ISPEC Tarım Bilimleri Dergisi, 10(1): 253-262, 2026
ISPEC Journal of Agricultural Sciences, 10(1): 253-262, 2026
DOI: https://doi.org/10.5281/zenodo.18654589

Assessment of Seed Characteristics in Sage (*Salvia fruticosa* Mill.) Populations

Tansu USKUTOĞLU [1*], Rıdvan UÇAR [1]
[1] Pamukkale University, Faculty of Agriculture, Department of Field Crops, Denizli
[*] Corresponding author: tansuuskutoglu@gmail.com

Abstract
Salvia fruticosa Mill. is a high-value aromatic perennial widely utilized in the pharmaceutical and food industries due to its potent essential oil profile and secondary metabolites. Despite its economic importance, the influence of environmental gradients on the physical seed characteristics of wild populations remains poorly understood. This study aimed to characterize the morphological and physical attributes of *S. fruticosa* seeds collected from 25 distinct wild populations across Denizli province, Türkiye, and to evaluate the impact of altitude and topographical factors on these traits. Physical parameters, including length, width, thickness, geometric mean diameter, sphericity, surface area, and thousand-seed weight, were systematically measured. Statistical analysis revealed significant morphological divergence among locations ($P<0.05$). Seed length and width ranged from 1.70 to 2.50 mm and 1.13 to 1.92 mm, respectively, while thousand-seed weight exhibited substantial variation between 4.07 g and 11.26 g. Principal Component Analysis (PCA) accounted for 88.4% of the total variance, identifying a robust positive correlation between seed dimensions and mass, while sphericity remained relatively independent. The results demonstrated that altitudinal gradients and aspect significantly influence seed quality, with higher elevations generally exerting a negative impact on seed dimensions and mass. Populations from lower altitudes and favorable microclimates exhibited superior physical traits. These findings highlight the extensive phenotypic diversity within Denizli's wild germplasm, providing a critical foundation for the selection of superior genotypes and the optimization of post-harvest processing in future breeding programs.

Research Article

Article History
Received :06.12.2025
Accepted :25.01.2026

Keywords
Salvia fruticosa Mill.
seed morphology
altitudinal gradient
thousand-seed weight

Citation: Uskutoğlu, T., Uçar, R., 2026. Assessment of Seed Characteristics in Sage (*Salvia fruticosa* Mill.) Populations. *ISPEC Journal of Agricultural Sciences*, 10(1): 253-262. DOI: https://doi.org/10.5281/zenodo.18654589

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1. Introduction

The majority of Lamiaceae taxa hold substantial economic and ecological value across the pharmaceutical, food, cosmetic, and perfumery industries, primarily due to their high content of essential oils, aromatic compounds, and diverse secondary metabolites (Coşge Şenkal et al., 2019; Kokten et al., 2022). Furthermore, many species within this family serve as vital bee pastures, providing essential nectar and pollen resources for apiculture (Uçar et al., 2025). The genus *Salvia* L. represents one of the most species-rich taxa of the Lamiaceae family. Historically, members of the *Salvia* genus have played a significant role in traditional medicine due to their healing potential; furthermore, their utilization as culinary ingredients and infusions remains widespread across various cultures (Topçu et al., 2013). The genus *Salvia* represents an extensive taxon of approximately 1,000 species, characterized by a subcosmopolitan distribution that spans a vast array of ecological environments globally (Koutsoulas et al., 2019; González-Gallegos et al., 2020; Coşge Şenkal and Uskutoğlu, 2021; Uskutoğlu, 2025). In the flora of Türkiye, the genus *Salvia* is represented by 100 species and a total of 107 taxa. Notably, the genus exhibits a high degree of endemism within the country, with nearly 50% of these species being endemic to the region (Tursun et al., 2021). *Salvia fruticosa* Mill. (syn. *S. triloba*) is an aromatic perennial herb of the Lamiaceae family and is regarded as one of the most economically important *Salvia* species, widely cultivated for culinary applications and medicinal uses (Arikat et al., 2004; Sharopov and Setzer, 2012). *S. fruticosa* has long been employed in traditional medicine, with its ethnobotanical uses varying across regions. In Lebanon, it has been commonly used to alleviate ulcer-related pain, whereas in Türkiye it has been used for urinary tract ailments. Across the Mediterranean basin, *S. fruticosa* is often regarded as more valuable than *S. officinalis* for medicinal purposes, largely due to its rich essential-oil profile. Essential oils obtained from *S. fruticosa* have been shown to exhibit antioxidant, antibacterial, and anti-inflammatory activities and have traditionally been applied in the management of skin infections (Topçu et al., 2017; Saab et al., 2022; Mróz and Kusznierewicz, 2023). However, the cultivation of medicinal plants aimed at the extraction of bioactive compounds is often constrained by several factors, including climatic conditions, seasonal variability, water availability, pest and disease pressure, as well as the limited availability of naturally occurring populations (Arikat et al., 2004). Genetic diversity is therefore essential to enhance resilience and stabilize the yield and quality of bioactive compounds under variable environmental and biotic stresses. Seeds represent a primary reservoir of this diversity and enable efficient conservation, exchange, and large-scale screening of germplasm. Accordingly, integrating diverse seed-derived populations into breeding programs is crucial for developing improved cultivars with consistent phytochemical profiles and superior agronomic performance. Denizli province hosts numerous populations of *S. fruticosa*; however, no comprehensive study has yet been conducted to systematically characterize these populations in terms of their genetic diversity, phytochemical profiles, and agronomic potential. To interpret complex datasets involving numerous physical variables, multivariate analysis serves as a powerful tool for uncovering hidden structures and relationships. Principal Component Analysis (PCA), in particular, is widely utilized to transform a set of correlated variables into a smaller number of uncorrelated components. This approach not only simplifies the interpretation of high-dimensional data but also allows for a clear visualization of the similarities and differences between sampling groups. Biplot diagrams further enhance this interpretation by projecting both observations and variables onto the same coordinate system, making it possible to assess which traits contribute most to the differentiation among groups and how they correlate with each other. This visualization effectively highlights the influence of external factors on the observed variation (Quinn and Keough, 2002; Jolliffe and Cadima, 2016). This study aimed to

determine the physical properties of *S. fruticosa* seeds, which serve as the fundamental basis for these broader investigations. Specifically, the study focused on characterizing *S. fruticosa* seeds by measuring key physical attributes, including length (mm), width (mm), thickness (mm), geometric mean diameter (Dg, mm), sphericity (Φ, %), surface area (S, mm^2), and thousand seed weight (TSW, g). Furthermore, it aimed to evaluate how these parameters are influenced by different collection locations and altitudes, as understanding these characteristics and their variation across locations is essential for optimizing post-harvest processing and future breeding efforts.

2.Material and Methods

2.1. Plant materials

The province of Denizli, including its constituent districts, serves as a key center of genetic diversity for sage (*S. fruticosa*). Seeds were sourced from diverse locations throughout the province during September 2024, with all samples collected from wild populations. Detailed information on the collection localities is summarized in Table 1. For sampling from natural habitats, preference was given to populations harbouring at least five plants to ensure adequate representation.

Table 1. Location information of *S. fruticosa* seeds collected from different sites in Denizli province

Location	Description Name	District	Coordinate	Altitude (m)
L1	Dağmarmara	Çal	38°05'58.5"N 29°13'54.7"E	595
L2	Baraj-1		38°08'44.6"N 29°13'56.1"E	708
L3	Sazak		38°05'10.5"N 29°15'28.5"E	856
L4	Sakızcılar		38°01'33.2"N 29°16'13.1"E	1.033
L5	Tutluca	Bozkurt	37°52'13.3"N 29°37'11.4"E	984
L6	Armutalan		37°53'53.6"N 29°35'52.7"E	1.200
L7	Mecidiye		37°55'28.5"N 29°37'42.7"E	1.244
L8	Avdan		37°53'43.0"N 29°39'35.7"E	1.266
L9	Beylerli	Çardak	37°41'50.2"N 29°38'22.1"E	915
L10	Havalimanı		37°50'06.1"N 29°45'20.3"E	940
L11	İncelertekkesi		37°41'20.6"N 29°35'54.6"E	1.161
L12	Söğütköy		37°40'23.0"N 29°36'19.5"E	1.206
L13	Saryeri		37°38'20.2"N 29°33'22.5"E	1.260
L14	Haytabey	Pamukkale	38°00'26.1"N 29°07'26.2"E	830
L15	Hierapolis		37°57'29.0"N 29°09'29.2"E	978
L16	Akdere		38°00'25.3"N 29°13'51.1"E	1.220
L17	Baraj-2	Güney	38°08'50.9"N 29°11'53.5"E	578
L18	Cindere		38°06'01.6"N 29°04'00.9"E	719
L19	Güney		38°09'11.5"N 29°05'58.5"E	876
L20	Kelleci	Babadağ	37°47'45.5"N 28°54'17.9"E	800
L21	Demirli		37°48'14.6"N 28°49'40.7"E	834
L22	Gülalan	Buldan	38°05'37.3"N 28°47'31.6"E	717
L23	Üçkuyu	Bekilli	38°16'08.0"N 29°27'35.9"E	955
L24	Aliveren	Acıpayam	37°13'55.9"N 29°26'33.4"E	1155
L25	Kale	Kale	37°26'00.6"N 28°52'17.8"E	1156



Figure 1. *Salvia fruticosa*: general habit (left), inflorescence and flowers (top right), and seeds (bottom right).

2.2. Measurement of physical and morphological properties

Seed morphological parameters, including length, width, and thickness, were determined using a stereomicroscope. Measurements were performed at 4x magnification, with the system calibrated against millimeter-grid paper to ensure precision. The geometric mean diameter (Dg), sphericity (Φ), and surface area of the seeds were calculated using the dimensions measured under the microscope, according to Eq. 1, Eq. 2, and Eq. 3, respectively (Bayram et al., 2016; Dumanoğlu et al., 2019; Uskutoğlu, 2025). Physical seed attributes were evaluated using three replicates of 20 seeds each. For the determination of thousand-seed weight (TSW), three independent batches of 100 seeds were weighed, and the results were multiplied by 10 to determine the weight of 1000 seeds.

Eq.1. $$D_g=(LWT)^{\frac{1}{3}}$$

Eq.2. $$\Phi = \left[\frac{(LWT)^{\frac{1}{3}}}{L}\right] * 100$$

Eq.3. $$S = \pi D_g^2$$

2.3. Statistics analysis

A completely randomized design with three replicates was employed to assess seed-related traits. Location effects were tested via one-way ANOVA, followed by Tukey's HSD for multiple mean comparisons. The threshold for statistical significance was set at $P<0.05$. Analyses and biplot visualization were performed using JMP software.

3. Results and Discussion

A substantial degree of morphological diversity was observed among the seed accessions sourced from different localities across the Denizli province. The broad morphological diversity identified in these sage populations offers substantial potential for the selection and development of improved cultivars. Statistical evaluations were performed on seed dimensions (length, width, and thickness), shape indices (Dg, Φ, S), and TSW. These analyses revealed critical insights

into the morphological divergence of seeds across different locations, with all evaluated traits exhibiting statistically significant differences ($P<0.05$). Seed length varied between 1.70 and 2.50 mm across the studied locations. Regarding geographical distribution, seeds sourced from L20 (Kelleci, Babadağ) and L22 (Gülalan, Buldan) exhibited the highest length values, while the lowest length was identified in population from L24 (Aliveren, Acıpayam). In terms of seed width, values ranged from 1.13 to 1.92 mm. Population sourced from L1 (Dağmarmara, Çal) and L20 (Kelleci, Babadağ) exhibited the maximum width, while the minimum width (1.13 mm) was observed in accessions from L24 (Aliveren, Acıpayam). Seed thickness values fluctuated between 1.73 and 2.19 mm. The maximum thickness was recorded in the L1 (Dağmarmara, Çal), whereas the minimum thickness was identified in population from the L18 (Cindere, Güney).

Table 2. Some physical characteristics of *S. fruticosa* seeds

Sample	Length (mm)	Width (mm)	Thickness (mm)	D_g (mm)	Φ (%)	S (mm^2)	TSW (g)
L1	2.44 ^{abc}	1.92 ^{a}	2.19 ^{a}	2.17 ^{ab}	88.97 ^{a}	14.80 ^{ab}	11.26 ^{a}
L2	2.23 $^{a-d}$	1.66 ^{abc}	1.92 ^{bcd}	1.92 $^{b-e}$	86.11 ^{abc}	11.64 ^{cde}	6.66 $^{d-i}$
L3	2.25 $^{a-d}$	1.62 ^{bc}	1.97 $^{a-d}$	1.93 $^{a-e}$	85.81 ^{abc}	11.69 ^{cde}	7.92 $^{b-e}$
L4	2.19 ^{cd}	1.58 ^{bc}	1.92 ^{bcd}	1.87 ^{cde}	85.82 ^{abc}	11.05 ^{cde}	6.13 $^{f-j}$
L5	2.24 $^{a-d}$	1.80 ^{abc}	2.01 ^{abc}	2.01 $^{a-e}$	89.73 ^{a}	12.66 $^{a-e}$	7.47 $^{b-f}$
L6	2.10 ^{d}	1.59 ^{bc}	1.85 ^{cd}	1.83 ^{de}	87.21 ^{ab}	10.57 ^{de}	5.11 $^{h-k}$
L7	2.23 $^{a-d}$	1.58 ^{bc}	1.90 ^{cd}	1.88 ^{cde}	84.63 ^{abc}	11.16 ^{cde}	6.55 $^{d-i}$
L8	2.20 ^{bcd}	1.60 ^{bc}	1.87 ^{cd}	1.87 ^{cde}	85.19 ^{abc}	11.03 ^{cde}	4.93 ^{ijk}
L9	2.25 $^{a-d}$	1.67 ^{abc}	1.94 $^{a-d}$	1.94 $^{a-e}$	86.05 ^{abc}	11.82 $^{b-e}$	7.06 $^{b-g}$
L10	2.41 ^{abc}	1.66 ^{abc}	1.89 ^{cd}	1.96 $^{a-e}$	81.40 ^{bc}	12.13 $^{a-e}$	7.32 $^{b-g}$
L11	2.23 $^{a-d}$	1.63 ^{abc}	2.01 ^{abc}	1.94 $^{a-e}$	86.92 ^{abc}	11.78 $^{b-e}$	6.25 $^{e-j}$
L12	2.20 ^{bcd}	1.73 ^{abc}	1.96 $^{a-d}$	1.96 $^{a-e}$	88.74 ^{a}	12.02 $^{a-e}$	5.92 $^{f-j}$
L13	2.27 $^{a-d}$	1.55 ^{c}	1.79 ^{cd}	1.84 ^{de}	81.16 ^{c}	10.66 ^{de}	4.51 ^{jk}
L14	2.19 ^{cd}	1.59 ^{bc}	1.84 ^{cd}	1.86 ^{cde}	84.90 ^{abc}	10.87 ^{de}	5.54 $^{g-k}$
L15	2.45 ^{abc}	1.69 ^{abc}	1.99 $^{a-d}$	2.02 $^{a-e}$	82.39 ^{bc}	12.76 $^{a-e}$	8.17 ^{bcd}
L16	2.23 $^{a-d}$	1.61 ^{bc}	2.03 ^{abc}	1.94 $^{a-e}$	86.85 ^{abc}	11.81 $^{b-e}$	8.59 ^{bc}
L17	2.28 $^{a-d}$	1.64 ^{abc}	1.90 ^{bcd}	1.92 $^{b-e}$	84.30 ^{abc}	11.63 ^{cde}	6.00 $^{f-j}$
L18	2.09 ^{d}	1.64 ^{abc}	1.73 ^{d}	1.81 ^{e}	86.54 ^{abc}	10.28 ^{ef}	4.07 ^{k}
L19	2.17 ^{cd}	1.63 ^{abc}	1.92 ^{bcd}	1.89 ^{cde}	87.16 ^{ab}	11.30 ^{cde}	6.38 $^{e-i}$
L20	2.50 ^{a}	1.92 ^{a}	2.16 ^{ab}	2.18 ^{a}	87.21 ^{ab}	14.89 ^{a}	6.11 $^{f-j}$
L21	2.48 ^{ab}	1.80 ^{abc}	1.91 ^{bcd}	2.04 $^{a-e}$	82.20 ^{bc}	13.04 $^{a-e}$	6.85 $^{c-h}$
L22	2.50 ^{a}	1.85 ^{ab}	2.02 ^{bcd}	2.11 ^{abc}	84.31 ^{abc}	13.96 ^{abc}	6.62 $^{d-i}$
L23	2.36 $^{a-d}$	1.81 ^{abc}	2.03 ^{abc}	2.05 $^{a-e}$	86.93 ^{abc}	13.25 $^{a-e}$	6.58 $^{d-i}$
L24	1.70 ^{e}	1.13 ^{d}	1.87 ^{cd}	1.52 ^{f}	89.71 ^{a}	7.26 ^{f}	8.84 ^{b}
L25	2.43 ^{abc}	1.85 ^{ab}	2.00 ^{abc}	2.08 $^{a-d}$	85.49 ^{abc}	13.58 $^{a-d}$	7.53 $^{b-f}$

Dg: Geometric mean diameter, Φ: Sphericity, S: Surface area, TSW: Thousand seed weigh. Groups not sharing the same letter are significantly different according to Tukey's HSD test ($p<0.05$).

Compared with several other *Salvia* species, namely *S. aegyptiaca*, *S. cabulica*, *S. coccinea*, *S. lanata*, *S. moorcroftiana*, *S. officinalis*, *S. plebeia*, *S. reflexa*, *S. santolinifolia*, and *S. splendens*, *S. fruticosa* exhibits markedly larger seeds. In these species, seed length and width generally remain below 0.4 mm (Jabeen et al., 2023). Although the seeds of *S. sclarea* are characterized by their large size (Uskutoğlu, 2025), those of *S. fruticosa* were found to be slightly larger in comparison. The seed dimensions of *S. fruticosa* (3.0–3.5 mm in length and 2.5 mm in width), as documented by Ghalia et al. (2020), surpass the values obtained in this research, indicating smaller seed sizes for the studied sage populations. Regarding other members of the genus, *S. bracteata*, *S. cadmica*, and *S. crypthantha* were characterized by larger seed dimensions (averaging 3.25 × 2.55 mm, 3.06 × 2.38 mm,

and 3.12 × 2.75 mm, respectively). In contrast, the seed sizes of *S. aethiopis*, *S. ceratophylla*, *S. candidissima* subsp. *candidissima*, *S. cyanescens*, and *S. virgata* demonstrated a close proximity to the values established for *S. fruticosa* (Özkan et al., 2009). The larger seed sizes documented by Ghalia et al. (2020) might stem from the genetic background of North African populations or serve as an evolutionary adaptation to drought. In such environments, producing larger seeds with increased nutrient storage is a critical strategy for ensuring reproductive success under water-limited conditions. The geometric mean diameter (D_g) values fluctuated between 1.52 mm (L24, Aliveren, Acıpayam) and 2.18 mm (L20, Kelleci, Babadağ) across the evaluated locations. Higher D_g values serve as a reliable indicator of overall seed magnitude, reflecting a general increase in seed dimensions. In comparison with other sages, the mean values were recorded as 1.5 mm for *S. sclarea* (Uskutoğlu, 2025), 1.7 mm for *S. viridis*, and 2.2 mm for *S. aethiopis*. Furthermore, higher values were observed in *S. cryptantha* (3.0 mm) and *S. tomentosa* (2.8 mm), while *S. sclarea* and *S. virgata* exhibited values of 2.0 mm and 1.9 mm, respectively (Bayram et al., 2017). While *S. aethiopis*, *S. cryptantha*, and *S. tomentosa* were characterized by larger seed dimensions, the Dg values recorded for *S. sclarea* and *S. virgata* demonstrated a high degree of similarity to the results obtained in the present study. Seed sphericity (Φ) values spanned a range from 81.16% (L13, Sarıyer, Çardak) to 89.73% (L5, Tutluca, Bozkurt), reflecting variations in seed geometry across different localities. Sphericity index (Φ) reaches unity 100 for perfectly spherical particles where all dimensions are equal, whereas it remains below 100 for seeds characterized by other geometric morphologies (Kaliniewicz et al., 2022). The fact that sphericity values for *S. fruticosa* seeds exceeded 80% indicates that the seeds possess a sub-spherical morphology, reflecting a high degree of geometric symmetry. Previous studies have determined seed sphericity indices of 64–67% in *S. hispanica L.(Ixtaina et al., 2008)* and 72–80% in *S. sclarea* (Tavakoli et al., 2014; Uskutoğlu, 2025), both of which are lower than the values observed in the present research. The surface area (*S*) of the seeds fluctuated between 7.26 and 14.89 mm², with the minimum and maximum values recorded in the L24 (Aliveren, Acıpayam) and L20 (Kelleci, Babadağ) locations, respectively. The S value represents a critical biophysical parameter, as it directly influences the seed's capacity for moisture absorption and the efficient uptake of essential nutrients during the early stages of germination (Uskutoğlu, 2025). Due to the extensive variability observed among different localities, the recorded S values were found to be in alignment with the morphological ranges established in previous studies on *Salvia* seeds (Bayram et al., 2017; Tavakoli et al., 2014). Notably, even the minimum S value recorded in this study surpassed the values reported by Ixtaina et al. (2008) for *S. hispanica* L. (approximately 6 mm²), highlighting the relatively larger seed morphology of the studied populations. The TSW of the evaluated populations spanned a range from 4.07 g (L18, Cindere, Güney) to 11.26 g (L1, Dağmarmara, Çal), indicating substantial variation in TSW across the collected locations. Dumanoğlu and Mokhtarzadeh (2020) reported TSW of 1.2 g, 7.1 g, and 0.6 g for *S. hispanica*, *S. tomentosa*, and *S. verticillata*, respectively. Notably, the TSW values obtained in the present study surpass those recorded for all three of these species, indicating a superior TSW in the evaluated populations. Similarly, Bayram et al. (2016) reported a TSW of 3.4 g for *S. virgata* Jacq., a value that is lower than the TSW recorded for *S. fruticosa*. The average TSW for *S. officinalis* L. has been reported as 8.8 g (Dumanoğlu and Sönmez, 2021), which falls within the range established for the *S. fruticosa* populations.

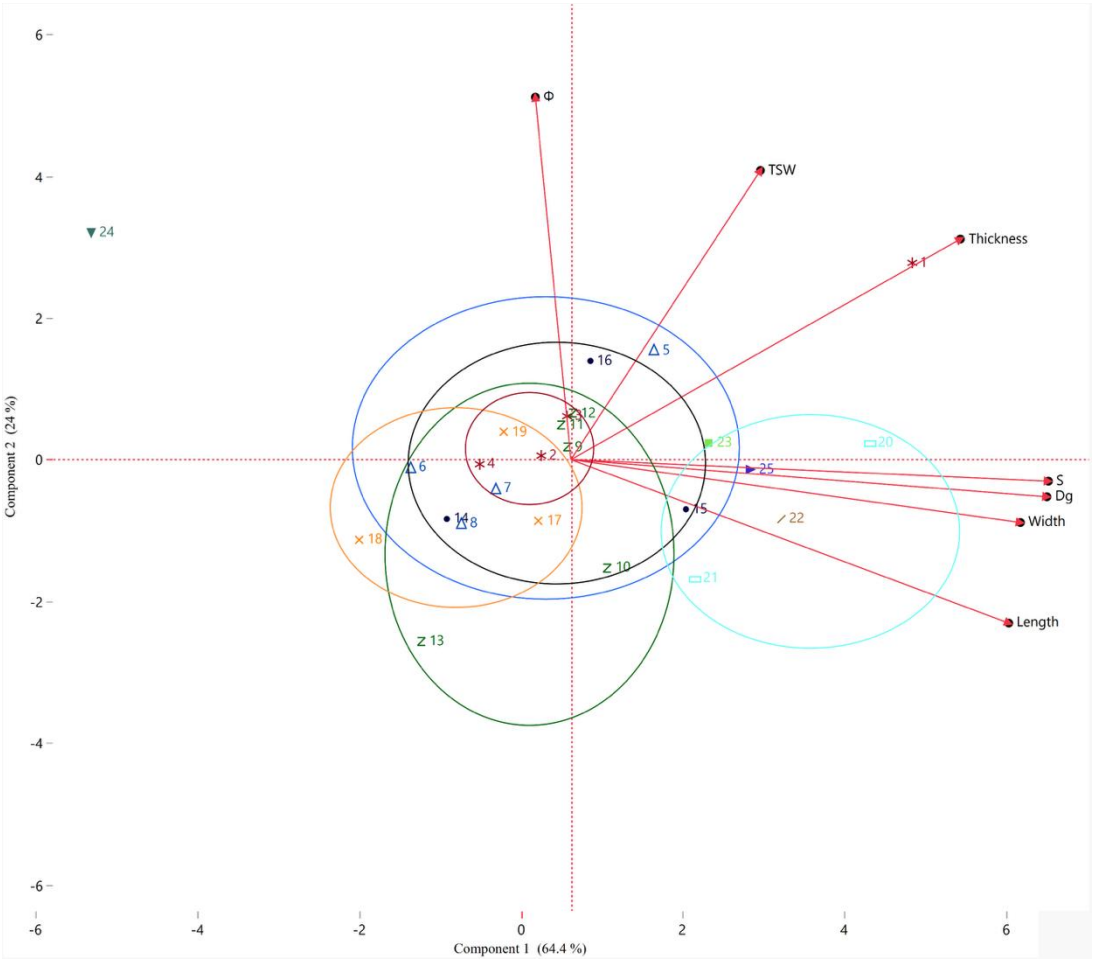


Figure 2. PCA biplot of physical characteristics of *S. fruticosa* seeds collected from different locations

The biplot effectively captures 88.4% of the total variance, with Principal Component 1 (PC1) accounting for 64.4% and Principal Component 2 (PC2) for 24.0%. This high cumulative explanatory power indicates that the majority of the variation in seed physical characterization is successfully represented by these two main axes, confirming the robustness and reliability of the dataset. The PCA biplot was interpreted following the standard multivariate framework, where the angle between vectors reflects the correlation among traits (narrow angles indicating positive correlations, orthogonal vectors indicating near-independence), and the projection of sampling locations onto trait vectors reflects their relative expression of each seed characteristic (Sall et al., 2017). A close grouping of the vectors representing length, width, *S*, and D_g was observed in the positive direction of the PC1. Such proximity reflects a robust positive inter-correlation between these parameters, highlighting their collective contribution to the physical characterization of the seeds. The vectors for TSW and thickness are also positioned within the positive quadrant of both PC1 and PC2. The acute angle formed between TSW and the dimensions of thickness, length, and width confirms that an increase in seed size is directly associated with a corresponding increase in seed weigh. The sphericity vector is positioned nearly orthogonal to the length and width vectors. This orientation reveals that seed sphericity is a morphological trait that remains relatively independent of absolute dimensional parameters, such as length and width. The light blue ellipse is situated within the positive region of PC1, aligning with the vectors for length, width, D_g, and *S*. This positioning indicates that the populations from this specific locality are characterized by significantly

larger and broader seed dimensions compared to the other studied populations. L24 and the orange ellipse are positioned on the negative side of PC1. These observations represent the populations with the minimum values for physical dimensional parameters (length, width, and weight), thereby identifying them as the smallest seeds within the entire dataset. The black and blue ellipses are positioned closer to the biplot origin, representing populations with mean values for the measured traits. In contrast, location situated in the upper region of the plot are characterized by higher sphericity indices. The clear separation of populations originating from different locations on the biplot, such as the isolation of L24 and the clustering of the group positioned on the right side, provides compelling evidence that the physical traits of *S. fruticosa* vary substantially in response to ecological conditions and/or underlying genetic diversity. Notably, the PC1 axis emerges as the primary discriminating factor, effectively representing the overall seed size gradient. Altitude increased along the transect from location L1 to L4 in the Çal district. The altitudinal gradient appeared to have a negative impact on seed characteristics; specifically, an inverse relationship was observed where seed quality and dimensions declined as elevation increased. Considering the regional topography, the fact that locations L1, L2, and L3 are predominantly situated on north-facing aspects, whereas L4 lies on a south-facing aspect, may represent one of the factors contributing to the observed differences in seed traits. In the Bozkurt district, the fact that elevations generally exceed 1,200 meters (L6, L7, and L8) appears to have adversely affected seed characteristics, likely due to the more challenging environmental conditions at these altitudes. Due to its lower elevation (under 1,000 m), location L5 hosted populations exhibiting enhanced seed traits relative to the other localities within the same district. Overall, the results indicate that the populations within this district were significantly influenced by variations in both aspect and altitude. Consistent observations were recorded for the populations sampled from the Çardak district, mirroring the trends identified in the previously discussed localities. The proximity of the Haytabey site to the Sarayköy basin appears to have influenced the seed traits of the local populations. The probable climatic stressors associated with this geographical feature exerted a negative impact on the morphological characteristics of the seeds. In the Güney district, locations L17 and L19 are situated within the Adıgüzel Dam basin, where they likely benefited from favorable microclimatic conditions. Consequently, these populations exhibited superior seed characteristics compared to location L18, which is located further from the dam at a lower topographic position. Due to the lack of significant altitudinal and aspectual variation among the locations in the Babadağ district, the evaluated populations exhibited similar seed characteristics.

4. Conclusion

Our findings highlight that the physical characteristics of *S. fruticosa* seeds are profoundly shaped by environmental and topographical factors, including altitude, aspect, and geographic positioning. The extensive phenotypic diversity identified here provides a valuable genetic resource for future selection and breeding programs. Furthermore, whether these physical variations correlate with alterations in the chemical profile of the seeds remains a critical question that warrants comprehensive investigation in subsequent research.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

Funding

This study received no financial support.

Ethical Committee Approval

This study did not involve human or animal subjects; therefore, ethical approval was not required.

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