Article

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Physical properties of seeds from seven Moroccan *Stachys* species: Comparative morphology and seed-trait variation

Abstract

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This study examines the physical properties of seeds from seven species of *Stachys* (*S. arenaria*, *S. circinata*, *S. fontqueri*, *S. germanica*, *S. officinalis*, *S. saxicola*, and *S. mouretii*) to assess their morphological diversity and potential applications. Measurements included seed dimensions, derived geometric parameters, density, porosity, moisture content, and thousand-seed mass. Results revealed significant variation across taxa. *S. germanica* had the largest seeds, the highest bulk density (601.77 kg m−3), a high true density (991.95 kg m−3), and the lowest porosity (38.78%), while *S. officinalis* showed the highest moisture content (13.81%) and a notably low aspect ratio (0.56). These findings provide quantitative seed-morphological data useful for species comparison, seed handling, and future integrative studies.

Key words: *Lamiaceae*, endemic species, morphology, Morocco.

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Introduction

Stachys L. (*Lamiaceae*) is one of its largest genera within this family, comprising approximately 371 species and 435 taxa globally (POWO 2025). Its taxa occupy a wide range of ecological zones from tropical to temperate regions, with their highest diversity observed in the Mediterranean and Iranian-Turanian regions (Bhattacharjee 1980). *Stachys* in Morocco includes 11 taxa reported as endemic to the country (Guarrigues 1979).

These annual or perennial herbs and subshrubs (Tomou & al. 2020) derive their name from the Greek *stachys* (“ear”), referring to their spike-like inflorescence (Guarrigues 1979). *Stachys* species are widely used in traditional medicine, with decoctions and infusions treating conditions such as gastric disorders, ulcers, asthma, rheumatism, and skin diseases (Goren & al. 2011; Tundis & al. 2014). Phytochemical investigations have identified numerous bioactive compounds, including iridoids, flavonoids, diterpenoids, and phenolic constituents, which have been associated with notable anti-inflammatory, antibacterial, antioxidant, cytotoxic, antidiabetic, and anti-Alzheimer activities (Piozzi & Bruno 2011; Maleki & al. 2001; Conforti & al. 2009; Jassbi & al. 2014; Bahadori & al. 2019).

Although *Stachys* species in Morocco show great potential for pharmacological use, scientific knowledge remains limited, particularly concerning their seed biology, taxonomy, and conservation. Meanwhile, climate change, overgrazing, and habitat degradation continue to threaten wild populations (Shaban & al. 2023). This highlights the urgent need for effective conservation strategies based on comprehensive biological and morphological data.

In recent decades, the demand for naturally derived compounds has surged, driven by their potential health benefits and reduced environmental impact. However, this demand, coupled with threats such as overgrazing and reduced rainfall linked to climate change, has placed significant pressure on the natural populations of *Stachys* species (e.g. Shaban & al. 2023). Therefore, there is an urgent need to preserve and rehabilitate degraded areas containing these valuable species.

Seed physical properties are key to understanding propagation, storage, and taxonomic relationships. Parameters such as size, shape, surface area, sphericity, density, porosity, and moisture content affect agricultural handling and germination potential and offer diagnostic traits useful in systematics (Ozarslan 2002). Studies have shown that seed morphology can help distinguish closely related taxa and clarify ambiguous classifications within complex orders like *Lamiales* (Schmid & al. 2005; Domina & Colombo 2005; Cervantes & Martín Gómez 2019).

This study examines the seed physical characteristics of seven Moroccan *Stachys* species from different ecological regions. Morphological and size analyses aim to support biodiversity conservation and promote sustainable use of these species in ecological, agricultural, and taxonomic contexts.

Materials and methods

Collection and storage of seeds

For this study, seeds from seven taxa of the genus *Stachys* were collected from natural populations in Morocco, representing diverse ecological regions. The collection details are summarized in Table 1.

Prior to physical characterization, the seeds were manually separated from the parent plants and carefully cleaned to remove foreign material and impurities. After cleaning, the seeds were stored in airtight plastic containers to preserve their quality. Storage was maintained under ambient laboratory conditions at the Regional Center for Agricultural Research in Errachidia. To minimize variation in storage conditions, the seeds were kept in plastic containers in an air-conditioned laboratory under relatively stable ambient conditions. The determination of the seeds' physical characteristics was conducted in the same laboratory. This ensured consistency and precision in the analysis, providing reliable data for further evaluation of the *Stachys* seeds' physical traits.

Determination of physical properties

Axial dimensions

To assess the size properties of seeds, fifteen seeds from each species were randomly selected for measurement.

Table 1. Seed collection sites of seven *Stachys* species.

Taxon	Collection site	Collection date
S. arenaria subsp. *divaricatidens* H.Lindb.	Azrou region, Ifrane province	July 2022
S. circinata L'Hér. subsp. *circinata*	Azrou forest, Ifrane province	June 2019
S. fontqueri Pau	Al Alwia, Tetouan province	July 2023
S. germanica subsp. *cordigera* Briq.	Commune of Mzefroune, Ouezzane province	May 2018
S. mouretii Batt. & Pit	Aguelmane Sidi Ali, Midelt Province	May 2019
S. officinalis subsp. *algeriensis* (de Noé) Franco	Réserve du Cap Spartel, Tanger province	May 2021
S. saxicola subsp. *platyodon* Maire	Foum el Anser, Beni Mellal province	June 2022

Seed length (L) and width (W) were measured using an Olympus SZX7 stereomicroscope equipped with an integrated camera (XCAM Family 1080P HDMI). The captured images were analyzed using ToupView software, ensuring precise and consistent measurements (Fig. 1). The thickness (T) of the seeds was measured using a Digital ABS AOS Caliper (Product code: 500-182-20), capable of measuring dimensions within the range of 0–150 ± 0.01 mm. This combination of advanced imaging tools and precise instrumentation ensured accurate data collection for characterizing the axial dimensions of the seeds.

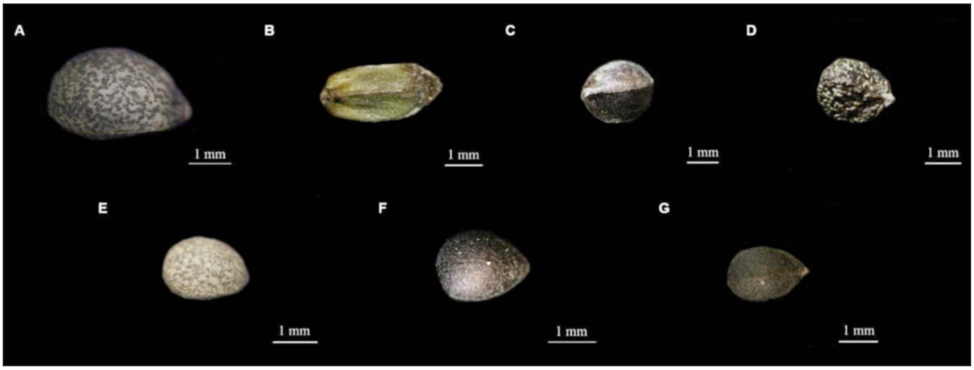


Fig. 1. Morphological diversity of seeds from the Stachys species analyzed in this study: A) *S. germanica*, B) *S. officinalis*, C) *S. circinata*, D) *S. saxicola*, E) *S. fontqueri*, F) *S. arenaria,* and G) *S. mouretii.* (Photos: I. Akhrif, A. Homrani Bakali).

Geometric properties

To determine the geometric properties, fifteen seeds from each species were analyzed. The following parameters were calculated based on seed dimensions: geometric mean diameter (Dg), arithmetic mean diameter (Da), equivalent mean diameter (De), and square mean diameter (Ds). The measurements of length (L), width (W), and thickness (T) were used to calculate these parameters according to equations (1) to (4) (Asoiro & al. 2020).

$$D_g = (LWT)^{1/3} \tag{1}$$

$$D_a = \frac{(L+W+T)}{3} \tag{2}$$

$$D_e = \frac{(D_g+D_a+D_s)}{3} \tag{3}$$

$$D_s = \left[\frac{LW+WT+TL}{3}\right]^{1/2} \tag{4}$$

Where L, W, T, D_g, D_a, D_e and D_s are all expressed in millimeters (mm).

Additionally, sphericity (S_p) and aspect ratio (R_a) of the seeds were also determined using the equations provided by (Mohsenin 1970; Koura & al. 2014; Asoiro & al. 2020):

$$S_p = \frac{(LWT)^{1/3}}{L} \tag{5}$$

$$R_a = \frac{W}{L} \tag{6}$$

The surface area (S) was estimated by the relationship in Equation (7) given by (Asonye & al. 2014; Hacıseferoğulları & al. 2007):

$$S = \frac{\pi (WT)^{\frac{1}{2}} L^2}{2L-(WT)^{\frac{1}{2}}} \tag{7}$$

Gravimetric properties

The true volume (V_s) and bulk volume (V_b) (expressed in cm^3) were determined using the water displacement method as described by (Asoiro & al. 2017). Subsequently, the true density (ρt), bulk density (ρb), and porosity (ε) of the seeds from the seven *Stachys* species were calculated using the following equations (8, 9, and 10):

$$\rho_t = \frac{M_s}{V_s} \tag{8}$$

$$\rho_b = \frac{M_b}{V_b} \tag{9}$$

$$\varepsilon = \left(\frac{\rho_t - \rho_b}{\rho_t}\right) \times 100 \tag{10}$$

where M_s and M_b are the solid mass (g) and bulk mass (g) of seeds, respectively. ρt and ρb are expressed in (kg/m³), while ε is expressed as a percentage (%).

Moisture content and one thousand seed mass

The moisture content (MC) of the seeds was evaluated according to ISTA standards (ISTA 2025). Seed samples were weighed to obtain the fresh mass (W_1) and then oven-dried at 105°C for 24 h and then reweighed to obtain the dry mass (W_2). Moisture content was calculated on a wet basis using equation (11):

$$MC = \left[\frac{(W_1 - W_2)}{W_1}\right] \times 100 \tag{11}$$

For the thousand-seed mass, the method described in standard NFV03-702 (AFNOR 1991) was employed. One hundred seeds of each species were counted and weighed and the resulting mass was multiplied by 10 to obtain the mass of 1000 seeds. Each measurement was performed in triplicate.

Statistical analysis

The differences among the measured seed properties were analyzed using a one-way analysis of variance (ANOVA) followed by the Student–Newman–Keuls (SNK) post-hoc test to identify significant differences. Additionally, a correlation analysis was conducted to explore the strength and direction of relationships among the variables. A principal component analysis (PCA) was performed to better understand the variability and clustering among the seed properties. All statistical analyses were carried out using SPSS 20 and XLSTAT 2014 software.

Results and discussion

The values of all the properties measured for the seven *Stachys* seed species are shown in Table 2.

Axial dimensions:

One-way ANOVA showed a highly significant effect of species on all measured axial dimensions and geometric seed properties, including length, width, thickness, geometric mean diameter, arithmetic mean diameter, square mean diameter, equivalent diameter, sphericity, aspect ratio, and surface area ($p < 0.001$). The SNK post-hoc test further separated the species into significantly different groups. Table 2 shows that mean seed length

Table 2. Axial dimensions and geometric properties of the *Stachys* seed species.

	S. arenaria	***S. circinata***	***S. fontqueri***	***S. germanica***	***S. mouretii***	***S. officinalis***	***S. saxicola***
L (mm)	2.18 ± 0.1^{e}	2.6 ± 0.16^{c}	2.04 ± 0.14^{e}	3.49 ± 0.16^{a}	1.97 ± 0.11^{f}	3.26 ± 0.46^{b}	2.43 ± 0.12^{d}
W (mm)	1.72 ± 0.11d	2.23 ± 0.17b	1.58 ± 0.08e	2.7 ± 0.16a	1.36 ± 0.07f	1.79 ± 0.14d	2.1 ± 0.09c
T (mm)	1.13 ± 0.06d	1.25 ± 0.07c	0.95 ± 0.04e	1.78 ± 0.08a	0.94 ± 0.03e	0.96 ± 0.06e	1.3 ± 0.04b
Dg (mm)	1.62 ± 0.07e	1.93 ± 0.08b	1.45 ± 0.06f	2.56 ± 0.1a	1.36 ± 0.05g	1.77±0.11d	1.87 ± 0.06c
Da (mm)	1.68 ± 0.08d	2.03 ± 0.08b	1.52 ± 0.07e	2.66 ± 0.1a	1.42 ± 0.06f	2 ± 0.17b	1.94 ± 0.06c
Ds (mm)	1.78 ± 0.08e	2.17 ± 0.09c	1.64 ± 0.08f	2.83 ± 0.11a	1.53 ± 0.07g	2.28 ± 0.23b	2.06 ± 0.07d
De (mm)	1.69 ± 0.08d	2.04 ± 0.08b	1.54 ± 0.07e	2.68 ± 0.1a	1.44 ± 0.06f	2.02 ± 0.17b	1.96 ± 0.06c
S_p	0.74 ± 0.03b	0.75 ± 0.05b	0.71 ± 0.03b	0.73 ± 0.02b	0.69 ± 0.02c	0.55 ± 0.05d	0.77 ± 0.03a
R_a	0.79 ± 0.04b	0.86 ± 0.11a	0.78 ± 0.04b	0.77 ± 0.05b	0.69 ± 0.04c	0.56 ± 0.08d	0.87 ± 0.05a
S (mm^2)	3.38 ± 0.34d	5.15 ± 0.51b	2.71 ± 0.33e	9.83 ± 0.85a	2.37 ± 0.26e	5.41 ± 1.03b	4.64 ± 0.36c

L: Length, W: Width, T: Thickness, Dg: Geometric mean diameter, Da: Arithmetic mean diameter, De: Equivalent mean diameter, Ds: Square mean diameter, S*p*: Sphericity, Ra: Aspect ratio, S: Surface area. Values are given as mean ± SD. Means with the same letter do not differ significantly according to SNK test at $p < 0.05$ (ns: not significant, *** Highly Significant at $p \leq 0.001$)

ranged from 1.97 ± 0.11 mm in *S. mouretii* to 3.49 ± 0.16 mm in *S. germanica*, mean width ranged from 1.36 ± 0.07 mm in *S. mouretii* to 2.7 ± 0.16 mm in *S. germanica,* while mean thickness ranged from 0.94 ± 0.03 mm in *S. mouretii* to 1.78 ± 0.08 mm in *S. germanica*. Among the species evaluated, *S. germanica* had the largest seeds overall and was significantly longer, wider and thicker, with mean dimensions of 3.49 ± 0.16 mm in length, 2.7 ± 0.16 mm in width, and 1.78 ± 0.08 mm in thickness. By contrast, *S. mouretii* and *S. fontqueri* generally showed the smallest seed dimensions and geometric values. For example, *S. mouretii* had mean dimensions of 1.97 ± 0.11 mm long, 1.36 ± 0.07 wide, and 0.94 ± 0.03 mm thick. *S. circinata* and *S. saxicola* displayed intermediate seed sizes.

The observed variability in seed dimensions among *Stachys* species indicates clear interspecific morphological differences. These dimensional differences are comparable to those reported for *Salvia hispanica* L. (Ixtaina & al. 2008). However, the present results should be interpreted primarily as quantitative seed-morphological evidence rather than as direct taxonomic evidence. Seed size alone does not constitute a sufficient basis for taxonomic reclassification. To support taxonomic arguments, seed traits should be evaluated together with other morphological characters, molecular data, karyology, germination behavior, dormancy, and ecological information. *S. germanica* clearly stands out with its large seeds, which may suggest differences in seed morphology and reserve allocation among the studied species. Additionally, this unique seed morphology of *S. germanica* may have taxonomic implications (Salmaki & al. 2013). Their phylogenetic findings place *S. germanica* in a clade or section distinct from *S. arenaria, S. circinata*, and *S. saxicola*. However, our seed dimensional data alone cannot independently support taxonomic reclassification proposals, such as the potential reassignment of *S. germanica* to another genus (e.g., *Eriostomum*). Regarding *S. officinalis,* our seed morphological observations are not intended to provide independent evidence for reclassification. The accepted placement of this taxon within *Betonica* has already been supported by previous morphological, anatomical, molecular, and phylogenetic evidence. Therefore, our seed dimensional data should be considered complementary to, rather than decisive for, the taxonomic interpretation of this species. Smaller seeds, as observed in *S. mouretii* and *S. fontqueri*, may suggest differences in seed allocation strategies; however, their ecological significance cannot be confirmed without germination, dormancy, dispersal, seedling-performance, and field-based ecological data.

Geometric properties:

One-way ANOVA showed highly significant interspecific differences in the geometric seed properties, including geometric mean diameter, arithmetic mean diameter, equivalent diameter, square mean diameter, sphericity, aspect ratio, and surface area ($p < 0.001$; Table 2). The SNK post-hoc test further confirmed that the studied species differed significantly in both seed size-related and seed shape-related traits.

S. germanica exhibited the highest geometric diameter (2.56 ± 0.10 mm), while *S. mouretii* had the smallest geometric diameter (1.36 ± 0.05 mm). Intermediate values were observed in *S. circinata* (1.93 ± 0.08 mm) and *S. saxicola* (1.87 ± 0.06 mm). The arithmetic diameter followed a similar pattern. *S. germanica* had the largest diameter (2.66 ± 0.10 mm), while *S. mouretii* had the smallest (1.42 ± 0.06 mm). *S. germanica* again had the highest square diameter (2.83 ± 0.11 mm), and *S. mouretii* and *S. fontqueri* exhibited the smallest square diameters (1.53 ± 0.07 mm and 1.64 ± 0.08 mm, respectively). Equivalent diameter was largest in *S. germanica* (2.68 ± 0.1 mm) and smallest in *S. mouretii* (1.44 ± 0.06 mm), reflecting the same trend observed across other size metrics.

Sphericity, which measures how closely the seed shape approximates a sphere, ranged from 0.55 ± 0.05 in *S. officinalis* to 0.77 ± 0.03 in *S. saxicola*. These differences were highly significant ($p < 0.001$). According to the SNK grouping, *S. saxicola* showed the highest sphericity group, whereas *S. officinalis* formed the lowest group. *S. mouretii* was also separated from the remaining intermediate species, while *S. arenaria, S. circinata, S. fontqueri,* and *S. germanica* occupied an intermediate group. Thus, *S. saxicola* had the most spherical seeds, while *S. officinalis* had a more elongated seed form. The experimental sphericity of *Stachys* was found to be higher than that of *Salvia hispanica L.* seeds (Ixtaina & al. 2008).

The aspect ratio representing the ratio of width to length was highest in *S. saxicola* (0.87 ± 0.05) and lowest in *S. officinalis* (0.56 ± 0.08). These differences were also highly significant ($p < 0.001$). The corrected SNK test separated *S. saxicola* and *S. circinata* into the highest group, whereas *S. officinalis* formed the lowest group. *S. mouretii* was also distinct from the intermediate species. The low aspect ratio of *S. officinalis* reflects its elongated seed morphology, characterized by relatively long seeds but narrow width, thereby distinguishing it from other Stachys species in terms of seed shape geometry. However, this morphological distinctiveness in seed shape does not independently determine taxonomic status.

Surface area was highest in *S. germanica* (9.83 ± 0.85 mm^2), reflecting its larger seed dimensions. *S. mouretii* and *S. fontqueri* had the smallest surface areas (2.37 ± 0.26 mm^2 and 2.71 ± 0.33 mm^2, respectively). These differences were highly significant ($p < 0.001$), with *S. germanica* clearly separated from the other species. The relatively high surface area of *S. officinalis* compared with its low sphericity and aspect ratio indicates that this species combines relatively large seed length with a narrow seed width, producing a distinctly elongated seed shape.

Overall, the geometric properties reinforce the significant morphological variability among *Stachys* species, with *S. germanica* consistently standing out for its large seeds and high surface area. Conversely, smaller species like *S. mouretii* and *S. fontqueri* showed the smallest geometric properties. *S. fontqueri* generally showed the smallest geometric values. *S. officinalis* showed a different pattern: although its seeds were relatively long, their narrow width resulted in low sphericity and aspect ratio values. This indicates shape distinctiveness, but it should not be interpreted as independent evidence for taxonomic reclassification.

The observed seed morphological variation among *Stachys* species may invite interpretations regarding potential ecological significance and evolutionary divergence; however, such interpretations must be understood as preliminary hypotheses requiring independent experimental validation and integration with multiple lines of evidence. The results of the current study on *Stachys* species align with findings in other genera within the *Lamiaceae* family and beyond. For example, *S. germanica*, with its large seeds, resembles traits observed in *Salvia hispanica* L., which also features relatively large seeds with high-energy reserves that enhance germination and seedling establishment (Ixtaina & al. 2008). Such traits may reflect similar selective pressures favoring larger seed size for enhanced competitiveness in nutrient-rich environments. Conversely, smaller seeds like those of *S. mouretii* (mean mass: 0.88 ± 0.01 g per 1000 seeds; mean surface area: 2.37 ± 0.26 mm²) and S. fontqueri (mean mass: 1.26 ± 0.03 g per 1000 seeds; mean surface area: 2.71 ± 0.33 mm²) are comparable to those in species such as *Mentha pulegium* L., where smaller seeds have been linked to adaptations for wind dispersal and colonization of nutrient-poor habitats (Panetta 1985, Chen & al. 2022). This suggests that *S. mouretii* may potentially exhibit similar ecological strategies favoring seed dispersal efficiency over individual seedling vigor.

The low aspect ratio (Ra = 0.56) and sphericity (Sp = 0.55) of *S. officinalis* are of particular interest and deviate significantly from typical *Stachys* seeds. These morphological traits support the distinctiveness of *S. officinalis* and its reclassification into *Betonica* genus but do not independently determine its established taxonomic classification (Schmid & al. 2005).

The observed variability in seed size and shape is consistent with studies in other plant families, such as *Fabaceae* and *Brassicaceae*, where seed morphological traits have been used to resolve taxonomic ambiguities and infer ecological adaptations (Erkul & al. 2015; Zhao & al. 2023; Zarre & al. 2024). These findings emphasize the importance of integrating seed morphology into taxonomic and phylogenetic studies, particularly in genera with complex classification histories like *Stachys*.

Gravimetric properties

Table 3 shows that species had a significant effect on bulk density and true density, whereas porosity did not differ significantly among species. Therefore, SNK post-hoc comparisons were interpreted only for bulk density and true density. The highest bulk density, ρb, was recorded *for S. germanica* (601.77 ± 21.21 kg m^{-3}), which formed a distinct SNK group (a) and was significantly different from all other species. Five species (*S. arenaria, S. circinata, S. fontqueri, S. mouretii,* and *S. saxicola*) formed a statistically homogeneous group (b) with bulk densities ranging from 459.61 ± 41.06 kg m^{-3} (*S. circinata*) to 528.5 ± 28.25 kg/m³ (*S. arenaria*), with no significant pairwise differences among them. The lowest bulk density was recorded for *S. officinalis* (326.89 ± 11.11 kg m^{-3}), forming a distinct third group (c) significantly different from both *S. germanica* and the other five species. For true density, *S. arenaria* and *S. fontqueri* exhibited the highest values (1003.69 ± 134.56 kg $m^{-3}$and 998.43 ± 38.85 kg m^{-3} respectively), forming a distinct SNK group (a*)*. *S. germanica* (991.95 ± 102.54 kg m^{-3}) was also statistically grouped with these species (SNK group a), suggesting that these three species (*S. arenaria, S. fontqueri*, and *S. germanica*) possess denser seed material relative to other species evaluated. The lowest true density was recorded for *S. officinalis* (653.77 ± 60.98 kg m^{-3}), forming a distinct group (c) significantly lower than all other species. However, it is important to note the relatively large standard deviations within some species (e.g., *S. arenaria*: ±134.56*; S. germanica*: ±102.54), which suggest substantial within-species variation in true density that may reflect environmental, developmental, or genetic factors.

Regarding the porosity, it is found to range from the lowest porosity (38.78 ± 8.24 %) for *S. germanica* to the highest porosity (49.79 ± 3.59 %) for *S. officinalis,* indicating a greater proportion of void space in the bulk seed mass. However, contrary to what the numerical ranges might suggest, ANOVA analysis revealed that porosity differences among species were not statistically significant (F = 1.44, p = 0.269, ns).

From a practical perspective, bulk density, true density, and porosity are important physical properties because they influence seed handling, storage capacity, aeration, drying, and separation processes. Density-based differences may also be useful in designing equipment for cleaning, grading, and processing seed lots (Ixtaina & al. 2008, Asoiro & al. 2020). The true density values observed in most studied *Stachys* species were generally within the range reported for *Salvia hispanica* L. seeds, whereas porosity values appeared numerically higher than those reported for that species (Ixtaina & al. 2008).

It is important to highlight that the porosity within the seed mass directly affects the resistance encountered during aeration and drying procedures.

The substantial variation in bulk density and true density among *Stachys* species could potentially reflect ecological or evolutionary divergence. Nevertheless, interpretations linking seed density to ecological strategies or environmental adaptation must be approached with considerable caution.

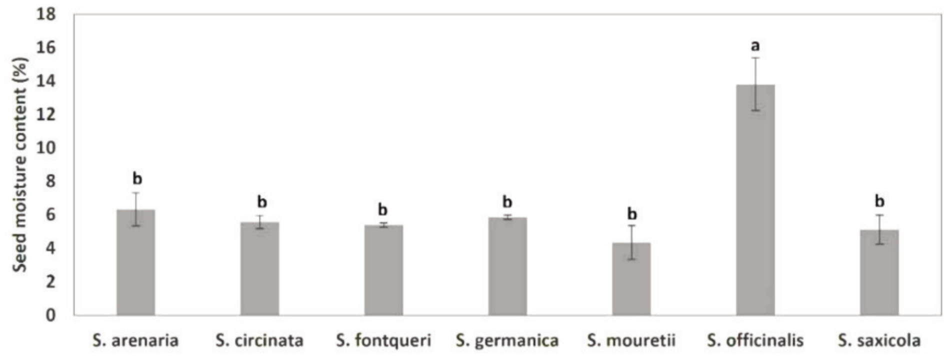
Table 3. Gravimetric properties of the *Stachys* seed species.

Species	ρ_b (kg m^{-3})	ρ_t (kg m^{-3})	ε (%)
S. arenaria	528.50 ± 28.25b	1003.69 ± 134.56a	46.59 ± 8.59a
S. circinata	459.61 ± 41.06b	766.89 ± 24.9bc	40.05 ± 5.22a
S. fontqueri	520.2 ± 33.52b	998.43 ± 38.85a	47.77 ± 5.26a
S. germanica	601.77 ± 21.21a	991.95 ± 102.54a	38.78 ± 8.24a
S. mouretii	522.98 ± 43.91b	921.89 ± 96.93ab	43.18 ± 1.59a
S. officinalis	326.89 ± 11.11c	653.77 ± 60.98c	49.79 ± 3.59a
S. saxicola	485.42 ± 26.75b	862.92 ± 99.12ab	43.41 ± 5.16a
Significance	***	**	ns

ρ_b: bulk density, $\rho_{t:}$ true density, ε: porosity
Values are given as mean ± SD.
Means with the same letter do not differ significantly according to SNK test at $p < 0.05$ (ns: not significant, **: significant at $p < 0.01$, *** Highly Significant at $p \leq 0.001$ level)

Moisture content and one thousand seed mass

Moisture content varied significantly among species (F = 40.11, $p < 0.001$) from 4.35 ± 1.02% in *S. mouretii* to 13.81 ± 1.58% in *S. officinalis* (Fig. 2). According to the SNK test, *S. officinalis* formed a distinct group (a), whereas all other species were grouped together (b), indicating that the main difference in moisture content was due to the markedly higher value observed in *S. officinalis*. The significantly higher MC in *S. officinalis* ($p < 0.001$) compared to others suggests its seeds may have greater water retention capabilities, likely influenced by environmental conditions or species-specific adaptations. Species with lower MC (e.g., *S. mouretii* and *S. saxicola*) may be adapted to drier habitats. Studies have reported that moisture range varies with species, emphasizing that lower MC values (a general trend in this study) align with orthodox seed behavior, which facilitates seed bank longevity (Ellis & al. 1991).



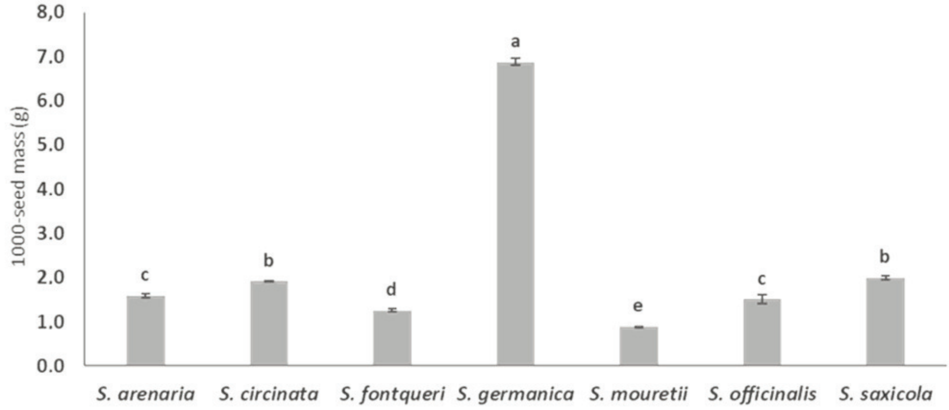
Bars with the same letter do not differ significantly according to SNK test at $p < 0.05$

Fig. 2. Seed moisture content of *Stachys* species.

The values of 1000-seed mass varied significantly from 0.88 ± 0.01 g for *S. mouretii* to 6.88 ± 0.08 g for *S. germanica.*

S. germanica had a significantly greater thousand-seed mass than the other *Stachys* species (Fig. 3). These values are lower than those reported for *Salvia hispanica L*. seeds (Ixtaina & al. 2008), except *S. germanica*. Seed mass can affect a plant species' ability to colonize and compete across various environmental gradients (Bu &. 2019). The thousand-seed mass of *S. officinalis* (1.51 ± 0.09 g) was slightly higher than that reported by Dušek & al. (2010) for *Betonica officinalis* (1.3 ± 0.1 g). These differences likely stem from the fact that the populations being studied belong to distinct varieties or subspecies.

Larger seeds (e.g., *S. germanica*) may ensure better seedling establishment and resilience in nutrient-poor conditions, while smaller seeds (e.g., *S. mouretii* and *S. fontqueri*) may represent a dispersal advantage or adaptation to limited-resource environments (Leishman & al. 2000; Sonkoly & al. 2017; Chen & al. 2022). Seed mass typically indicates the amount of energy a seed contains and its potential for mobility (Coomes & Grubb 2003). Therefore, it is likely that seed mass plays a significant role in determining the geographic distribution of seed plants (Chen & al. 2022).



Histograms with the same letter do not differ significantly according to SNK test

Fig. 3. Mass of 1000 seeds of *Stachys* species.

Multivariate analysis of the physical properties of the Stachys seeds

Six components were extracted, which described 100 % of the variability of the original traits (Tab. 4). The first two components (F1 and F2) explain 90.54% of the total variance (59.0 % by F1 and 31.54 % by F2). This means the first two axes sufficiently summarize the variability in the dataset, making them critical for interpretation. The first component, F1 is positively associated with variables related to size and mass including L, W, T, Da, Dg, Ds, De, S and m and negatively associated with pt (density) and, which suggests species with larger seeds tend to have lower density and sphericity. The second component, F2, is mostly correlated to MC (%) (moisture content) and ε (%) (porosity), suggesting these traits are independent of seed size and mass (Figs. 4 & 5).

Table 4. Eigenvalues and explained variance for the six principal components derived from 15 quantitative seed traits measured in seven *Stachys* species.

	F1	F2	F3	F4	F5	F6
Eigenvalue	8.850	4.731	1.000	0.385	0.023	0.012
(%)	58.998	31.539	6.669	2.565	0.151	0.077
% Cumulative variance	58.998	90.537	97.206	99.771	99.923	100.000

PCA analysis

The PCA revealed clear differentiation among the studied *Stachys* species based on their seed physical traits. Four main patterns can be distinguished in the F1–F2 plane. *S. germanica* was positioned separately on the positive side of F1, reflecting its association with large seed size, high surface area, and high 1000-seed mass. This confirms that *S. germanica* is the most distinctive species in terms of seed size-related traits. *S. officinalis* was positioned separately on the positive side of F2, in the upper part of Fig. 5. This separation is mainly related to its high moisture content and porosity, together with its low sphericity and aspect ratio. Thus, *S. officinalis* differs from the other species mainly in seed water status and shape-related traits rather than in overall seed size alone. Conversely, *S. mouretii*, *S. arenaria,* and *S. fontqueri* are in the lower-left part of the PCA plot (negative F1 and F2 values), indicating lower seed size and mass traits, MC (%) (moisture content), and ε (%). This group appears to exhibit higher density (pt) and sphericity (Sp), which are inversely related to seed size. These species likely produce smaller, denser seeds with lower moisture content and porosity. This combination of traits may reflect adaptations to specific ecological conditions. The last group composed of *S. circinata* and *S. saxicola,* lies near the center-right of the PCA plot and indicates moderate size traits, MC (%) and ε (%). These species exhibit a balance of seed traits which reflects a trade-off between dispersal poten-

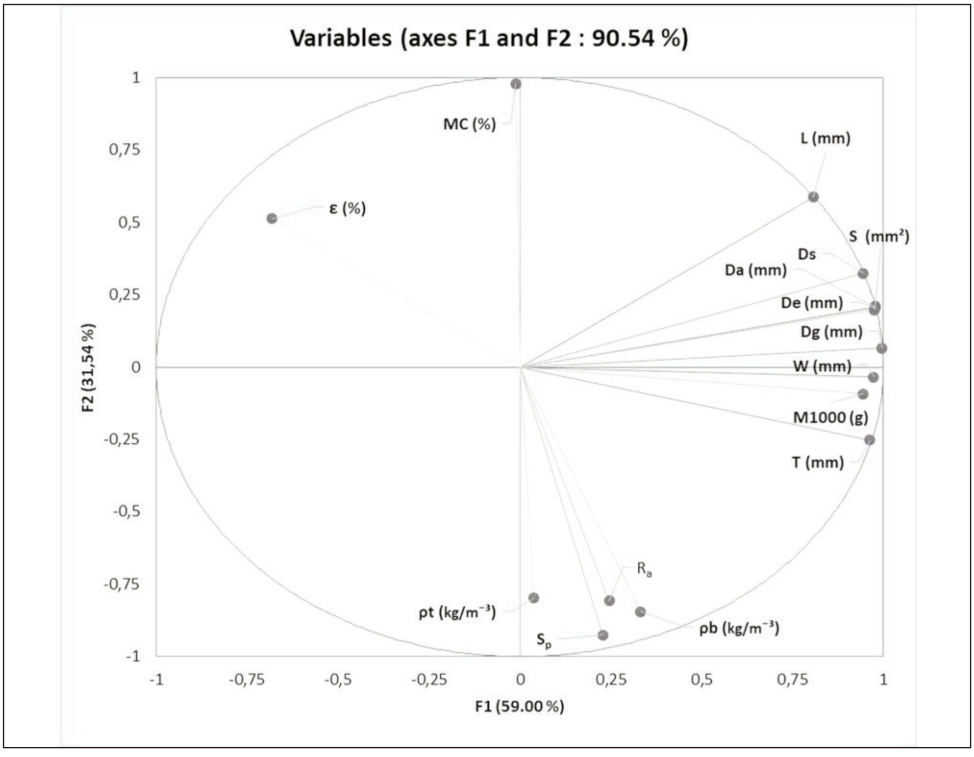


Fig. 4. PCA correlation circle of the physical seed traits measured in the seven *Stachys* species.

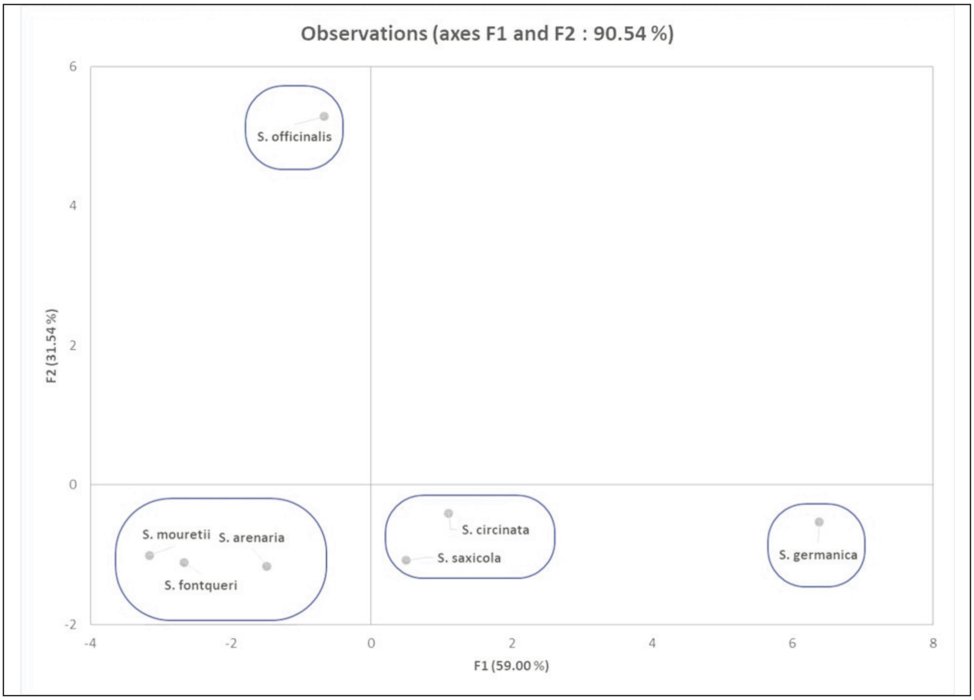


Fig. 5. Positions of the seven *Stachys* species in the orthogonal plane defined by the principal components (F1-F2 plane) of the seed physical characteristics.

tial and resource allocation. These traits may reflect adaptation to habitats with intermediate resource availability or moderate environmental stress, such as rocky areas (*S. saxicola*) or semi-arid to subhumid zones (*S. circinata*) (Fennane & al. 2007).

The PCA highlights clear differentiation among species based on seed traits, which could be taxonomically significant in future studies. The physical characteristics of *Stachys* seeds, such as surface area, aspect ratio, and shape, can provide valuable insights into species classification within the genus. For example, the seeds of *Stachys officinalis* exhibit a notably low aspect ratio (0.56) compared to other species in the genus. This is particularly interesting as these data support the prior placement of *S. officinalis* within *Betonica*. *Betonica* is already distinguished from *Stachys* by having a persistent rosette of leaves, flowering stems lateral to rootstock, sessile flowers, flowers and bracteoles with a broad and hardened base, and anther cells that are parallel (Bhattacharjee 1980). The corolla of *Betonica* species, including *B. officinalis*, is characterized by its tubular structure and a distinctly more slender bifid upper lip, which is often straight and less lobed (Fig. 6).

Recent molecular phylogenetic studies (Scheen & al. 2010; Bendiksby & al. 2011; Salmaki & al. 2013) have confirmed that *Betonica* forms a distinct lineage within the tribe *Stachydeae* and is not closely related to *Stachys*.

Salmaki & al. (2013) conducted a comprehensive molecular phylogenetic analysis of the tribe *Stachydeae* within the *Lamiaceae* family and they identified *S. germanica* as part of a distinct clade within the tribe, separate from other species such as *S. arenaria, S. circinata,* and *S. saxicola*. This phylogenetic positioning suggests that *S. germanica* may also warrant reclassification into a different genus, such as *Eriostomum*. The same study supports that *Betonica* is distinct from *Stachys* and more closely related to *Galeopsis*.

These floral distinctions, combined with seed morphology, emphasize the morphological divergence between *Betonica* and *Stachys*. Although most taxonomists treat *S. officinalis* as *Betonica officinalis*, many regional floras, including those of Morocco, continue to use the name *Stachys officinalis*.

Ecologically, large-seeded species like *S. germanica* may favor seedling establishment under stable conditions, while small-seeded species such as *S. mouretii*, *S. arenaria*, and *S. fontqueri* may be better suited to unpredictable, nutrient-poor environments where dispersal and dormancy are key survival strategies. Seeds with higher moisture content (like S. officinalis in Tangier) may favor rapid germination when water is available, while low moisture seeds (*S. mouretii* and others) may reflect drier or less predictable conditions, where dormancy and long-term viability can be advantageous (Fenner & Thompson 2006).

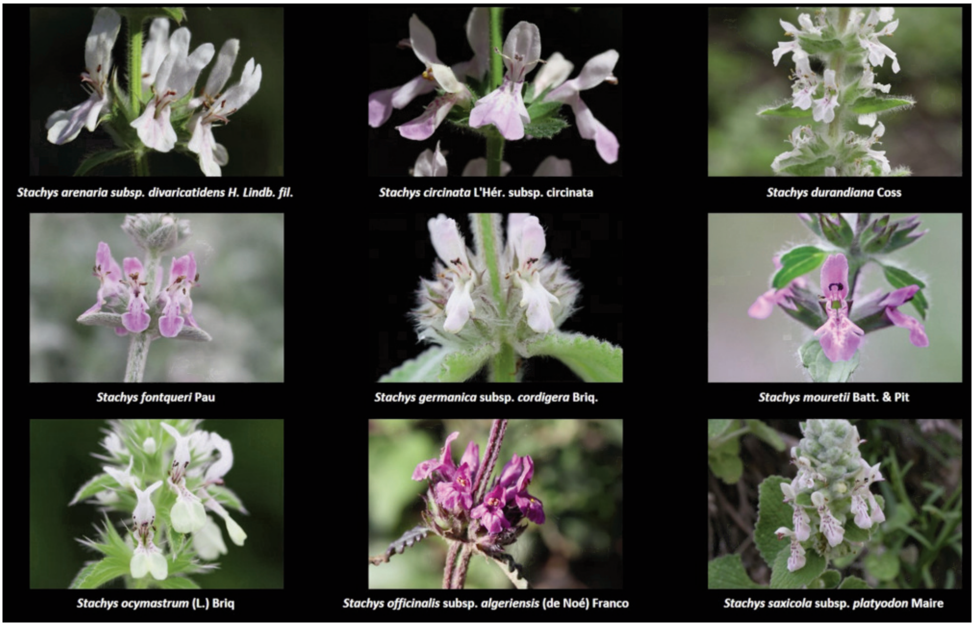


Fig. 6. Morphological flower characteristics of the selected Moroccan *Stachys* taxa (Photographic credit: A. Homrani Bakali).

Conclusion

This study highlights significant interspecific variability in seed traits among the *Stachys* species, likely reflecting ecological adaptation to diverse habitats. The clear distinctions in seed morphology, moisture content, and physical properties provide useful quantitative characters for comparing species and may help to describe patterns of morphological differentiation within the group. *S. germanica* was clearly distinguished by its larger seed dimensions, greater surface area, and higher 1000-seed mass, whereas *S. mouretii, S. fontqueri,* and *S. arenaria* generally showed smaller seed dimensions and lower seed mass. *S. officinalis* showed a distinct profile mainly related to its higher moisture content and more elongated seed shape, as reflected by its lower sphericity and aspect ratio. This pattern is consistent with its morphological distinctiveness, but it should be considered complementary to previous systematic evidence distinguishing *Betonica* from *Stachys*, not as independent taxonomic proof. *S. circinata* and *S. saxicola* displayed intermediate seed traits.

Overall, the results demonstrate that seed physical traits can contribute valuable information for species comparison within *Stachys*. Nevertheless, ecological and taxonomic interpretations require caution, because this study did not directly assess germination, dormancy, dispersal ability, seedling performance, genetic variation, karyology, or field-based ecological responses. Future studies combining seed morphology with molecular, karyological, reproductive, germination, dormancy, and ecological data will be necessary to clarify the functional and systematic significance of these seed traits.

Limitations and perspectives

We acknowledge that the sample size used in this study, 15 seeds per taxon for most morphometric measurements, represents a limitation. This constraint was mainly related to the limited availability of mature and viable seeds from natural populations. Therefore, the results should be interpreted as preliminary comparative seed-morphological data rather than as definitive evidence of ecological adaptation or taxonomic separation. Future studies should include larger and more representative samples from multiple populations across the distribution range of each taxon. Integrating seed morphology with germination experiments, dormancy studies, seedling-performance assays, karyology, molecular data, and broader morphological characters would provide a stronger basis for evaluating the ecological and systematic significance of the observed seed-trait variation.

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