the best sugar beet genotypes and providing essential information for the genetic improvement of sugar beet in future projects. In summary, the discussion emphasizes the significance of trait variability, the influence of environmental factors on gene expression, and the associations observed in sugar beet traits across different studies. The use of advanced analytical techniques, such as biplot analysis, contributes to a comprehensive understanding of genotype-trait interactions in sugar beet cultivation. The incorporation of diverse studies provides a robust foundation for the discussion, reinforcing the validity and relevance of the findings.

CONCLUSIONS

The study identified G3, G8, G18, and G19 as the best sugar beet genotypes for most of the measured traits, making them suitable recommendations for farmers. The research highlights the efficacy of multivariate factor analysis and clustering as valuable methods for interpreting genotype × trait interaction types. To achieve higher yields, it is emphasized that considerations for growth uniformity, stem diameter, and tuber size should be taken into account, in addition to plant number at harvesting. Such findings contribute to the understanding of the complex relationships between genotypes and traits, providing practical insights for optimizing sugar beet cultivation and yield.

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REFERENCES

Abbasi, Z., Majidi, M. M., Arzani, A., Rajabi, A., Mashayekhi, P., & Bocianowski, J. (2015). Association of SSR markers and morpho-physiological traits associated with salinity tolerance in sugar beet (*Beta vulgaris* L.). *Euphytica, 205,* 785–797.

Abou-Elwafa, S. F., Amin, A. E. E. A., & Eujayl, I. (2020). Genetic diversity of sugar beet under heat stress and deficit irrigation. *Agronomy Journal, 112,* 3579–3590.

Bojović, R., Popović, V., Janković, S., Rajičić, V., Ikanović, J., Remiković, M. A., & Simić, D. (2019). Effect of genotype on morphological and quality features of sugar beet. *Agriculture and Forestry*, 65, 29–38.

de Los Campos, G., Sorensen, D., & Gianola, D. (2015). Genomic heritability:what is it?. *PLoS Genetics, 11,* e1005048.

***FAOSTAT (2022). Food and Agricultural Organization of the United Nations. http://faostat.fao.org [last accessed 11.8.2024].

Fasahat, P., Aghaeezadeh, M., Hosseinpour, M., & Sadeghzadeh-Hemayati, S. (2021). Correlation between root weight and sugar content; do we have to continue traditional hypothesis? *Plant Physiology Reports, 26,* 188–191.

Ghaffari, H., Tadayon, M. R., Bahador, M., & Razmjoo, J. (2022). Biochemical and yield response of sugar beet to drought stress and foliar application of vermicompost tea. *Plant Stress, 5,* 100087.

Hasanvandi, M. S., Hosseinpour, M., Rajabi, A., Mahmoudi, S. B., Taleghani, D. Sadeghzadeh, Hemayati, S., & Parmoon, G. (2022). Evaluation of new autumn sown sugar beet cultivars for quantitative and qualitative traits in Khuzestan province. *Journal of Crops Improvement, 24(4),* 1117–1132.

Hassani, M., Heidari, B., Dadkhodaie, A., & Stevanato, P. (2018). Genotype by environment interaction components underlying variations in root, sugar and white sugar yield in sugar beet (*Beta vulgaris* L.). *Euphytica, 214,* 79.

Hu, X. H., Jian-Zhou, C., & Hong-Yang, Z. (2019). Comprehensive evaluation of different sugar beet varieties by using principal component and cluster analyses. *Journal of Physics: Conference Series, 1176,* 042021.

Jalilian, M., Dehdari, M., Amiri-Fahliani, R., & Movahedi-Dehnovi, M. (2017). Study of cold tolerance of different sugar beet (*Beta vulgaris* L.) cultivars at seedling growth stage. *Environmental Stresses in Crop Sciences, 10(3),* 475–490.

Kiymaz, S., & Ertek, A. (2015). Yield and quality of sugar beet (*Beta vulgaris* L.) at different water and nitrogen levels under the climatic conditions of Kırsehir, Turkey. *Agricultural Water Management, 158,* 156–165.

McGrath, J. M., & Panella, L. (2018). Sugar beet breeding. *Plant Breeding Reviews, 42,* 167–218.

Nabizadeh, E., & Fotohi, K. (2018). Study of relationships among qualitative and quantitative traits in sugar beet genotypes infected with *rhizoctonia*. *Journal of Crop Breeding, 10,* 94–103.

Nasri, R., Kashani, A. S., Paknejad, F., & Ghorbani, M. S. S. (2012). Correlation and path analysis of yield and quality of sugar beet in both direct seeding and transplanting of saline lands. *Agriculture and Horticulture, 8,* 226–313.

Romano, A., Sorgona, A., Lupini, A., Araniti, F., Stevanato, P., Cacco, G., & Abenavoli, M. R. (2013). Morpho-physiological responses of sugar beet (*Beta vulgaris* L.) genotypes to drought stress. *Acta Physiologiae Plantarum, 35,* 853–865.

Salgotra, R. K., & Chauhan, B. S. (2023). Genetic diversity, conservation, and utilization of plant genetic resources. *Genes, 14,* 174.

Singer, S. D., Laurie, J. D., Bilichak, A., Kumar, S., & Singh, J. (2021). Genetic variation and unintended risk in the context of old and new breeding techniques. *Critical Reviews in Plant Sciences, 40,* 68–108.

Tsialtas, J. T., & Maslaris, N. (2013). Nitrogen effects on yield, quality and K/Na selectivity of sugar beets grown on clays under semi-arid, irrigated conditions. *International Journal of Plant Production, 7,* 355–372.