Plant, Algae, and Environment, Vol. 10, Issue 2, June 2026

Cluster Analysis of Genetic Variation based on Some Morphological Traits of Summer Savory Genotypes

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Received: 2026-01-22   Accepted: 2026-06-19

Abstract

This study investigated the morphological variability among 29 summer savory accessions using a randomized block design with four replications. Morphological characteristics, biomass-related traits, and essential oil content were evaluated, and the genetic relationships among accessions were assessed using multivariate cluster analysis based on Euclidean distance. Significant differences were detected among the accessions for most measured traits, with high coefficients of variation observed for plant fresh weight, stem fresh weight, root fresh weight, and other biomass-related characteristics, indicating substantial genetic variability within the germplasm. Cluster analysis identified three distinct groups of genotypes. Cluster-I consisted of 13 accessions with the highest values for biomass production and essential oil content. Cluster II contained three accessions, primarily from northwest Iran, with higher plant heights, stem lengths, and internode distances.. Cluster-III, which included 13 accessions, exhibited high essential oil content and moderate biomass. These clusters suggest that specific genotypes are better suited for enhancing different agronomic and biochemical traits, such as biomass production and essential oil yield, which are critical for cultivar release in summer savory. The genetic variability observed among the accessions provides a promising foundation for selective breeding programs focused on optimizing both biomass production and essential oil content. The findings of the current study provide deeper insights into the genetic potential of summer savory and highlight its suitability for genetic improvement programs aimed at enhancing both yield performance and essential oil content. The identification of valuable genotypes with high biomass and essential oil content highlights the significance of conserving landraces and harnessing their genetic diversity in future breeding efforts.

Keywords: Dendrogram, Dry weight of plant, Genetic variation, Essential oil

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Introduction

In recent years, there has been an increasing global demand for the cultivation of medicinal plants, even in regions with less favorable environmental conditions. Medicinal plants provide valuable alternatives to synthetic drugs and play a crucial role in traditional medicine, with over 80% of the world's population relying primarily or exclusively on herbal remedies (Awoke et al., 2025). Summer savory (*Satureja hortensis* L.), a member of the Lamiaceae family, is originated to the Mediterranean region, and is characterized by slender, aromatic foliage and typically grows to a height of 30–60 cm. Widely available in dried form, summer savory is commonly used as a seasoning for meats and other dishes. The plant's extracts and essential oils have been recognized for their natural antimicrobial and antioxidant properties, making them valuable in food preservation and phytotherapy (Dimitrijević et al., 2025). The yield and quality of medicinal plants are influenced by genetic factors, environmental conditions, and their interactions. Understanding these influences is essential for developing effective cultivation strategies. Previous studies have shown that local landraces of summer savory can exhibit substantial variability in morphological traits and essential oil content, highlighting the need for targeted breeding programs to enhance their agronomic and medicinal potential (Abuhashem et al., 2023).

it is essential to monitor and survey their regions of distribution to prevent the loss of wild species and traditional landraces, . Morphological assessment of genetic variation serves as a valuable approach to understanding trait interrelationships, offering crucial insights for breeders in developing improved cultivars and for effective germplasm management (Gangappa et al., 2022). Significant phenotypic variability in desirable agronomic traits has been observed in summer savory (Estaji et al., 2018; Sabaghnia et al., 2024b). Local landraces, due to their environmental adaptation, often exhibit substantial genetic diversity, which can influence the chemical profile and biological properties of their essential oils and extracts. Studies on yield performance, agronomic traits, and essential oil content in various summer savory genotypes have revealed considerable differences in both the quantity and quality of these traits (Dodoš et al., 2021; Hosseinpour-Azad, 2023). Evaluating genetic variation is a fundamental step in identifying promising germplasm resources for breeding and genetic improvement programs. In such efforts, selecting genetically diverse parents is crucial, as it can result in higher heterosis and a broader range of variation among offspring. The use of cluster analysis to assess genetic diversity and determine genotypic distances is an appropriate and effective approach reflecting the authors' familiarity with advanced statistical methodologies. However, it is recommended that the introduction briefly justify the selection of this method over alternative statistical approaches. Specifically, highlighting advantages such as the capacity to handle multidimensional data, identify population structure, and achieve more accurate differentiation among genetic groups would underscore the superiority of cluster analysis and reinforce the study's theoretical foundation. Genotypic distances, which are essential for selecting diverse parents, can be effectively estimated using multivariate statistical tools such as cluster analysis (Houmanat et al., 2021). This method assesses genetic relationships based on multiple morphological traits and provides a powerful framework for examining genetic diversity (Azam et al., 2023). Essential oil production in medicinal plants such as summer savory is influenced by various factors, among which morphological traits like plant height and dry weight play a crucial role. These traits can affect both the quantity and quality of essential oils, either directly or indirectly. Plant height is typically associated with the photosynthetic capacity, whereas taller plants generally possess a more developed photosynthetic system, including a greater number of leaves, which enhances the ability of plant to synthesize secondary metabolites such as essential oils. This expanded leaf area increases the production of energy and essential precursors required for biosynthetic pathways, including the mevalonic acid pathway and the methylerythritol phosphate pathway, both central to the synthesis of terpenoids and other essential oil components. Similarly, plant dry weight is regarded as an indicator of overall biological performance, whereas Higher dry weight usually reflects more robust vegetative and reproductive growth, which may be accompanied by an increased number or density of secretory glands on the aerial organs. These glands are the primary sites for the production and storage of essential oils in savory. Thus, a higher dry weight often suggests enhanced anatomical development and a greater potential for essential oil biosynthesis and accumulation. Similar approaches have been successfully applied in the genetic evaluation of various vegetable and medicinal crops, including *Portulaca oleracea* (Mohebodini et al., 2024) and *Onobrychis viciifolia* (Sabaghnia et al., 2025a), highlighting their utility in breeding programs.

Morphological and agronomic traits, beyond their role in assessing genetic diversity, are valuable tools for the classification of genotypes in summer savory (*Satureja hortensis* L.). Morphological traits such as plant height, dry weight, number of branches, and leaf area play a key role in evaluating the performance of medicinal plants and are of great economic and medicinal importance. These traits not only indicate the growth potential and biomass of the plant, but are also directly or indirectly related to the production of secondary compounds such as essential oils, alkaloids, and flavonoids. From an economic point of view, plants with stronger growth and higher essential oil yield are suitable options for commercial cultivation. Such plants, while reducing production costs, lead to increased productivity per unit area. As a result, selecting genotypes with superior morphological traits can improve the quality and quantity of active ingredients and increase profitability for farmers and related industries. Previous research has demonstrated the effectiveness of these traits in distinguishing high-performing genotypes. For instance, Hadian et al. (2010) evaluated 30 summer savory genotypes from various regions of Iran and identified high-yielding accessions from Esfahan (53 g/plant), Maragheh (41 g/plant), and Yasouj (40 g/plant). Similarly, Khadivi-Khub et al. (2014) assessed 57 accessions based on agronomic traits and extracted three principal components related to biomass, stem characteristics, and floral traits. Their study also reported positive correlations between leaf traits and plant height with inflorescence attributes, and cluster analysis grouped the genotypes into two distinct clusters. In another study, Vozhdehnazari et al. (2022) reported substantial morphological variation and differences in essential oil composition among 30 Iranian summer savory landraces. The most important principal components identified included essential oil quality, number of main branches, and leaf width, reinforcing the utility of morphological traits in genetic studies. Given these findings, morphological traits have been widely and successfully used to evaluate genetic variation in summer savory. Therefore, the current investigation aimed to explore the genetic variation among Iranian summer savory accessions collected from diverse natural habitats based on morphological traits and essential oil content.. In addition, cluster analysis was performed to classify the accessions, and the key characteristics distinguishing the identified clusters were evaluated.

Materials and methods

Experiment and traits

This study was conducted as a field trial at the experimental farm using a randomized block layout beneficiating from four replicates and ten random samples from each replicate. The field (38°15′′N 48°17′E) with elevation 1351 m and average relative humidity 70 %, had maximum mean daily 21-26 °C, minimum mean daily 10-13 °C, and daily mean 14-19 °C. A total of 29 summer savory accessions were gathered from various areas of Iran regarding the traditional cultivation of summer survey (Table 1). Local field preparation practices, including soil plowing in autumn, soil loosening, and manual weed control, were carried out prior to sowing. Accessions were sown with a spacing of 20 × 20 cm between plants regarding the size of the plant and advice of previous investigations (Fathi et al. 2021). Each experimental unit consisted of four rows, and the trial was arranged in four replications. Based on the results of soil analysis, fertilization was applied at rates of 60 kg nitrogen, 50 kg phosphorus pentoxide, and 30 kg potassium oxide, which were applied per hectare. Agronomic and morphological traits were recorded at the flowering stage by sampling five randomly selected plants per plot. The measured traits included internode distance (DI), plant height (PH), number of leaflets on the main stem (LMS), stem length (SL), leaf area of the main stem leaves (LAMS), root length (RL), and leaf area of the lateral branch leaves (LALB). The leaf area was assessed via the AM300 tool (Bio-Scientific Ltd). For yield-related traits, the two central rows of each plot were harvested to determine stem fresh weight (SFW), plant fresh weight (PFW), and root fresh weight (RFW). After oven drying the samples, stem dry weight (SDW), plant dry weight (PDW), and root dry weight (RDW) were measured. All weighing was performed using an electronic balance with 0.1 g precision. Essential oil (EO) content was determined by hydrodistillation. Fifty grams of shoot samples from each plot were distilled with 500 ml of distilled water for four hours via a Clevenger-type device under 100 °C and atmosphere pressure. Then, the extracted essential oil was dehydrated using anhydrous sodium sulfate to remove residual moisture and then stored in sealed vials under a 4 °C refrigerator for further analysis.

Table 1. Name and coordinates of the collections with altitude for summer savory genotypes

#	Name	Region	Altitude	Coordinates
G1	Shush	Khuzestan	84	32° 11'N 48° 15'E
G2	Tabriz-I	E-Azarbaijan	1361	38° 06'N 46° 16'E
G3	Ardabil	Ardabil	1339	38° 15'N 48° 17'E
G4	Razan-I	Isfahan	1854	35° 23'N 49° 02'E
G5	Mashhad	Razavi Khorasan	1022	36° 15'N 59° 36'E
G6	Sistan	Sistan	1530	27° 35'N 60° 35'E
G7	Tonkabon-II	Mazandaran	-18	36° 48'N 50° 52'E
G8	Shiraz	Fars	1519	39° 35'N 52° 34'E
G9	Qom	Qom	965	34° 38'N 50° 52'E
G10	Kermanshah	Kermanshah	1330	34° 19'N 47° 04'E
G11	Sanandaj	Kurdistan	1577	35° 19'N 46° 58'E
G12	Parsabad	Ardabil	61	39° 37'N 47° 54'E
G13	Sardasht	W-Azarbaijan	1528	36° 09'N 45° 28'E
G14	Tuserkan-II	Hamadan	1864	34° 33'N 48° 27'E
G15	Hamedan	Hamadan	1841	34° 48'N 48° 30'E
G16	Tabriz-II	E-Azarbaijan	1361	38° 06'N 46° 16'E
G17	Isfahan	Isfahan	1601	32° 39'N 51° 39'E
G18	Qazvin	Qazvin	1307	36° 16'N 49° 59'E
G19	Tuserkan-I	Hamadan	1864	34° 33'N 48° 27'E
G20	Ilam	Ilam	1364	33° 38'N 46° 22'E
G21	Borujerd	Lorestan	1963	34° 01'N 48° 44'E
G22	Kelachay	Gilan	-13	37° 05'N 50° 21'E
G23	Arak	Markazi	1737	34° 05'N 49° 42'E
G24	Dezful	Khuzestan	150	32° 23'N 48° 25'E
G25	Razan-II	Isfahan	1854	35° 23'N 49° 02'E
G26	Tehran	Tehran	1187	35° 41'N 51° 23'E
G27	Tonkabon-I	Mazandaran	-18	36° 48'N 50° 52'E
G28	Sarab	E-Azarbaijan	1682	37° 56'N 47° 32'E
G29	Qeshm	Hormozgan	79	26° 48'N 55° 53'E

Statistical analysis

The shape of distribution was assessed for normality in the traits using the Shapiro–Wilk test via Minitab 17.0 (Minitab Inc., US). Also, the homogeneity of variances was tested via Levene's test. For performing the clustering of individuals and variables, an agglomerative hierarchical approach was applied to classify both genotypes and measured traits, based on the standardized values using the squared Euclidean distance metric. The resulting distance matrix was then employed to construct dendrogram diagrams using Ward's method due to low cophenetic measure, which focuses on minimizing within-cluster variance. These dendrograms were utilized to illustrate the structural relationships among the summer savory genotypes and traits, and were generated using STATISTICA version 14.0 (TIBCO Inc., USA). To ensure the reliability of the cluster analysis and to validate the selected number of clusters, the dendrogram cut-off point was assessed using multivariate analysis of variance (MANOVA). The analysis was performed on the original dataset, including all measured traits, and the significance of cluster separation was evaluated using four multivariate test statistics: Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root. All statistical analyses were conducted using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). The significance levels obtained from these multivariate tests were used to assess the validity of the selected cluster solution. . Consequently, the most meaningful position for the cutoff line in the dendrograms was selected based on these statistical validations.

Results and discussion

According to Table 2, descriptive statistics such as the coefficient of variation (CV) were used to assess trait variability. Traits with CV values greater than 20% were considered to have relatively high variation (Sabaghnia et al. 2024a). They included stem fresh weight (SFW), plant fresh weight (PFW), root fresh weight (RFW), leaflets per main stem (LMS), stem dry weight (SDW), plant dry weight (PDW), and root dry weight (RDW), all of which indicated considerable variability among the genotypes. Traits with CV values between 10% and 20% were considered moderately variable, including stem length (SL), leaf area of main stem leaves (LAMS), and leaf area of lateral branch leaves (LALB). In contrast, traits such as plant height (PH), root length (RL), and essential oil (EO) content exhibited relatively low variation, with CV values below 10% (Table 2). These results indicate that most of the measured traits exhibited high or moderate levels of genetic variation, providing valuable potential for selecting desirable genotypic combinations in breeding programs. Comparatively, Khadivi-Khub et al. (2014) reported high CV values for plant height, stem weight, and total plant weight across 94 samples from eight populations of summer savory. Similarly, Fathi et al. (2021), in their study on 20 accessions, observed high variability in plant dry weight and days to seed formation, while reporting low CV values for plant height and some qualitative traits. In the current study, plant dry weight (PDW) ranged from 4.84 to 12.44 g per plant, with a mean of 8.63 g; stem dry weight ranged from 4.54 to 11.68 g, averaging 8.24 g per plant. Root dry weight (RDW) varied between 0.30 and 0.74 g, with an average of 0.49 g per plant (Table 2). These broad ranges further support the existence of significant phenotypic differences among accessions for most traits. For essential oil content, the studied accessions exhibited a range from 1.94% to 2.86%, with an average of 2.42%. In contrast, Khadivi-Khub et al. (2014) reported values from 0.6% (Yazd landrace) to 1.4% (Ilam landrace), and Fathi et al. (2021) recorded even lower EO content, ranging from 0.03% to 0.83%. Environmental conditions such as temperature, precipitation, soil type, and altitude significantly influence essential oil biosynthesis in medicinal plants, whereas in semi-arid climates with higher solar radiation and temperature fluctuations can enhance secondary metabolite production, including essential oils. Cultivation methods, such as irrigation frequency, fertilization, and harvesting time, as well as post-harvest processing techniques, can also affect the quantity and quality of essential oil yield. Also, variations in sampling stages like collecting plant material at different phenological phases, can lead to substantial differences in essential oil concentration. Therefore, the current germplasm demonstrates superior potential in terms of essential oil yield and may serve as a promising genetic resource for future breeding efforts targeting high EO content.

The dendrogram generated to explore the clustering pattern among summer savory accessions (Fig. 1) classified the genotypes into three distinct clusters, as determined by a statistically significant cutoff line. This line point was validated using multiple multivariate analysis of variance (MANOVA) statistics, including the index of Pillai, the λ measure of Wilks, the criteria of Hotelling, and the α of Roys, all of which confirmed the significance of the cluster division (Table 3). Based on this classification, the summer savory accessions were grouped as follows: Cluster-I consisted of 13 accessions, Cluster-II included only three accessions (G2, G13, and G16), and Cluster-III contained the remaining 13 accessions (Fig. 1). The cluster mean values for all evaluated traits are presented in Table 4, providing key insights into the distinguishing features of each group. Cluster-I showed the highest mean values across nearly all traits, particularly in economically important characteristics such as biomass yield and essential oil (EO) content. However, it recorded the lowest values for the leaf area of main stem leaves (LAMS) and lateral branch leaves (LALB), along with moderate values for plant height (PH), stem length (SL), and internode distance (DI). This suggests that accessions in Cluster-I possess generally superior agronomic performance and can be prioritized in breeding programs aiming for yield enhancement. Cluster-II, comprising accessions G2 (Tabriz-I), G13 (Sardasht), and G16 (Tabriz-II), exhibited high values for PH, SL, DI, LAMS, and LALB, while maintaining moderate levels in most other traits. However, it displayed the lowest values for the number of leaflets per main stem (LMS) and root dry weight (RDW). Notably, all these accessions originated from the northwestern regions of Iran, characterized by cold semi-arid climates. Given the complementary nature of traits between Clus-

Table 2. Description of information on traits in 29 summer savory genotypes

	Mean	SD†	Min	Max	CV‡
PFW	55.73	13.09	32.18	86.32	23.50
SFW	54.13	12.88	31.16	88.64	23.79
RFW	1.88	0.50	1.02	3.22	26.66
PH	60.25	4.15	53.14	74.76	6.89
SL	43.86	4.92	36.96	60.23	11.21
RL	16.50	1.46	13.50	19.64	8.84
DI	3.49	0.49	2.92	5.12	14.05
LMS	25.62	7.44	5.46	33.34	29.03
PDW	8.63	1.93	4.84	12.44	22.42
SDW	8.24	1.82	4.54	11.68	22.14
RDW	0.49	0.10	0.30	0.74	20.61
EO	2.42	0.24	1.94	2.86	9.84
LAMS	1.36	0.18	1.08	1.90	13.32
LALB	1.25	0.14	1.01	1.58	11.13

†SD, standard deviation; ‡CV, coefficient of variation. Traits are: plant fresh weight (PFW), stem fresh weight (SFW), root fresh weight (RFW), plant height (PH), stem length (SL), root Length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), stem dry weight (SDW), root dry weight (RDW), essential oil (EO), leaf area of main stem's leaves (LAMS), and leaf area of lateral branches' leaves (LALB).

ter-I and Cluster-II, these two groups could serve as heterotic groups in crossbreeding programs to enhance genetic variability and trait expression.

Environmental constraints may select for genotypes with increased plant height, stem elongation, and leaf surface area, as observed in Cluster II, to maximize light capture and gas exchange in a limited growing window. At the same time, these genotypes may allocate fewer resources to below-ground biomass (e.g., root dry weight), prioritizing rapid above-ground growth. Furthermore, the cooler climate may also affect essential oil biosynthesis pathways, particularly those sensitive to temperature, by altering the activity of key enzymes such as terpene synthases (Dobhal et al. 2024). Cluster-III accessions demonstrated high averages for root length (RL) and EO content, with moderate values for RFW, PH, SL, DI, and LMS, but low performance in other traits. These accessions may be considered valuable for breeding efforts focused on improving root

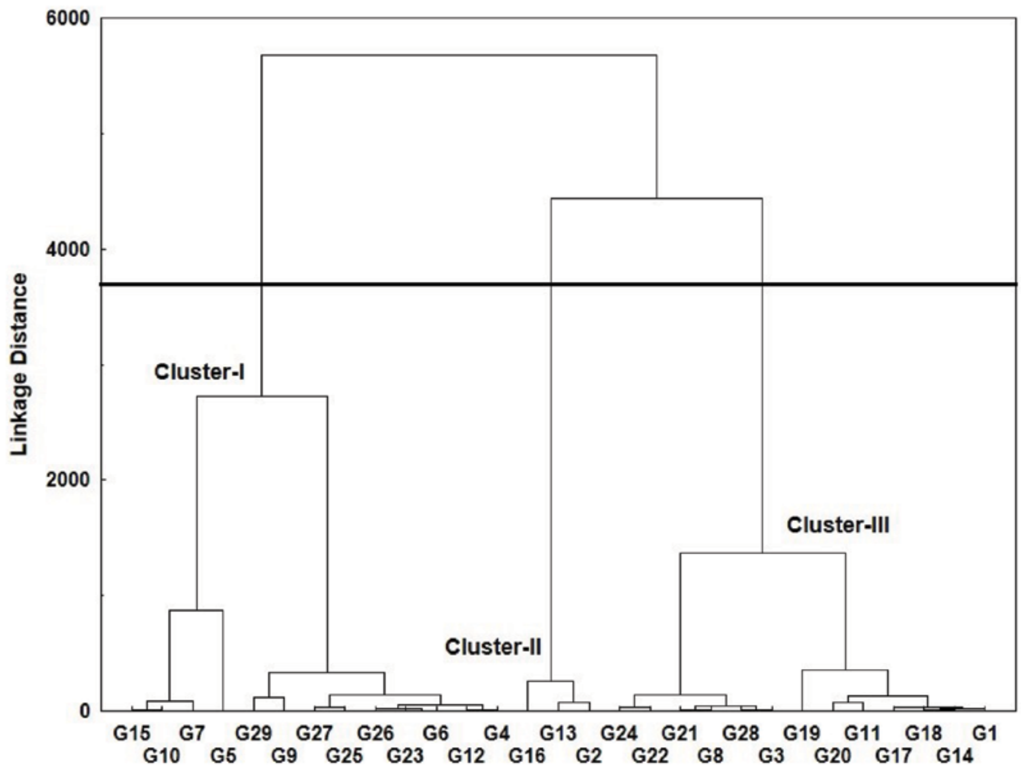

Fig. 1. Dendrogram of clustering for 29 genotypes of summer savory.

development and essential oil production. According to Zawiślak and Nurzyńska-Wierdak (2017), there is often a positive relationship between essential oil content and biomass-related traits, particularly plant dry weight has frequently been reported. Aalthough this relationship is often influenced by environmental conditions resulting in variations in its strength and significance. A more comprehensive physiological understanding of the interactions between biomass and EO biosynthesis is still needed to optimize breeding strategies. The current findings suggest that simultaneous selection for both biomass yield and essential oil content can significantly enhance the economic value of summer savory in diverse growing environments.

Another dendrogram was generated to examine the structure among traits (Fig. 2), with the significance of the cutoff line verified through multivariate analysis indices: the index of Pillai, the λ measure of Wilks, the criterion of Hotelling, and the α of Roys (Table 5). Based on this analysis, the traits were grouped into three distinct clusters: Group-I included plant height (PH), stem length (SL), internode distance (DI), leaf area of main stem leaves (LAMS), and leaf area of lateral branch leaves (LALB); Group-II comprised leaflets per main stem (LMS), root length (RL), and essential oil content (EO); and Group-III consisted of biomass-related traits, such as fresh weight of plants, stems and roots (PFW, SFW, and RFW), and dry weight of plants, stems and roots (PDW, SDW, and RDW) (Figure 2). Fathi et al. (2021) reported significant positive correlations among traits such as plant height, stem length, internode distance, and

Table 3. Four procedures of multivariate ANOVA for determining the cutoff line of dendrogram in genotypes

Procedure	Value	F†	Hypothesis df‡	Error df	Sig.
Pillai's Trace	1.85	12.33	28	28	0.00
Wilks' Lambda	0.01	16.37	28	26	0.00
Hotelling's Trace	50.04	21.45	28	24	0.00
Roy's Largest Root	43.19	43.19	14	14	0.00

†F, statistic of F ratio; ‡df, degrees of freedom

Table 4. Means of traits for the four detected clusters of genotypes

Characters	Cluster-I	Cluster-II	Cluster-III
PFW	67.63	53.84	44.27
SFW	65.61	52.12	43.11
RFW	2.24	1.52	1.60
PH	59.40	69.63	58.94
SL	42.49	56.08	42.42
RL	16.94	14.53	16.52
DI	3.29	4.76	3.39
LMS	29.01	6.09	26.73
PDW	10.12	9.05	7.04
SDW	9.77	8.70	6.60
RDW	0.56	0.39	0.44
EO	2.40	2.12	2.50
LAMS	1.35	1.70	1.29
LALB	1.25	1.51	1.18

Traits are: plant fresh weight (PFW), stem fresh weight (SFW), root fresh weight (RFW), plant height (PH), stem length (SL), root Length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), stem dry weight (SDW), root dry weight (RDW), essential oil (EO), leaf area of main stem's leaves (LAMS), and leaf area of lateral branches' leaves (LALB) the leaf areas of both the main stem and lateral branches. However, for optimizing essential oil content, traits like leaflets per main stem and root length may prove particularly important. The current summer savory germplasm shows substantial potential in terms of both biomass production and essential oil content (with 3800 Euclidean distance), making it a valuable resource for future breeding programs.

One of the most critical traits in summer savory is the essential oil content, which has both culinary and medicinal applications. In the current study, the magnitudes of essential oil were observed in range 1.94-2.86%, with an average of 2.42%, which is comparable to the findings of Khadivi-Khub et al. (2014), who reported an essential oil content range from 0.57% to 1.36% across different populations. These variations in essential oil content suggest that there is considerable potential for enhancing this trait through breeding. Zawiślak and Nurzyńska-Wierdak (2017) found that biomass-related traits like plant dry weight are positively correlated with essential oil content under specific farming conditions. This indicates that high biomass genotypes could potentially also have higher essential oil yields, which would be beneficial for both the pharmaceutical and food industries. In this study, accessions from Cluster-III, which exhibited high essential oil content (2.5%) and moderate biomass (7.04 g plant dry weight), appear to

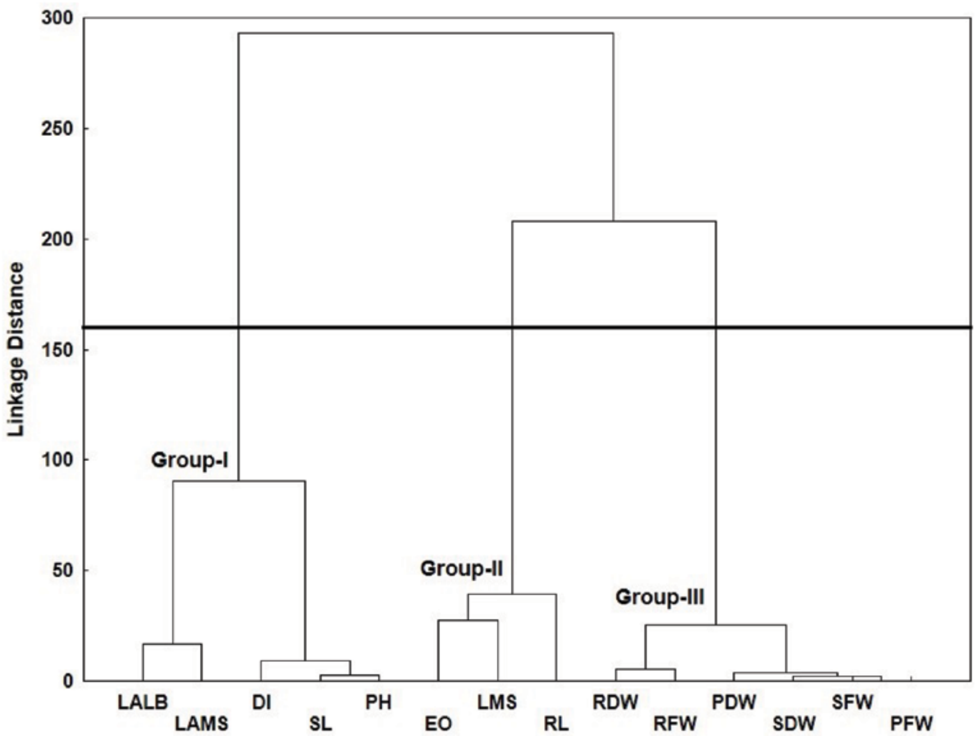

Fig. 2. Dendrogram of clustering for traits of summer savory; Traits are: plant fresh weight (PFW), stem fresh weight (SFW), root fresh weight (RFW), plant height (PH), stem length (SL), root Length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), stem dry weight (SDW), root dry weight (RDW), essential oil (EO), leaf area of main stem's leaves (LAMS), and leaf area of lateral branches' leaves (LALB)

hold promise for future breeding efforts focused on improving essential oil yield without compromising plant growth and biomass production.

The geographical origin of summer savory accessions has been shown to influence their morphological and agronomic traits. In the present study, the summer savory genotypes from northwest Iran, particularly those from regions with cold semi-arid climates (like Ardabil with elevation 1351 m, average relative humidity 70 %, maximum mean daily 21-26 °C, minimum mean daily 10-13 °C, and daily mean 14-19 °C), such as Tabriz-I, Sardasht, and Tabriz-II, were grouped into Cluster-II. These accessions exhibited higher values for plant height, stem length, and internode distance, and were characterized by moderate values for other traits. This finding aligns with previous studies that reported the influence of geographical regions on the morphological traits of medicinal plants (Hadian et al., 2010; Vozhdehnazari et al., 2022). The accessions from these cold semi-arid regions may have adapted to harsher environmental conditions, which could explain the observed morphological traits. The significant genetic diversity observed among accessions collected from different regions highlights the importance of preserving local landraces. These landraces possess valuable traits that may be advantageous in specific environmental conditions, making them essential for developing adaptable and resilient cultivars (Lazaridi et al., 2021). Therefore, the genetic improvement of summer savory through the use of local landraces should be a priority for breeders.

Current research reveals several practical implications for summer savory breeding programs. the identification of genetically diverse accessions with high potential for biomass production and essential oil yield provides a solid foundation for developing improved cultivars. Breeding programs can focus on combining the desirable traits from different clusters, such as high biomass from Cluster-I and high essential oil content from Cluster-III, to create new cultivars with superior performance. Also, the genetic variability observed in the study indicates that there is significant potential for improving summer savory through selective breeding (Sabaghnia et al., 2025b). By choosing parent plants with high genetic diversity, breeders can enhance heterosis (with 3800 Euclidean distance) and produce offspring with improved traits. For example, cross-

Table 5. Four procedures of multivariate ANOVA for determining the cutoff line of dendrogram in traits

	Value	F†	Hypothesis df‡	Error df	Sig.
Pillai's Trace	2.00	21.13	22	4	0.00
Wilks' Lambda	0.01	17.00	22	2	0.00
Hotelling's Trace	64.98	28.25	22	2	0.00
Roy's Largest Root	47.88	47.23	11	2	0.00

†F, statistic of F ratio; ‡df, degrees of freedom

es between accessions from Cluster-I and Cluster-II could result in offspring with enhanced biomass production and improved morphological traits, while crosses between Cluster-II and Cluster-III could increase essential oil content without compromising plant growth. Finally, the current study emphasizes the importance of conserving and utilizing local landraces of summer savory in breeding programs. Adapted to specific environmental conditions, these landraces represent a valuable reservoir of genetic diversity that are not found in commercial cultivars. Their integration into breeding strategies can improve the adaptability, resilience, and overall performance of future cultivars, thereby supporting the sustainable cultivation of summer savory across a wide range of agroecological environments.

Conclusions

The study of summer savory genotypes revealed significant genetic variation across various morphological and agronomic traits. Cluster analysis identified three distinct groups of accessions with differing characteristics, which can be utilized for targeted breeding programs aimed at improving biomass and essential oil content. The high variability in traits such as plant height, stem length, and essential oil content suggests that this germplasm has strong potential for future breeding efforts. Furthermore, understanding the relationships between traits, such as biomass production and essential oil yield, is essential for improving the economic value of summer savory for pharmaceutical and industrial application. The findings indicate the importance of incorporating both biomass and essential oil content into breeding programs to enhance the overall performance of summer savory in diverse agricultural systems. Despite, providing valuable insights into morphological traits and essential oil content of summer savory germplasm, this study has certain limitations. Most notably, the chemical composition of the essential oil was not analyzed, its composition is a major determinant of essential oil quality and commercial value. Future studies integrating phytochemical profiling with morphological, agronomic, and molecular characterization will provide a more comprehensive foundation for breeding programs aimed at developing superior summer savory cultivars..

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