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Quantitative and Qualitative Characteristics of Bolting-Resistant Hybrids in Autumn-Sown Sugar Beet

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ABSTRACT

To evaluate new bolting-resistant sugar beet hybrids for quantitative and qualitative characteristics, and their susceptibility to Cercospora disease and resistance to bolting, an experiment was conducted in two regions of Iran: Dezful and Gachsaran, under autumn sowing conditions. The study involved fifteen bolting-resistant hybrid varieties and five check varieties. The experiment was designed as a randomized complete block design. Due to non-homogeneity of variances across environments, analyses were conducted separately for each location, based on Bartlett's test. The mean comparison indicated that hybrid G13 exhibited the highest white sugar yield in the Dezful environment, with an output of 9.00 tons ha^{-1}. Similarly, hybrid G7 achieved the highest yield in the Gachsaran environment, producing 12.90 tons ha^{-1}, outperforming other hybrids. Cluster analysis in Dezful revealed that the third cluster, which includes genotypes G13 and G14, was the best based on studied traits. In contrast, cluster five was the best in the Gachsaran environment. This cluster comprises eight genotypes: G1, G2, G6, G7, G10, G11, G12, and G14. Additionally, the biplot analysis conducted in Dezful identified G13 and G8 as the top-performing hybrids. Biplot analysis indicated that among the hybrids studied, G7, G6, G11, G3, G9, and G5 exhibited more favorable traits compared to the other hybrids in the Gachsaran environment. Overall, the results identified hybrids G13 (SC(990014 × 990008) × S1-990002) and G8 (SC(990019 × 990007) as superior due to their higher quantitative and qualitative yields and reduced susceptibility to Cercospora disease in the Dezful environment. Similarly, hybrids G7 (SC(990015 × 990007) × S1-990002), G6 (SC(990014 × 990007) × S1-990002), and G11 (SC(990023 × 990007) × S1-990002) were recognized as superior in the Gachsaran environment, thanks to their favorable quantitative and qualitative yields and lower bolting percentages compared to the other hybrids. Therefore, selected hybrids were introduced to develop bolting-resistant varieties.

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1. Introduction

Sugar beet (*Beta vulgaris* L.) is an important agricultural and industrial plant, mainly used in the sugar industry (Akyüz and Ersus, 2021) and is considered one of the most important sources of sugar production in the world after sugarcane (Monteiro *et al*., 2018). It is estimated that about 20 to 30 percent of global sugar production comes from sugar beet (Ribeiro *et al*., 2016; Kuska *et al*., 2020; Sarica, 2024). Sugar beet is the main source of sugar production in Iran, and approximately 60 percent of the country's sugar production comes from this plant and the rest from sugarcane. In 2023, the sugar beet harvest area was reported to be 106,763 hectares from 12 provinces of the country, of which 82,430 hectares were spring-sown and 24,333 hectares were autumn-sown (SBSI, 2023). Cultivating sugar beet in the spring, when most of its growth occurs during the hot summer months, leads to increased water consumption. Additionally, irrigating sugar beet during the summer heat results in significant water loss due to evaporation. This increased water demand in regions experiencing water scarcity can create challenges, and in severe cases, may even lead to the abandonment of cultivating this

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economically and strategically important crop. To address these issues, autumn sowing of sugar beet has been proposed for several reasons. Firstly, it can help mitigate water problems and reduce overall water consumption. Secondly, the crop exhibits higher water-use efficiency during its growth period, which coincides with seasonal rainfall. Lastly, autumn sowing ensures a steady supply of sugar in areas where cultivation is feasible (Mansouri, 2025).

In autumn-sown sugar beet, the plant's water requirements are lower due to the cooler temperatures during its growth period compared to spring-sown. Additionally, the primary water supply for sugar beet comes from autumn and winter rainfall. As a result, water use efficiency is enhanced, and the damage caused by drought stress during the growth period is minimized (Taleghani *et al*., 2011). Besides improving water use efficiency, another advantage of autumn sowing is the natural control of various pests and diseases, including viral infections, powdery mildew, and nematodes. Despite the advantages and benefits of autumn-sown sugar beet over spring-sown, bolting remains a significant limitation for autumn planting. In the relatively mild climate of Mediterranean countries, autumn-sown sugar beet can often be cultivated without experiencing bolting (Metzger *et al*., 2005; Schnepel and Hoffmann, 2016). However, in regions like Central Europe, autumn cultivation subjects the plants to winter cold. When the plants are exposed to low temperatures in winter, it leads to vernalization (Schnepel and Hoffmann, 2016). This is followed by long-day conditions in spring, which trigger the production of flowering stems and induce flowering in the plants (Milford *et al*., 2010). The transition from the vegetative phase to the reproductive phase interrupts the storage of photosynthetic materials in the roots (Milford and Limb, 2008), resulting in reduced sugar content and sugar yield (Hoffmann and Kluge-Severin, 2011). The impact of bolting can vary based on the growth stage of the plants, with early bolting during the growth period potentially leading to a significant reduction in root yield of up to 50% (Hoffmann and Kluge-Severin, 2011). Generally, bolting produces sugar beet with a high percentage of stem tissue and low amounts of root tissue (Hoffmann and Kluge-Severin, 2011). As a result, bolted plants are unsuitable for sugar production (Reinsdorf *et al*., 2014). Therefore, it is essential to develop and breed sugar beet genotypes that are resistant to bolting, while also ensuring high quantitative and qualitative yields in autumn-sown. Consequently, this study aimed to investigate the quantitative and qualitative traits of various bolting-resistant sugar beet hybrids.

2. Materials and methods

In this study, fifteen bolting-resistant single-cross lines were developed after conducting a qualitative screening of the O-type (Male sterility maintainer line) lines in the Sugar Beet Seed Institute (SBSI). These lines were then crossed with a bolting-resistant pollinator line, designated S1-990002, resulting in the creation of fifteen new hybrid lines (Table 1).

Table 1. The origin of bolting-resistant hybrids and checks in the experiment

Genotype	Origin	Genotype	Origin
G1	SC(990015 × 990006) × S1-990002	G11	SC(990023 × 990007) × S1-990002
G2	SC(990019 × 990006) × S1-990002	G12	SC(990029 × 990007) × S1-990002
G3	SC(990020 × 990006) × S1-990002	G13	SC(990014 × 990008) × S1-990002
G4	SC(990022 × 990006) × S1-990002	G14	SC(990015 × 990008) × S1-990002
G5	SC(990023 × 990006) × S1-990002	G15	SC(990029 × 990014) × S1-990002
G6	SC(990014 × 990007) × S1-990002	Check1	SBSI - 12 (SHR01-P.12, SBSI, Iran)
G7	SC(990015 × 990007) × S1-990002	Check2	Homa (SBSI, Iran)
G8	SC(990019 × 990007) × S1-990002	Check3	Antek (STRUBE, Germany)
G9	SC(990020 × 990007) × S1-990002	Check4	Rosagold (Kuhn & Co, Belgium)
G10	SC(990022 × 990007) × S1-990002	Check5	Monatunno (Syngenta, Switzerland)

To accomplish this, in March 2023, we transferred winter-vernalized stecklings of the pollinator line along with the single-cross lines to isolated plots (15 isolates) in Ekbatan station of Hamedan, where the crosses were conducted. In these plots, the pollinator line, serving as the paternal line, was planted in two rows on the sides, while the single-cross lines, serving as the maternal lines, were planted in four rows in the center of the isolated plot. Each row was four meters long, with a distance of 60 cm between the rows. In late July 2023, hybrid seeds were harvested from the maternal lines. The hybrids developed in this study, along with a

domestic bolting-resistant check variety (Homa), a bolting-sensitive check variety (SBSI12), and three foreign bolting-resistant check varieties (Rosagold, Antek, and Monatunno), were evaluated in an experiment designed as a randomized complete block design. This experiment included four replications and was conducted in two regions of Iran: Dezful and Gachsaran, under autumn planting conditions.

The experimental cultivation took place in Dezful on September 21 and in Gachsaran on October 2, 2023. The Gachsaran region experiences a slightly cooler climate in winter compared to the Dezful region. To minimize the risk of bolting, planting in Gachsaran is typically conducted a few days later than in Dezful. Each experimental plot measured 8 meters in length and consisted of three rows with a spacing of 60 cm between the rows. Irrigation and all agricultural operations, including planting, tilling, and harvesting of the sugar beet, were conducted according to local practices, at the appropriate levels and on the scheduled dates. Data collection involved counting the number of established plants before and after the frost period, determining the number of bolted plants in early June, and calculating the bolting percentage based on the total number of plants. Due to the absence of bolting in Dezful, this evaluation was limited to Gachsaran. In Dezful, Cercospora leaf spot disease poses a significant concern, so the severity of infection caused by this disease was assessed while evaluating different sugar beet genotypes. The severity of leaf infection with Cercospora leaf spot disease was recorded on a scale from 1 to 9 in Dezful. A score of 1 indicates no infection in the plant, whereas a score of 9 signifies that the plant is fully infected.

During the harvesting season, we removed half a meter from both the top and bottom of each plot to create a margin. The roots from all three planting lines of each plot were then harvested to assess root yield and prepare the pulp. Each plot's pulp sample, which included all the roots from the middle planting line, was analyzed in the Sugar Technology Laboratory of the Sugar Beet Seed Institute. We measured various quality traits, including sugar content (SC, %), sodium (Na, meq.100 g^{-1} pulp), potassium (K, meq.100 g^{-1} pulp) and nitrogen (N, meq.100 g^{-1} pulp) concentrations. The characteristics assessed included white sugar content (WSC, %), alkalinity ratio (Alc), molasses sugar (MS, %), sugar yield (SY, $t.ha^{-1}$), white sugar yield (WSY, $t.ha^{-1}$), and the extraction coefficient of sugar (ECS, %), all determined using Equations 1–6 following Taleghani et al. (2024).

$$Alc = \frac{(Na + K)}{N} \quad (1)$$

$$MS = 0.343 \times (K + Na) + 0.094 \times (N) - 0.31 \quad (2)$$

$$WSC = SC - (MS + 0.6) \quad (3)$$

$$SY = RY \times SC \quad (4)$$

$$WSY = RY \times WSC \quad (5)$$

$$ECS = \left(\frac{WSC}{SC}\right) \times 100 \quad (6)$$

To conduct a combined analysis, we first performed Bartlett's test to assess the homogeneity of variance across environments for different traits. To determine whether there were differences among the hybrids regarding the traits studied, we utilized a two-way analysis of variance (ANOVA) within a randomized complete block design, consisting of four replications. The means of the hybrids were compared using the least significant difference (LSD) test. To group the hybrids, we employed cluster analysis based on Euclidean distance using the Ward method (Hamzeh *et al.*, 2024). In addition, the principal component analysis (PCA) method was used to reduce the number of variables in the dataset to a limited set of principal components (PCs), effectively summarizing the information. A biplot analysis was performed based on the PCA to illustrate the relationships between the selected PCs and various hybrids.

3. Results and discussion

To obtain bolting-resistant varieties, evaluations should be conducted in environments with similar climates since the environment significantly affects the rate of bolting. On the other hand, studies have indicated that different sugar beet genotypes exhibit varying levels of bolting resistance (Ghasemi *et al.*, 2020; Taleghani *et al.*, 2022). Accordingly, before introducing new genotypes, a preliminary evaluation is conducted across various genotypes in different regions. The selection and screening of genotypes for introduction in these regions are based on their initial responses to

bolting resistance observed during preliminary experiments. Considering that the Dezful and Gachsaran regions have similar climates, we evaluated new hybrids in these two areas using genotypes that were chosen based on the results of preliminary experiments. In other words, the genotypes assessed in Dezful and Gachsaran differ from those evaluated in other autumn cultivation regions. Consequently, the environments for evaluating these genotypes were limited to the Dezful and Gachsaran regions.

3.1. Variance analysis and mean comparison

The result of Bartlett's test indicated the non-homogeneity of the variances for two environments ($p < 0.05$) in all measured traits of sugar beet (Table 2). Therefore, combined analysis was not feasible, and all analyses were performed separately for each environment. The results of ANOVA in the Dezful environment showed that the effect of genotype was significant in all studied traits of sugar beet (p-value < 0.05, Table 3).

Table 2. Bartlett's test for variance homogeneity of the measured traits of sugar beet versus environment

	RY	SC	SY	Na	K	N	Alc	WSC	WSY	ECS	Ms
Chi-square	37.57	21.62	68.36	39.59	8.98	4.93	67.89	24.68	70.99	29.59	18.38
p-value	<0.001	<0.001	<0.001	<0.001	<0.003	<0.026	<0.001	<0.001	<0.001	<0.001	<0.001

p-value < 0.05, indicating non-homogeneity of variance.

Table 3. Variance analysis (ANOVA) for the quantitative and qualitative traits of autumn-sown sugar beet at Dezful environment

Traits	S.O.V			CV (%)
	Block (df=3)	Genotype (df=19)	Error (df=57)	
RY	276**	123**	25.1	7.01
SC	0.80^{ns}	1.39**	0.29	4.03
SY	4.18**	2.52**	0.44	6.98
Na	2.97**	0.37*	0.21	16.1
K	3.83**	0.16*	0.08	6.84
N	5.54**	2.48**	0.38	11.8
Alc	0.58**	0.16**	0.02	12.2
WSC	1.07^{ns}	2.30**	0.46	6.44
WSY	3.90**	2.25**	0.35	7.91
ECS	24.1**	20.7**	5.26	2.91
Ms	0.46**	0.15**	0.05	10.2
Cercos	0.48*	3.45**	0.13	9.22

ns, * and **: non-significant, significant at the 1% and 5% probability level, respectively. Cercos: Cercospora score.

A comparison of the mean root yield between genotypes in the Dezful environment revealed that most hybrids outperformed the check yield. The highest root yield was recorded for hybrid G13, with a yield of 83.8 tons per hectare, while the lowest yield was from hybrid G2, at 66.08 tons per hectare. When comparing these hybrids to the domestic cultivar Homa, it was found that, except for hybrids G2, G3, and G5, all other hybrids had higher root yields than Homa (Table 4). All the hybrids studied had lower sugar and white sugar contents compared to the foreign check group. The hybrid that exhibited the highest values in these traits among other hybrids was hybrid G8, which had sugar and white sugar contents of 13.76% and 11.2%, respectively (Table 4). In terms of sugar yield and white sugar yield, hybrid G13 outperformed the others, achieving a sugar yield of 11.28 tons per hectare and a white sugar yield of 9 tons per hectare. Additionally, hybrid G8 also performed well, with a sugar yield of 10.12 tons per hectare and a white sugar yield of 8.23 tons per hectare. Hybrid G13 produced higher sugar yield and white sugar yield than Antek, the top foreign check variety. Overall, hybrid G13 (SC(990014 × 990008) × S1-990002) exhibited the highest sugar yield and white sugar yield compared to all other hybrids and checks. Additionally, this hybrid recorded the lowest Cercospora score, indicating the least amount of Cercospora infection (Table 4). Therefore, hybrid G13 can be considered the best option for the Dezful environment in the experiment. The analysis of variance results in the Gachsaran environment indicated that the genotype had a significant effect on all studied traits of sugar beet (p-value < 0.05, Table 5).

A comparison of the mean hybrid yields in the Gachsaran environment indicated that the root yields of all the hybrids were lower than those of the foreign check varieties. Among the hybrids, G6, G7, G8, and G11 exhibited higher root yields compared to the others (Table 6). The highest sugar content and white sugar content were found in the foreign check variety Antek, which had values of 16.66% and 13.85%, respectively. Among the hybrids, G3, G7, and G13 recorded the highest sugar contents at 12.36%, 12.39%, and 12.48%, respectively, with corresponding white sugar contents of 15.95%, 15.76%, and 15.75%. Among the hybrids studied, hybrids G6, G7, and G11 exhibited the highest values for both sugar yield and white sugar yield. Additionally, these three hybrids had a bolting rate of less than 1% (Table 6).

Table 4. Mean comparison of different sugar beet genotypes in terms of quantitative and qualitative characteristics in the Dezful environment

Genotype	RY (t ha^{-1})	SC (%)	SY (t ha^{-1})	Na (meq g^{-1})	K (meq g^{-1})	N (meq g^{-1})	Alc	WSC (%)	WSY (t ha^{-1})	ECS (%)	Ms (%)	Cercos
G1	73.21	13.46	9.84	1.71	4.44	6.01	1.04	10.50	7.67	77.95	2.36	4.00
G2	66.08	13.50	8.89	1.75	4.40	5.12	1.22	10.62	6.98	78.63	2.28	3.88
G3	67.65	13.48	9.08	1.71	4.23	6.02	0.99	10.58	7.13	78.47	2.30	3.50
G4	70.87	12.71	9.00	2.06	3.89	6.41	0.93	9.78	6.91	76.93	2.33	3.75
G5	67.26	13.59	9.15	1.54	4.25	5.52	1.06	10.80	7.27	79.26	2.19	4.00
G6	75.31	13.10	9.86	1.91	4.25	5.11	1.23	10.22	7.69	77.94	2.28	3.75
G7	72.70	13.68	9.94	1.57	4.36	5.53	1.11	10.84	7.88	79.21	2.24	3.25
G8	73.60	**13.76**	**10.12**	1.37	3.92	4.96	1.11	**11.20**	**8.23**	81.28	1.97	3.50
G9	72.06	13.33	9.60	1.97	4.32	5.27	1.20	10.38	7.48	77.90	2.34	4.13
G10	72.65	13.15	9.56	1.74	4.17	5.34	1.13	10.33	7.52	78.54	2.22	3.50
G11	71.91	13.28	9.57	1.31	4.17	5.19	1.10	10.62	7.67	79.95	2.06	3.75
G12	69.90	13.13	9.17	2.21	4.28	6.33	1.07	10.02	7.00	76.29	2.51	3.88
G13	**83.80**	13.48	**11.28**	1.68	4.10	4.88	1.20	10.74	**9.00**	80.65	2.13	2.25
G14	82.07	12.94	10.62	2.07	4.59	5.49	1.22	9.85	8.08	76.07	2.49	3.25
G15	75.21	13.30	9.99	1.77	4.29	5.82	1.04	10.38	7.80	77.96	2.32	3.13
SBSI-12	67.86	12.10	8.20	2.53	4.46	5.21	1.35	8.93	6.05	73.76	2.57	3.75
Homa	69.73	12.78	8.89	1.96	4.26	4.73	1.32	9.91	6.90	77.38	2.27	3.75
Antek	72.52	14.78	10.71	1.52	3.87	2.93	1.88	12.36	8.96	83.60	1.81	5.38
Rosagold	64.93	14.59	9.47	1.41	3.93	4.00	1.35	12.09	7.84	82.86	1.90	6.88
Monatunno	58.88	13.56	7.96	2.04	4.02	4.90	1.26	10.74	6.28	79.10	2.23	4.63
LSD5%	7.09	0.76	0.94	0.66	0.41	0.88	0.21	0.96	0.84	3.25	0.32	0.51
LSD1%	9.44	1.02	1.26	0.88	0.54	1.17	0.27	1.28	1.12	4.32	0.43	0.68

Cercos: Cercospora score.

Table 5. Variance analysis (ANOVA) for the quantitative and qualitative traits of autumn sugar beet at the Gachsaran environment

Traits	S.O.V			CV (%)
	Block (df=3)	Genotype (df=19)	Error (df=57)	
RY	265^{ns}	582**	132	11.6
SC	2.14^{ns}	4.20**	0.82	6.01
SY	15.02**	22.3**	3.18	11.8
Na	0.54^{ns}	4.26**	0.75	16.4
K	0.52*	1.47**	0.15	7.32
N	1.02^{ns}	1.17**	0.46	18.7
Alc	0.26^{ns}	1.82**	0.15	15.6
WSC	2.60^{ns}	7.69**	1.36	10.2
WSY	11.3**	20.6**	2.68	14.2
ECS	18.3^{ns}	97.2**	14.3	5.00
Ms	0.14^{ns}	0.62**	0.12	11.8
Bolting	0.19^{ns}	17.8**	0.69	21.3

ns, * and **: non-significant, significant at the 1% and 5% probability level, respectively.

Therefore, they can be regarded as superior hybrids for introduction in the Gachsaran environment. Hybrid G7 (SC(990015 × 990007) × S1-990002), which produced a white sugar yield of 12.9 tons per hectare and had a bolting rate of 0%, was identified as the best hybrid in the Gachsaran environment during this experiment. This hybrid outperformed the domestic check variety Homa, which yielded 11.2 tons per hectare, and the foreign check variety Monatunno, which yielded 12.53 tons per hectare. Only two foreign varieties, Antek and Rosagold, had higher white sugar yields G7, at 15.38 tons and 16.02 tons per hectare, respectively (Table 6).

3.2. Cluster analysis

Fig. 1 illustrates the dendrogram of the heat map resulting from the cluster analysis of sugar beet genotypes, along with the quantitative and qualitative traits studied in the Dezful environment. The cluster analysis revealed that the genotypes in the Dezful environment can be categorized into four distinct groups (Fig. 1). Additionally, the analysis of variance indicated significant differences among these groups regarding root yield, sugar content, sugar yield, white sugar content, extraction coefficient of sugar, and level of Cercospora infection (Table 7).

In the first cluster, there were only two foreign check varieties, Rosagold and Monatunno, which had higher sugar content, white sugar content, extraction coefficient of sugar, and Cercospora infection than the other three clusters, as well as the average of the total clusters. The second cluster included three genotypes, G2, G3, and G5, along with the foreign check variety Antek. In the third cluster, two genotypes, G13 and G14, were grouped. The genotypes in this cluster exhibited the highest root yield and sugar yield, along with the lowest infection rate of Cercospora among other clusters (Fig. 1 and Table 7). Therefore, based on

the results of the cluster analysis conducted in the Dezful environment, the third cluster, which includes genotypes G13 and G14, was identified as the best cluster based on the traits studied. In a study conducted in the Lorestan environment, Sadeghzadeh Hemayati et al. (2024) classified 12 sugar beet cultivars into five groups based on their quantitative and qualitative characteristics using cluster analysis. In a separate study, 44 sugar beet hybrids, along with three commercial cultivars, were also grouped into four clusters through cluster analysis in Hamedan. The fourth cluster, which included seven hybrids (No. 20, 23, 24, 25, 31, 37, and 43) along with two foreign cultivars, Sakara and BTS 213, was identified as the best cluster in terms of both quantitative and qualitative characteristics (Hassani *et al*., 2021).

Table 6. Mean comparison of different sugar beet genotypes in terms of quantitative and qualitative characteristics in Gachsaran environment

Genotype	RY (t ha^{-1})	SC (%)	SY (t ha^{-1})	Na (meq g^{-1})	K (meq g^{-1})	N (meq g^{-1})	Alc	WSC (%)	WSY (t ha^{-1})	ECS (%)	Ms (%)	bolting (%)
G1	99.01	14.99	14.87	3.28	5.43	4.27	2.09	11.31	11.23	75.37	3.08	0.81
G2	98.57	14.89	14.64	2.81	6.19	3.74	2.42	11.16	10.95	74.88	3.13	0.59
G3	97.75	**15.95**	15.53	2.65	5.97	3.67	2.38	12.36	11.99	77.30	2.99	0.30
G4	95.49	14.94	14.18	3.28	5.57	3.92	2.31	11.24	10.63	75.14	3.10	0.00
G5	96.04	15.44	14.84	2.52	5.62	3.46	2.41	12.03	11.57	77.92	2.81	0.00
G6	**103.83**	15.55	**16.15**	2.52	5.62	4.50	1.84	12.05	**12.53**	77.46	2.90	0.93
G7	**103.31**	**15.76**	**16.36**	2.46	5.55	3.59	2.23	**12.39**	**12.90**	78.36	2.78	**0.00**
G8	**105.98**	14.80	15.64	3.58	5.36	4.08	2.26	11.06	11.66	74.61	3.14	4.41
G9	95.77	15.53	14.81	2.44	5.62	3.61	2.36	12.14	11.57	78.04	2.79	2.00
G10	100.31	15.04	14.89	3.16	5.66	3.72	2.41	11.37	11.19	75.44	3.07	0.60
G11	**105.29**	15.45	**16.27**	2.66	5.95	3.99	2.31	11.84	**12.46**	76.51	3.02	0.34
G12	101.78	14.83	15.10	3.40	5.65	3.86	2.38	11.07	11.27	74.66	3.16	0.73
G13	82.75	**15.75**	13.02	2.95	4.73	3.68	2.18	12.48	10.34	79.23	2.67	4.49
G14	100.85	14.25	14.37	3.50	5.70	3.93	2.36	10.44	10.52	73.22	3.21	0.77
G15	82.62	15.41	12.72	3.53	5.75	4.19	2.24	11.55	9.52	74.82	3.27	1.51
SBSI-12	66.91	11.49	7.65	6.99	5.44	2.42	5.15	6.71	4.45	57.85	4.18	93.61
Homa	105.74	14.23	15.14	4.68	4.65	3.11	3.06	10.44	11.20	72.51	3.19	6.11
Antek	110.62	16.66	18.47	2.79	3.93	2.40	2.80	13.85	15.38	83.03	2.22	0.00
Rosagold	125.27	15.68	19.68	2.72	4.06	3.21	2.12	12.76	16.02	81.38	2.32	0.28
Monatunno	111.68	14.74	16.44	3.49	4.91	3.41	2.54	11.25	12.53	76.17	2.89	0.00
LSD5%	16.32	1.28	2.52	1.22	0.55	0.96	0.55	1.65	2.32	5.36	0.50	3.45
LSD1%	21.72	1.71	3.36	1.63	0.74	1.28	0.73	2.19	3.08	7.14	0.67	4.59

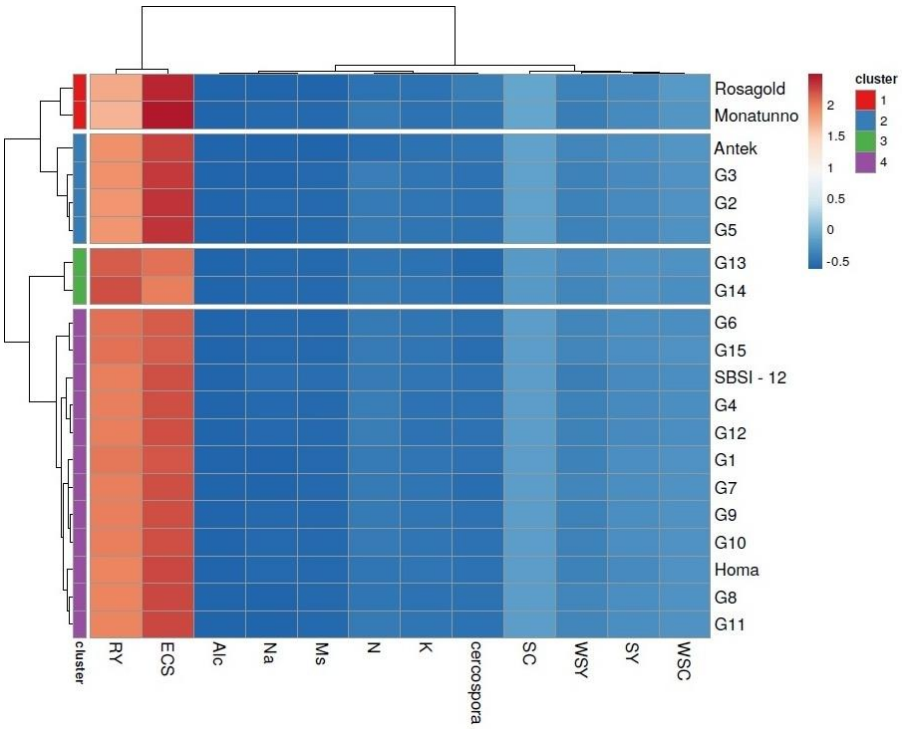


Figure 1. Heat map dendrogram of cluster analysis for sugar beet genotypes and their quantitative and qualitative characteristics in Dezful

Table 7. Variance analysis and Mean comparison of clusters in terms of quantitative and qualitative characteristics in Dezful

	df	RY	SC	SY	Na	K	N	Alc	WSC	WSY	ECS	Ms	Cercos
Inter groups	3	162**	0.84*	1.80*	0.05^{ns}	0.05^{ns}	0.83^{ns}	0.03^{ns}	1.37*	0.89^{ns}	18.2*	0.04^{ns}	3.48**
Intra groups	16	6.13	0.25	0.43	0.10	0.04	0.58	0.04	0.44	0.50	4.62	0.03	0.37
Cluster 1	-	61.9^{d}	14.1^{a}	8.71^{b}	1.72^{a}	3.97^{a}	4.45^{a}	1.30^{a}	11.4^{a}	7.06^{a}	80.9^{a}	2.06^{a}	5.75^{a}
Cluster 2	-	68.4^{c}	13.8^{ab}	9.46^{b}	1.63^{a}	4.19^{a}	4.89^{a}	1.29^{a}	11.1^{ab}	7.58^{a}	79.9^{ab}	2.14^{a}	4.19^{b}
Cluster 3	-	82.9^{a}	13.2^{b}	10.9^{a}	1.87^{a}	4.34^{a}	5.18^{a}	1.21^{a}	10.3^{b}	8.54^{a}	78.4^{bc}	2.31^{a}	2.75^{c}
Cluster 4	-	72.1^{b}	13.1^{b}	9.48^{b}	1.84^{a}	4.23^{a}	5.49^{a}	1.36^{a}	10.2^{b}	7.40^{a}	77.9^{c}	2.29^{a}	3.68^{b}
Mean	-	71.3	13.6	9.65	1.77	4.18	5.00	1.23	10.8	7.65	79.3	2.20	4.09

ns, * and **: non-significant, significant at the 1% and 5% probability level, respectively.

Cluster analysis of sugar beet genotypes based on quantitative and qualitative traits in the Gachsaran environment also showed that the genotypes were classified into five groups (Fig. 2). Analysis of variance in terms of the studied characteristics showed that there was a significant difference between the groups in terms of all traits except for potassium and nitrogen concentration (Table 8).

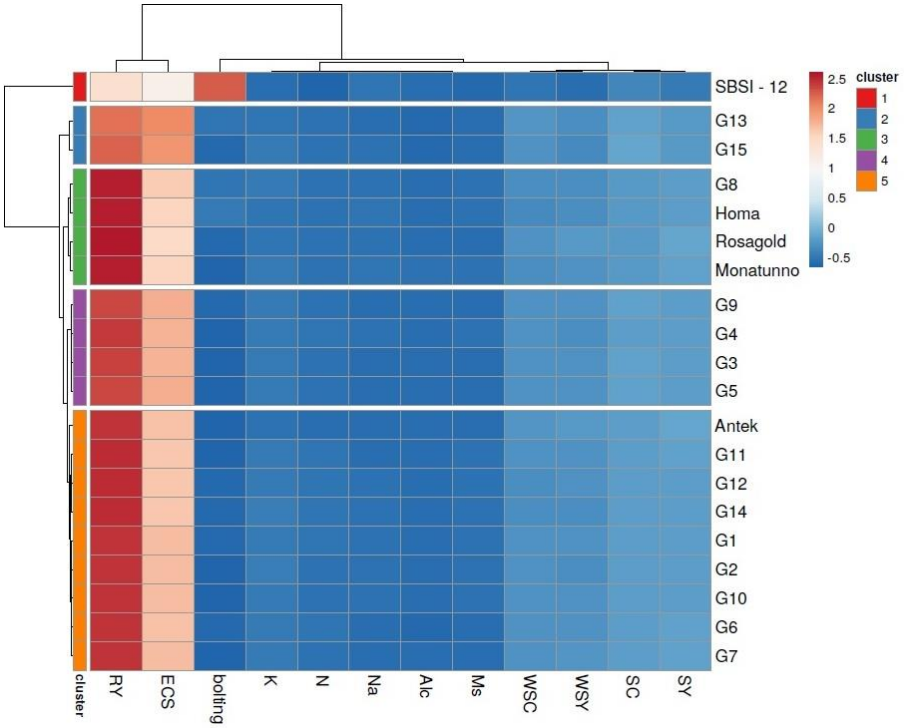


Figure 2. Heat map dendrogram of cluster analysis for sugar beet genotypes and their quantitative and qualitative characteristics in Gachsaran

Table 8. Variance analysis and Mean comparison clusters in terms of quantitative and qualitative characteristics in Gachsaran

	df	RY	SC	SY	Na	K	N	Alc	WSC	WSY	ECS	Ms	bolting
Inter groups	4	599**	3.62**	19.8**	4.11**	0.56^{ns}	0.49^{ns}	1.89**	6.18**	16.2**	84.3**	0.37*	19.3**
Intra groups	15	24.4	0.36	1.78	0.25	0.32	0.24	0.07	0.79	2.23	8.29	0.09	0.48
Cluster 1	-	66.9^{d}	11.5^{b}	7.65^{c}	6.99^{a}	5.44^{a}	2.42^{a}	5.15^{a}	6.71^{b}	4.45^{c}	57.8^{b}	4.18^{a}	93.6^{a}
Cluster 2	-	82.7^{c}	15.6^{a}	12.9^{b}	3.24^{bc}	5.24^{a}	3.93^{a}	2.21^{b}	12.1^{a}	9.93^{b}	77.0^{a}	2.97^{b}	3.00^{b}
Cluster 3	-	112^{a}	14.9^{a}	16.7^{a}	3.62^{b}	4.74^{a}	3.45^{a}	2.49^{b}	11.4^{a}	12.8^{a}	76.2^{a}	2.88^{b}	2.70^{b}
Cluster 4	-	96.3^{b}	15.5^{a}	14.8^{ab}	2.72^{c}	5.69^{a}	3.66^{a}	2.36^{b}	11.9^{a}	11.4^{ab}	77.1^{a}	2.92^{b}	0.57^{b}
Cluster 5	-	102^{b}	15.3^{a}	15.7^{a}	2.95^{bc}	5.52^{a}	3.78^{a}	2.32^{b}	11.7^{a}	12.1^{ab}	76.5^{a}	2.95^{b}	0.53^{b}
Mean	-	92.1	14.5	13.5	3.90	5.33	3.45	2.91	10.7	10.1	72.9	3.18	20.1

ns, * and **: non-significant, significant at the 1% and 5% probability level, respectively.

In the first group, only the sensitive check SBSI12 was included. This check exhibited both the lowest quantitative and qualitative yield, as well as the highest rate of bolting among all clusters, indicating it is particularly sensitive to bolting. None of the sugar beet genotypes fell within this cluster, indicating that they have suitable resistance to bolting for cultivation in the Gachsaran environment. Based on the results of the cluster analysis, the fifth cluster was identified as the best cluster in the Gachsaran environment. This cluster

comprises eight genotypes: G1, G2, G6, G7, G10, G11, G12, and G14, along with the foreign check variety Antek (Fig. 2 and Table 8). It was selected for its lowest rate of bolting and high white sugar yield. A study classified 47 sugar beet lines, along with three check varieties, into three groups using cluster analysis in Hamedan. The first group was identified as the best in terms of disease resistance traits, exhibiting higher traits compared to the average of all clusters and the other groups (Mansouri *et al*., 2024a).

3.3. Factor analysis and biplot

In the factor analysis using the principal component analysis method conducted in both Dezful and Gachsaran environments, two factors were selected based on having eigenvalues greater than one. In Dezful, the first factor accounted for 55.5 percent of the total variation, while the second factor explained 23.6 percent, resulting in a cumulative total of 79.1 percent. In Gachsaran, the first factor explained 70.4 percent and the second factor accounted for 18.8 percent, leading to a cumulative total of 89.3 percent of the total variation (Table 9). The study traits were assigned to different factors based on the values of the factor coefficients after performing a Varimax rotation of the factors. Factor coefficients greater than 0.5 were considered significant, regardless of their positive or negative sign (Mansouri *et al*., 2024b).

Factor analysis using principal component analysis in the Dezful environment revealed that the first factor, with an eigenvalue of 6.65, accounted for the largest proportion of variation at 55.5%. This factor exhibited significant positive coefficients for the traits of sodium, potassium and nitrogen concentration, and molasses percentage, while showing significant negative coefficients for sugar content, alkalinity ratio, white sugar content, white sugar yield, the extraction coefficient of sugar, and Cercospora infection. The second factor explained 23.6% of the variation, with an eigenvalue of 2.83, and showed positive and significant coefficients for root yield and sugar yield (Table 9).

In Gachsaran, the first factor had an eigenvalue of 8.45 and accounted for 70.4% of the total variation. It showed significant positive coefficients with root yield, sugar content, sugar yield, white sugar content, white sugar yield, and sugar extraction coefficient. Conversely, it displayed significant negative coefficients with sodium concentration, alkalinity, molasses percentage, and bolting percentage. The second factor had an eigenvalue of 2.26 and represented 18.8% of the total variation. It exhibited a significant positive coefficient with potassium and nitrogen concentrations (Table 9). Mansouri et al. (2024b) evaluated sugar beet lines using principal component analysis. Their findings indicated that the first two principal components accounted for 72.05% and 26.05% of the variance in the data, respectively, resulting in a total explanation of 98.10% of the observed variations. Additionally, their biplot analysis revealed that the check cultivars Novodoro and FC-709-2, along with the lines S1-140279, S1-140279, S1-140279, S1-140279, S1-140279, S1-140279, and S1-140279, exhibited a positive correlation with the first factor, leading to their identification as superior lines.

Table 9. The results of factor analysis by principal component analysis (coefficients, eigenvalue, and variance) in Dezful and Gachsaran environments

Traits	Dezful		Gachsaran	
	PC1	PC2	PC1	PC2
RY	-0.02	0.96	0.77	-0.29
SC	-0.93	-0.09	0.94	0.08
SY	-0.46	0.84	0.91	-0.25
Na	0.78	-0.19	-0.91	-0.31
K	0.66	0.27	-0.27	0.87
N	0.78	0.21	0.29	0.88
Alc	-0.59	-0.22	-0.86	-0.47
WSC	-0.96	-0.09	0.96	-0.03
WSY	-0.70	0.69	0.94	-0.28
ECS	-0.98	-0.01	0.98	-0.03
Ms	0.96	0.07	-0.93	0.29
Cercos	-0.53	-0.69		
bolting			-0.90	-0.30
Eigenvalue	6.65	2.83	8.45	2.26
Variance (%)	55.5	23.6	70.4	18.8
Cumulative variance (%)	55.5	79.1	70.4	89.3

Biplot analysis conducted in the Dezful and Gachsaran environments revealed that the traits of sugar content, white sugar content, sugar yield, white sugar yield, and sugar extraction coefficient were aligned with vectors pointing in the same direction and at a low angle to each other (Figs. 3 and 4). This indicates a positive relationship among these traits. Conversely, the traits of sodium, potassium and nitrogen concentrations, and also molasses sugar, were represented by vectors pointing in the opposite direction, suggesting a negative relationship between root impurities and sugar yield traits. Other researchers have also noted this negative and inverse relationship between root impurities and sugar yield traits (Mansouri *et al*., 2025; Tazikeh *et al*., 2023; Azizi *et*

al., 2021). Root impurities were found to be directly related to the sugar content of molasses, significantly reducing both the percentage of extractable sugar and the sugar extraction coefficient by affecting the extractability of sugar.

In the Dezful environment, the biplot analysis showed that the root yield vector was approximately oriented at a 90-degree angle to the vectors representing sugar content, white sugar content, and the sugar extraction coefficient (Fig. 3). This indicates a relatively inverse relationship between root yield and these traits in this particular setting. Tazikeh et al. (2023) also noted a negative and significant correlation between root yield and both sugar content and white sugar content, supporting our findings. In the Gachsaran environment, the vector for bolting rate was directed opposite to the vectors of sugar yield traits, including sugar content, white sugar content, sugar yield, and white sugar yield. Simultaneously, it aligned in the same direction as the vectors for root impurity content, which includes sodium, potassium, and nitrogen levels (Fig. 4). In other words, an increase in the bolting rate leads to a decrease in sugar yield and an increase in root impurity content. Tazikeh et al. (2023) reported a decline in sugar beet root quality due to bolting, which corroborates our observations.

In Dezful, a strong relationship was observed between sugar yield and white sugar yield with the G13 and G8 hybrids. These hybrids were positioned in the opposite direction from the vectors associated with root impurities, indicating that they exhibited low levels of these impurities in their roots. Furthermore, based on their location relative to the first two components, the G13 and G8 hybrids showed a negative correlation with PC1 and a positive correlation with PC2 (Fig. 3). They were identified as the best hybrids in the biplot analysis conducted in Dezful. Conversely, the sensitive check variety SBSI12 was recognized as the least favorable genotype among those tested. This was expected, as it demonstrated a positive correlation coefficient with PC1 and a negative correlation coefficient with PC2. Additionally, SBSI12 was located in the opposite direction and at the farthest distance from the vectors of sugar content, white sugar content, sugar yield, white sugar yield, and the sugar extraction coefficient in Dezful (Fig. 3). In the Gachsaran environment, biplot analysis revealed a strong relationship between the foreign varieties Antek and Rosagold and the traits of sugar content, white sugar content, sugar yield, and white sugar yield. These varieties were positioned at a large angle relative to the traits associated with root impurities, including sodium, potassium, nitrogen, and molasses sugar (Fig. 4). In this environment, both Antek and Rosagold exhibited desirable traits related to the first two principal components (PC1 and PC2) and were selected as the best genotypes. Among the hybrids studied, G7, G6, G11, G3, G9, and G5 demonstrated more favorable traits compared to the other hybrids in the Gachsaran environment. This was due to their positive correlation with PC1, which indicated their superior performance based on the biplot results (Fig. 4). Similar to findings in the Dezful environment, the sensitive check variety SBSI12 was identified as the least desirable genotype in Gachsaran, as it was positioned in the opposite direction and at the greatest distance from the vectors related to sugar yield.

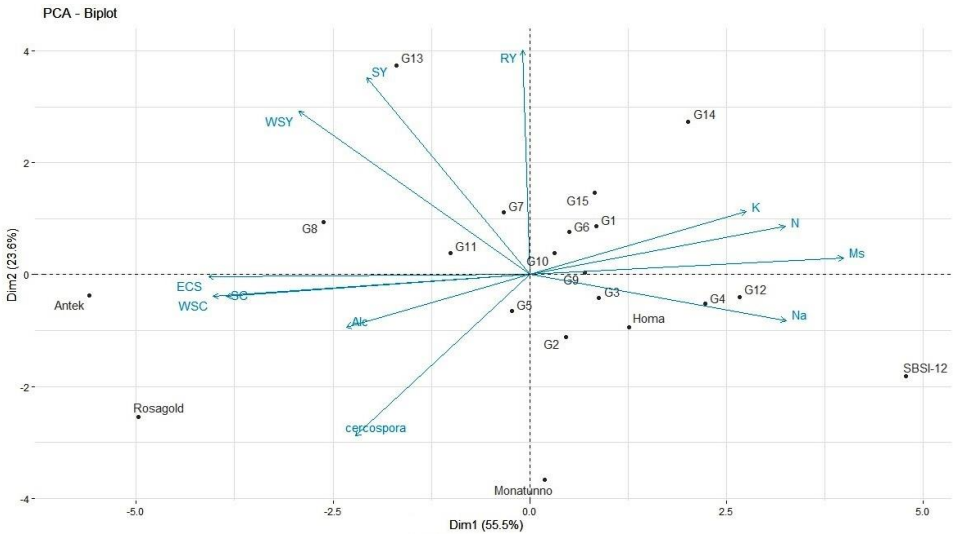


Figure 3. Scatter biplot diagram of sugar beet genotypes based on the first and second components in Dezful

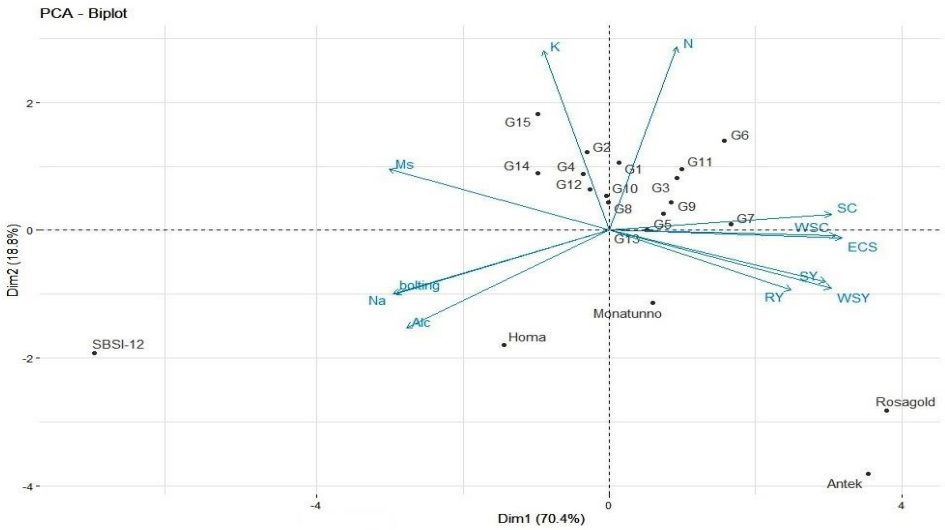


Figure 4. Scatter biplot diagram of sugar beet genotypes based on the first and second components in Gachsaran

4. Conclusion

The results of the experiment indicated that the studied hybrids responded differently in the Dezful and Gachsaran environments. As a result, the superior hybrids were identified uniquely in each setting, confirming the interaction between genotype and environment. Based on the evaluations conducted, hybrids G13 (SC(990014 × 990008) × S1-990002) and G8 (SC(990019 × 990007) were selected as the best performers in the Dezful environment, while hybrids G7 (SC(990015 × 990007) × S1-990002), G6 (SC(990014 × 990007) × S1-990002), and G11 (SC(990023 × 990007) × S1-990002) were chosen in the Gachsaran environment. These hybrids exhibited high quantitative and qualitative characteristics, strong resistance to bolting, and minimal infection by Cercospora disease. They have been identified and introduced for the development of bolting-resistant varieties.

Abbreviation

Alc: alkalinity ratio; Cercos: Cercospora score; ECS: Extraction Coefficient of Sugar; K: Potassium; MS: Molasses Sugar; N: Nitrogen; Na: Sodium; RY: Root Yield; SC: Sugar Content; SY: Sugar Yield, WSC: White Sugar Content; WSY: White Sugar Yield.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

Hamed Mansouri conceived the concept, was involved in the preparation of hybrids and performed manuscript preparation. Mohammad Saeed Hasanvandi carried out the field experiments in Dezful and Gachsaran and data acquisition. Hamze Hamze was involved in the preparation of hybrids.

Informed consent

The authors declare not to use any patients in this research.

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Generative AI statement

The author declares that generative AI (artificial intelligence) tools, including Grammarly & QuillBot,

were used to enhance the language & clarity of this work. The author takes full responsibility for the accuracy & integrity of the content.

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