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ORIGINAL RESEARCH

Characterization of the morphological and ecological characteristics of the endemic *Phlomis chimerae* Boissieu, in Antalya, Türkiye

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Abstract
Phlomis chimerae Boissieu is an endemic species found in the western region of Antalya, Türkiye. Due to its pharmacological properties, the species is being harvested indiscriminately and faces increasing anthropogenic pressure. This study aimed to determine the morphological diversity and habitat conditions of *P. chimerae* in its natural populations and to evaluate its potential for use as an ornamental plant. Morphological characterization was performed on 44 individuals representing nine natural populations, sampled at intervals of ≥100 m, based on 39 characters. Variance, principal component, and cluster analyses were performed on the obtained mean values. The findings revealed that the species has a very narrow distribution range, occurring primarily on steep slopes from sea level to 500 m. It was determined that approximately 70% of the populations preferred habitats oriented east-southeast-south-southwest. PCA and UPGMA analyses confirmed that morphological characteristics showed significant variation within and between populations.The results are expected to provide a scientific basis for understanding the distribution of *P. chimerae*, evaluating it as an ornamental plant, and conducting breeding studies for the conservation of the species.

Keywords Lamiaceae · Ornamental plant · Morphological characteristics · Medicinal aromatic plants · Endemic species

Introduction

Phlomis chimerae Boissieu is a locally endemic species belonging to the family Lamiaceae, native to Türkiye and naturally distributed in the western part of Antalya. According to the Red Data Book of Turkish Plants, it is classified as “Lower Risk (conservation-dependent)” (Başer, 2000a; Ekim et al. 2000). The species mostly occurs in *Pinus brutia* forests, maquis

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vegetation, and rocky habitats within Mediterranean ecosystems (Celik et al. 2005; Dadandı 2002; Deniz and Aykurt 2016).

The genus *Phlomis* comprises approximately 100 species worldwide (Mathiesen et al., 2011). In the *Flora of Turkey* by Davis et al. (1965), the genus is represented by 50 taxa, including 40 species and subspecies and 10 hybrids. A later revision study evaluated 58 taxa, including 39 species and subspecies and 19 hybrids (Dadandı 2002). In the "List of Turkish Plants," the genus is represented by 52 taxa, including 39 species and subspecies and 13 hybrids (Güner et al., 2012). Within this genus, *P. chimerae* represents a geographically restricted endemic taxon with ecological and conservation relevance.

Locally known as "Çalba" or "Kimera Şalbası" (Deniz and Aykurt 2016; Baytop 2015), *P. chimerae* is a perennial dwarf shrub reaching approximately 30 cm in height. The species blooms between April and August (Deniz and Aykurt 2016). It exhibits distinctive morphological characteristics, including greenish leaves with stellate hairs on the upper surface and densely tomentose, whitish lower surfaces (Davis et al. 1965; Deniz and Aykurt 2016). The flowers are yellow, 25–30 mm in length, with characteristic bracts (Deniz and Aykurt 2016). These structural traits, together with its compact growth form and drought tolerance, enhance its ornamental potential in Mediterranean landscape applications.

Similar to many members of the Lamiaceae family, *P. chimerae* is rich in volatile and aromatic oils and is evaluated among medicinal and aromatic plants (Valant-Vetschera et al. 2003). Its major chemical constituents include β-caryophyllene, α-pinene, and germacrene-D (Celik et al. 2005), along with iridoids, flavonoids, phenylpropanoids, phenylethanoids, lignans, neolignans, diterpenoids, alkaloids, and essential oils (Kamel et al. 2000; Zhang and Wang 2008). These phytochemicals are associated with antiseptic, antioxidant, antimicrobial, and anti-inflammatory properties (Amor et al. 2009; Zhang and Wang 2008). The essential oil profile includes β-caryophyllene (31.6%), α-pinene (11%), and germacrene-D (6.1%) (Celik et al. 2005). Its high monoterpene (27.9%) and sesquiterpene (62.5%) content further supports its pharmaceutical and cosmetic applications (Başer, 2000a). Additionally, some species of the genus are traditionally used as herbal tea for respiratory and digestive disorders (Sokovic et al., 2002; Amor et al. 2009).

In the context of increasing biodiversity loss and habitat degradation, the conservation and sustainable utilization of locally endemic species have become strategically important for the ornamental plant industry (Krigas et al. 2021; Pipinis et al. 2022). The use of ecologically adapted native species in landscape design provides significant environmental and economic advantages by conserving genetic resources and ensuring plant material suited to local climatic and edaphic conditions (Kayıkçı and Güzel 2023). This approach strengthens ecosystem services and contributes to local economies.

Natural plant populations represent valuable genetic resources due to their high variability (Gray 1996; Chung et al. 2023). Although morphological traits are influenced by environmental conditions, they are widely used to assess genetic diversity and intraspecific variation (Hien et al. 2007; Kumar et al. 2025). Flower and leaf characters guide species identification, cultivation potential, and suitable habitat selection (Zhang et al. 2020; Gao et al. 2023). Understanding distribution patterns and ecological requirements is therefore crucial for effective conservation strategies. Although the species has been taxonomically described in Flora of Turkey (Davis et al. 1965), no comprehensive popu-

lation-level study has evaluated the morphological variation and habitat relationships of natural *P. chimerae* populations. This gap represents an important limitation for both conservation planning and ornamental plant development. Therefore, this study aims to (i) determine morphological variation in natural populations of *P. chimerae* in Antalya, (ii) evaluate its relationships with habitat and edaphic factors, and (iii) assess its suitability as an ornamental species.

Materials and methods

Study area and habitat characteristics

The study area includes natural populations of *P. chimerae* distributed in the Kemer, Kumluca, and Döşemealtı districts of Antalya, located in the eastern Mediterranean region of southwestern Türkiye. The region is bordered by the Mediterranean Sea to the south and the Taurus Mountains to the north. It has a typical Mediterranean climate, with an annual average temperature of 19.0 °C, maximum temperature of 45.0 °C, minimum temperature of −4.6 °C, and annual precipitation of 1059.4 mm (Turkish State Meteorological Service, 2023).

Field sampling

Plant samples were collected from nine natural populations in western Antalya during the flowering period (April–August 2021). In total, 44 individuals representing nine locations were sampled for morphological measurements. A minimum distance of ≥100 m was maintained between individuals to reduce spatial autocorrelation and ensure representative sampling of population variation. Individuals were located from sea level up to approximately 500 m elevation. Sampling sites were determined based on previous occurrence records and known altitudinal limits of the species.

The plant material was collected by authors Ceren Selim, Merve Yildiz and İ. Gökhan Deniz and voucher specimens were deposited in the Herbarium of the Faculty of Education, Akdeniz University (AKDE), under the record "AKDE 11312". The species was taxonomically identified by Prof. Dr. İ. Gökhan Deniz, taxonomist at Akdeniz University, based on morphological characteristics and comparison with the Flora of Turkey.

Sampling sites and digital elevation model data are presented in Fig. 1. Coordinates, elevation, slope, and aspect information for each sampled individual are given in Table 1.

Morphological measurements

Morphological parameters were measured from 44 individuals collected from the field during the generative period (March–July 2021). Measured traits included plant height (Fig. 2A), canopy diameter, leaf and flower structures (length/width/petiole length), inflorescence and floral structure characteristics, calyx and corolla dimensions, and lip structures (Fig. 2B). Mean values were calculated for each parameter. In addition, color measurements were performed using the CIELAB colorimetric system on the second pair of leaves located below the inflorescence, based on 10 randomly selected flowers from each individual.

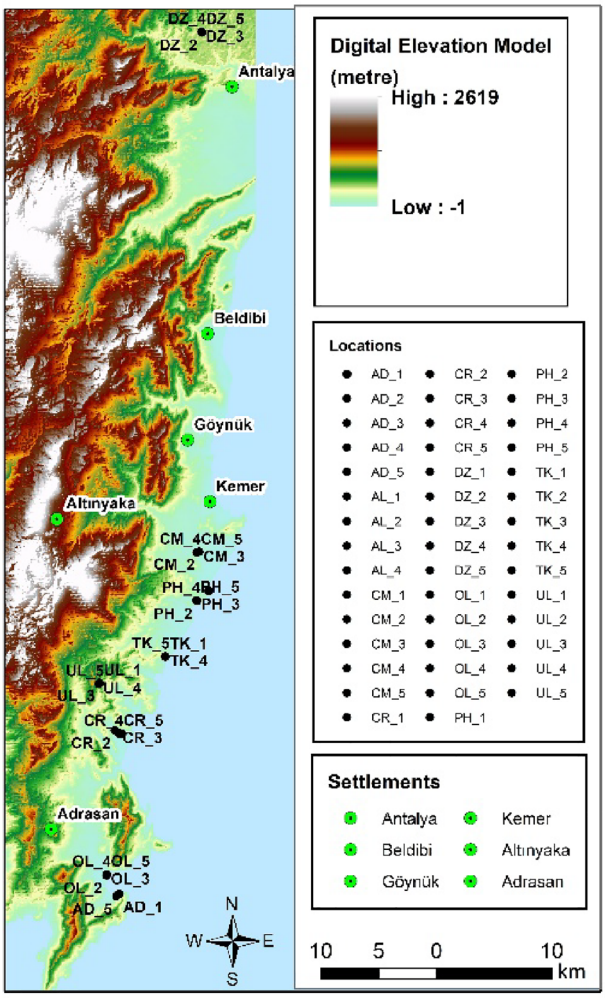

Fig. 1 Digital elevation map of the study area and location of sampling individuals. *Individual codes: UL1:Ulupınar1, UL2: Ulupınar2, UL3: Ulupınar3, UL4: Ulupınar4, UL5: Ulupınar5, PH1: Phaselis1, PH2:Phaselis2, PH3:Phaselis3, PH4:Phaselis4, PH5:Phaselis5, TK1: Tekirova1, TK2: Tekirova2, TK3: Tekirova3, TK4: Tekirova4, TK5: Tekirova5, AL1: Alacasu1, AL2: Alacasu2, AL3: Alacasu3, AL4: Alacasu4, OL1: Olimpos1, OL2: Olimpos2, OL3: Olimpos3, OL4: Olimpos4, OL5: Olimpos5, DZ1: Düzlerçamı1, DZ2: Düzlerçamı2, DZ3: Düzlerçamı3, DZ4: Düzlerçamı4, DZ5: Düzlerçamı5, AD1: Adrasan1, AD2: Adrasan2, AD3: Adrasan3, AD4: Adrasan4, AD5: Adrasan5, CR1: Çıralı1, CR2: Çıralı2, CR3: Çıralı3, CR4: Çıralı4, CR5: Çıralı5, CM1: Çamyuva1, CM2: Çamyuva2, CM3: Çamyuva3, CM4: Çamyuva4, CM5: Çamyuva5

Ecological and edaphic traits

Habitat types in which the species naturally occurs (stony, rocky, and maquis habitats) and associated plant communities were identified. Topographical parameters (slope, aspect, and elevation) were mapped using ASTER DEM data with 30-m resolution in ArcMap (ESRI version 20). Soil samples collected from each location were analyzed for pH, organic matter, and macro/micronutrient contents.

Statistical analysis

Descriptive statistics (mean, standard deviation, minimum, maximum) were calculated. The Shapiro–Wilk test was used to assess the normality assumption. For variables with normal distribution, one-way analysis of variance (ANOVA) was applied to test differences among locations, followed by Tukey's test for pairwise comparisons. When normality was not sat-

Table 1 GPS, altitude and aspect data of populations and sampling individuals

Origin site	Codes of individuals	Genotype name	Latitude (*N*)/Longitude (E)		Slope (%)	Altitude	Aspect
Döşemealtı District	**DUZLERÇAMI POPULATION**						
	DZ1	DÜZLERÇAMI-1	36.972763°	30.536230°	4	241	East
	DZ2	DÜZLERÇAMI-2	36.972823°	30.535956°	3	297	Northeast
	DZ3	DÜZLERÇAMI-3	36.972981°	30.535893°	2	297	East
	DZ4	DÜZLERÇAMI-4	36.973040°	30.535746°	2	295	East
	DZ5	DÜZLERÇAMI-5	36.972872°	30.536040°	4	296	East
Kemer District	**ALACASU POPULATION**						
	AL1	ALACASU-1	36.536791	30.556577	4	20	Southeast
	AL2	ALACASU-2	36.536921	30.556716	5	22	South
	AL3	ALACASU-3	36.536834	30.556595	4	24	Southeast
	AL4	ALACASU-4	36.536879	30.556465	4	27	Southeast
	ULUPINAR POPULATION						
	UL1	ULUPINAR-1	36.462540°	30.453441°	13	463	East
	UL2	ULUPINAR-2	36.462499°	30.453233°	15	468	East
	UL3	ULUPINAR-3	36.462776°	30.453219°	17	452	East
	UL4	ULUPINAR-4	36.461940°	30.452944°	25	475	East
	UL5	ULUPINAR-5	36.461902°	30.453031°	25	471	East
	ÇAMYUVA POPULATION						
	CM1	ÇAMYUVA-1	36.567255°	30.546418°	10	35	Northwest
	CM2	ÇAMYUVA-2	36.567227°	30.546446°	9	35	Northwest
	CM3	ÇAMYUVA-3	36.567240°	30.546493°	9	29	Northwest
	CM4	ÇAMYUVA-4	36.566759°	30.544140°	7	24	Northwest
	CM5	ÇAMYUVA-5	36.566649°	30.544124°	7	22	Northwest
	ÇIRALI POPULATION						
	CR1+	ÇIRALI-1	36.426034°	30.469479°	5	10	Southwest
	CR2	ÇIRALI-2	36.426028°	30.469668°	9	15	Southwest
	CR3	ÇIRALI-3	36.424114°	30.472935°	3	2	Southwest
	CR4	ÇIRALI-4	36.423372°	30.476588°	2	3	Southeast
	CR5	ÇIRALI-5	36.423577°	30.473770°	6	1	South
	TEKİROVA POPULATION						
	TK1	TEKİROVA-1	36.484655°	30.516487°	11	42	East
	TK2	TEKİROVA-2	36.484709°	30.516471°	11	41	East
	TK3	TEKİROVA-3	36.484705°	30.516391°	11	40	East
	TK4	TEKİROVA-4	36.484697°	30.516359°	13	41	East
	TK5	TEKİROVA-5	36.484752°	30.516285°	15	45	East
	PHASELIS POPULATION						
	PH1	PHASELİS-1	36.528659°	30.545564°	11	18	Southwest
	PH2	PHASELİS-2	36.528769°	30.545409°	10	14	Southwest
	PH3	PHASELİS-3	36.528877°	30.545430°	10	18	Southwest
	PH4	PHASELİS-4	36.528953°	30.545418°	10	27	Southwest
	PH5	PHASELİS-5	36.529303°	30.545065°	15	18	Southwest

Table 1 (continued)

Origin site	Codes of individuals	Genotype name	Latitude (*N*)/Longitude (E)		Slope (%)	Altitude	Aspect
Kumluca District	**ADRASAN POPULATION**						
	AD1	ADRASAN-1	36.298284°	30.477655°	2	6	Northwest
	AD2	ADRASAN-2	36.298181°	30.477771°	3	13	Northwest
	AD3	ADRASAN-3	36.298033°	30.477530°	4	13	Northwest
	AD4	ADRASAN-4	36.298065°	30.477182°	4	5	Northwest
	AD5	ADRASAN-5	36.296403°	30.475116°	9	32	Northwest
	OLIMPOS POPULATION						
	OL1	OLİMPOS-1	36.312568°	30.465285°	12	47	Southeast
	OL2	OLİMPOS-2	36.312675°	30.465254°	13	49	Southeast
	OL3	OLİMPOS-3	36.312790°	30.465210°	15	50	Southeast
	OL4	OLİMPOS-4	36.313159°	30.465384°	15	52	Southeast
	OL5	OLİMPOS-5	36.313435°	30.465349°	24	54	East

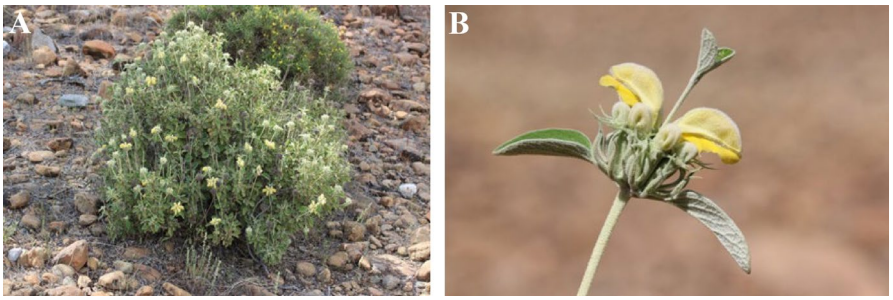

Fig. 2 Morphological characteristics of *P. chimerae*: (**A**) general habit; (**B**) flower and leaf structure (Original photograph)

isfied, the Kruskal–Wallis H test was used, and significant results were further evaluated with the Bonferroni–Dunn procedure. Relationships between quantitative variables were examined using Pearson's correlation test for parametric data and Spearman's correlation test for non-parametric data. Statistical significance was accepted at $p < 0.05$. Principal component and cluster analyses were performed using PROC FACTOR and PROC CLUSTER procedures in SAS statistical software to evaluate morphological and ecological relationships among individuals and populations. A heatmap was generated using the ggplot package in R software.

Results

Topographic and habitat characteristics

P. chimerae is distributed within the districts of Kumluca, Kemer, and Döşemealtı, across an altitudinal gradient ranging from 1 m to 475 m above sea level (Table 1), an area characterized by considerable variation in slope. Digital elevation model analysis and slope mapping

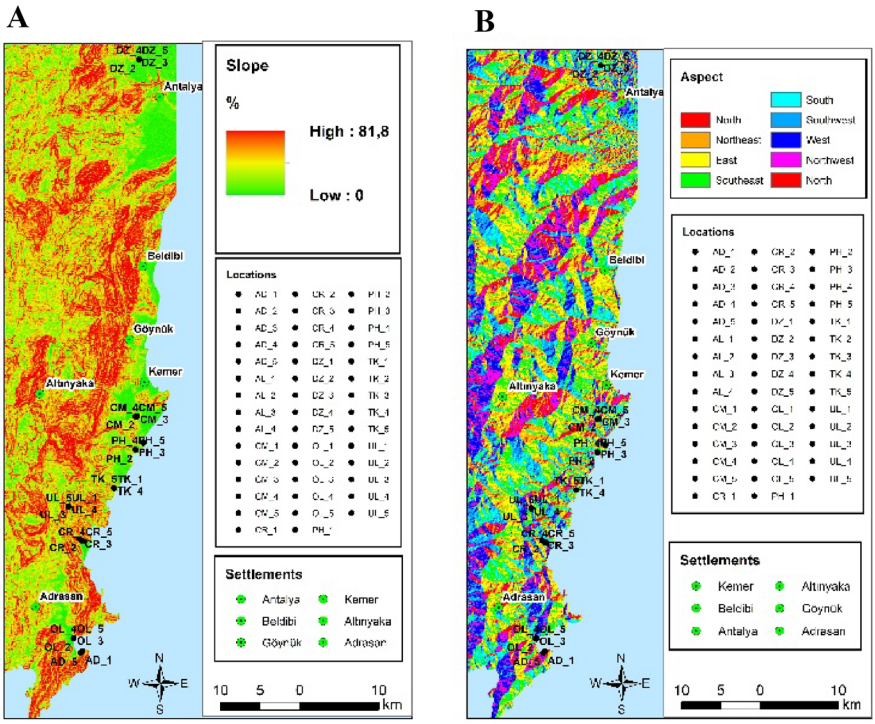

Fig. 3 (**A**) Slope and (**B**) aspect maps of the study area. *Individual codes: UL1:Ulupınar1, UL2: Ulupınar2, UL3: Ulupınar3, UL4: Ulupınar4, UL5: Ulupınar5, PH1: Phaselis1, PH2:Phaselis2, PH3:Phaselis3, PH4:Phaselis4, PH5:Phaselis5, TK1: Tekirova1, TK2: Tekirova2, TK3: Tekirova3, TK4: Tekirova4, TK5: Tekirova5, AL1: Alacasu1, AL2: Alacasu2, AL3: Alacasu3, AL4: Alacasu4, OL1: Olimpos1, OL2: Olimpos2, OL3: Olimpos3, OL4: Olimpos4, OL5: Olimpos5, DZ1: Düzlerçamı1, DZ2: Düzlerçamı2, DZ3: Düzlerçamı3, DZ4: Düzlerçamı4, DZ5: Düzlerçamı5, AD1: Adrasan1, AD2: Adrasan2, AD3: Adrasan3, AD4: Adrasan4, AD5: Adrasan5, CR1: Çıralı1, CR2: Çıralı2, CR3: Çıralı3, CR4: Çıralı4, CR5: Çıralı5, CM1: Çamyuva1, CM2: Çamyuva2, CM3: Çamyuva3, CM4: Çamyuva4, CM5: Çamyuva5

(Fig. 3A) revealed a strong association between the species' distribution and topographic features. The majority of sampled individuals occurred below 100 m elevation; slope values across sampling sites varied between 2% and 25%. The highest slope values were recorded in the Ulupınar population (mean 19%), whereas the lowest slopes were observed in Düzlerçamı and Adrasan (2–4%). Overall, 81.8% of the sampling locations were situated on moderate to steep slopes.

Aspect analysis (Fig. 3B) indicated a clear directional distribution pattern. East-facing slopes accounted for 34% of individuals, northwest-facing slopes for 22%, southeast-facing slopes for 18%, and southwest-facing slopes for 18%. The remaining individuals were distributed across other orientations at lower frequencies.

Habitat observations showed that the species predominantly occurred in rocky and stony substrates, often within Pinus brutia forest understories and maquis vegetation. Individuals were generally found in open or semi-open areas with well-drained soils.

Morphological variation among populations

Vegetative traits

Significant differences were detected among populations in plant height parameters (PHMIN, PHMAX, PHAVE) ($p < 0.05$; Table 2). The highest mean plant height values were recorded in the Tekirova, Çıralı, and Çamyuva populations, whereas Düzlerçamı exhibited the lowest height measurements.

In contrast, canopy diameter parameters (PDMIN, PDMAX, PDAVE) did not show statistically significant differences among populations ($p > 0.05$), indicating relatively stable horizontal growth across sites.

Leaf morphological traits exhibited significant inter-population variation (Table 3). Leaf length (LL) and leaf width (LW) differed significantly among populations ($p < 0.05$). The Çamyuva and Phaselis populations showed higher mean leaf dimensions, whereas Düzlerçamı and Alacasu presented comparatively smaller leaves. Petiole length (PETL) also varied significantly, with longer petioles observed in Tekirova and Olympos populations.

Floral and reproductive traits

Significant differences were observed in several floral characteristics (Table 3). Spike width (SW), spike length (SL), and flower stalk length (PEDL) varied significantly among populations ($p < 0.05$). Tekirova and Olympos populations exhibited greater spike width and longer peduncles compared to other populations.

Calyx width (CW) and calyx length (CL) showed significant variation ($p < 0.05$), whereas calyx tooth length (CTL) did not differ significantly among populations ($p > 0.05$). Corolla dimensions, including corolla width (COW) and corolla length (COL), also displayed statistically significant variation across populations.

Circular flower number (CFN) did not differ significantly among populations ($p > 0.05$), indicating relative stability in this reproductive trait.

Leaf colorimetric traits

Colorimetric analysis revealed significant differences among populations in lightness (LGHT), chroma (CROMA), and hue angle (HUE) values ($p < 0.05$; Table 3).

Tekirova and Adrasan populations exhibited higher lightness values, whereas Düzlerçamı showed lower LGHT measurements. Chroma values were highest in Tekirova and Çamyuva populations. Hue angle varied significantly among populations, with Alacasu exhibiting the highest mean HUE value and Çıralı the lowest.

These results demonstrate clear inter-population differentiation in leaf pigmentation traits.

Table 2 Between population differences in ecological and growth traits of *P. chimerae*

Source of variation	*df	SLP	ALT	ASP	**PHMIN	PHMAX	PHAVE	PDMIN	PDMAX	PDAVE
Mean squares between locations	8	-	-	-	-	-	-	1941.59	3281.82	2255.34
P value		$<0.0001^2$	$<0.0001^2$	$<0.0001^2$	0.036^2	0.002^2	0.006^2	0.12^1	0.145^1	0.103^1
Error Mean Squares	35	-	-	-	-	-	-	5.35	7.11	5.68
Test statistic (F(Anova)/ χ^2KW)		37.606	40.351	41.346	16.480	24.283	21.423	1.756	1.656	1.836
Locations	**Mean±Standard Deviation**									
***DZ	5	3±1e	285.2±24.72abc	2.8±0.45e	29.6±5.55b	71±2.24b	50.3±3.51b	88±24.89	133±17.88	110.5±3.70
AL	4	4.25±0.5e	23.25±2.99ab	4.25±0.5c	58.75±2.5a	111.25±27.8ab	85±14.72a	130±27.08	212.5±49.91	171.25±3.70
UL	5	19±5.66a	465.8±8.87abc	3±0de	47.4±8.59ab	111±5.48ab	79.2±6.57ab	120±36.91	207±69.24	163.5±48.46
CM	5	8.4±1.34cde	29±6.04ab	8±0a	49±15.57ab	128±30.33a	88.5±21.98a	146±40.37	212±25.88	179±26.55
CR	5	5±2.74de	6.2±6.06ab	5.4±0.89b	52±13.04a	142±31.94a	97±20.19a	158±37.01	196±29.66	177±32.71
TK	5	12.2±1.79bc	41.8±1.92ab	3±0de	46±7.42ab	155±20.92a	100.5±12.42a	116±28.80	164±49.29	140±38.56
AD	5	4.4±2.7e	13.8±10.85ab	8±0a	44±6.52ab	119±20.74a	81.5±12.07a	126±46.15	176±44.49	151±44.07
PH	5	11.2±2.17bcd	19±4.8ab	6±0b	40±3.54ab	111±20.74ab	75.5±11.24ab	130±25.49	176±46.15	153±31.74
OL	5	15.8±4.76ab	50.4±2.7abc	3.8±0.45 cd	45±16.2ab	122±8.37a	83.5±10.69a	136±23.02	188±47.64	162±33.09
All Locations mean±std		9.36±6.06	105.66±155.13	4.93±2.02	45.45±11.81	119.09±29.6	82.27±18.66	127.73±35.51	184.32±47.16	156.02±37.68
Min.		2	1	2	23	70	46.5	50	110	95
Max.		25	475	8	65	190	125	200	290	225

[1]Analysis of variance (ANOVA), [2]Kruskal Wallis H (KW) test were used.*df: degree of freedom. The different lowercase letters throughout the column indicate statistical significance ($p<0.05$). **SLP: Slope, ALT: Altitude, ASP: Aspect, PHMIN: Plant height minimum, PHMAX: Plant height maximum, PHAVE: Plant height average, PDMIN: Plant distribution area diameter minimum, PDMAX: Plant distribution area diameter maximum, PDAVE: Plant distribution area diameter average. ***DZ: Düzlerçamı, AL: Alcasu, UL: Ulupinar, CM: Çamyuva, CR: Cirali, TK: Tekirova, AD: Adrasan, PH: Phaselis, OL: Olympos

Edaphic variation among populations

Soil chemical properties

Soil pH values ranged between 6.5 and 7.5 across populations, with a mean value of 6.96. No statistically significant differences were detected among populations in terms of pH ($p > 0.05$; Table 4). Calcimetric lime content differed significantly among populations ($p < 0.05$). The highest lime content was recorded in the Ulupınar population (3.76%), whereas Düzlerçamı exhibited the lowest values. Soil salinity (SALT) showed significant variation among populations ($p < 0.05$). The highest salinity levels were measured in Çamyuva, while the lowest values were recorded in Düzlerçamı. Soil saturation (SOSAT) values ranged from 42% to 121%, with a mean of 70.36%. Significant differences were detected among populations ($p < 0.05$). Phaselis exhibited the highest saturation values, whereas Adrasan and Olympos showed comparatively lower levels. Organic matter (OM), total nitrogen (N), and available phosphorus (P) did not differ significantly among populations ($p > 0.05$).

Soil nutrient status

Available potassium (K) levels varied significantly among populations ($p < 0.05$). The highest K concentrations were observed in Çıralı, while Düzlerçamı exhibited the lowest values. Extractable magnesium (Mg) also showed significant inter-population differences ($p < 0.05$), with Çıralı presenting the highest concentrations. Iron (Fe) and manganese (Mn) contents differed significantly among populations ($p < 0.05$). The highest Fe concentrations were recorded in Çıralı and Phaselis, whereas Olympos showed the lowest values. Mn followed a similar distribution pattern. Copper (Cu) content also varied significantly ($p < 0.05$), while zinc (Zn) and calcium (Ca) did not show statistically significant differences among populations ($p > 0.05$). Overall, soil analyses revealed substantial edaphic heterogeneity across sampling sites.

Trait–environment relationships

Correlation analysis revealed significant associations between topographic, edaphic, and morphological variables (Fig. 4). Elevation showed a significant negative correlation with mean plant height (PHAVE) ($r = -0.39$, $p < 0.05$), indicating reduced plant height at higher altitudes. A positive correlation was detected between canopy diameter and plant height ($r = 0.57$, $p < 0.05$). Leaf length (LL) was positively correlated with leaf width (LW) ($r = 0.64$, $p < 0.05$) and aspect ($r = 0.31$, $p < 0.05$). Petiole length (PETL) was positively associated with elevation ($r = 0.42$, $p < 0.05$) and leaf length ($r = 0.57$, $p < 0.05$). Significant positive correlations were observed between plant height parameters and several floral traits, including spike length (SL) and flower stalk length (PEDL) ($p < 0.05$). Among edaphic variables, potassium (K) content showed positive correlations with minimum plant height (PHMIN) ($r = 0.31$, $p < 0.05$), mean canopy diameter (PDAVE) ($r = 0.31$, $p < 0.05$), and calyx width (CW) ($r = 0.33$, $p < 0.05$). Iron (Fe) exhibited a negative correlation with spike width (SW) ($r = -0.33$, $p < 0.05$), whereas zinc (Zn) was negatively correlated with upper lip length (ULL) ($r = -0.46$, $p < 0.05$). Leaf color parameters were significantly associated with multiple morphological variables. Lightness (LGHT), chroma (CROMA), and hue angle (HUE) showed

Table 3 Trait differences among *P. chimerae* populations

Mean squares and *P* values											
Source of variation	*df	**LW(cm)	LL(cm)	PETL(cm)	SW(cm)	SL(cm)	PEDL(cm)	CFN	CW(mm)	CL(mm)	CTL(mm)
Mean squares between locations	**88**	-	-	0.152	-	-	-	0.334	-	0.027	0.024
P value		0.044[2]	0.005[2]	0.004[1]	0.007[2]	0.015[2]	0.001[2]	0.121[1]	0.045[2]	0.015[1]	0.168[1]
Error Mean Squares	335	-	-	0.038	-	-	-	0.070	-	0.017	0.019
Test statistic (F(Anova)/χ^2 KW)		15.922	22.163	3.520	21.014	18.949	25.633	1.753	15.801	2.847	10.814
In-location		**Mean±Standard Deviation**									
DZ***	55	1.8±1.16ab	2.1±0.18b	0.8±0.21b	1.83±0.34b	2.23±0.24b	3.81±0.98 cd	1.5±0.21	0.44±0.05b	1.15±0.09ab	0.64±0.07
AL	44	1.4±0.17b	1.97±0.12b	0.76±0.12b	1.93±0.45ab	2.48±0.16ab	3.34±0.65d	1.92±0.70	0.55±0.2a	1.23±0.15ab	0.61±0.12
UL	55	1.58±0.28ab	2.27±0.52ab	0.79±0.22b	2.06±0.26ab	2.66±0.1a	4.5±1.07bcd	2.14±0.56	0.48±0.02ab	1.32±0.12a	0.68±0.06
CM	55	2.19±0.34a	3.04±0.44a	1.28±0.31a	2.25±0.46ab	2.64±0.11a	4.7±0.41abcd	2±0.38	0.41±0.03b	1.12±0.08b	0.67±0.08
CR	55	1.7±0.2ab	2.44±0.22ab	1.11±0.16ab	2.19±0.29ab	2.63±0.11a	4.83±0.82abcd	1.58±0.19	0.51±0.06ab	1.15±0.10ab	0.69±0.14
TK	55	1.94±0.29ab	2.71±0.2ab	1.10±0.16ab	2.78±0.44a	2.66±0.12a	6.13±1.33a	2.34±0.63	0.47±0.04ab	1.29±0.07ab	0.80±0.19
AD	55	1.63±0.38ab	2.3±0.47ab	1.05±0.26ab	2.65±0.75ab	2.7±0.13a	5.59±0.61abc	1.82±0.34	0.49±0.09ab	1.26±0.10ab	0.80±0.09
PH	55	1.91±0.24ab	2.92±0.42a	1.07±0.15ab	2.38±0.25ab	2.54±0.05a	5.1±0.92abcd	1.92±0.42	0.45±0.03ab	1.14±0.03ab	0.64±0.06
OL	55	1.78±0.41ab	2.48±0.56ab	0.95±0.18ab	2.85±0.43a	2.66±0.14a	6.59±0.98a	1.84±0.46	0.43±0.05b	1.17±0.08ab	0.75±0.17
All Locations mean ± sd	8	1.78±0.49	2.48±0.49	1.00±0.25	2.33±0.52	2.58±0.19	4.99±1.27	1.90±0.47	0.47±0.08	1.21±0.11	0.70±0.13
Min.		0.99	1.47	0.49	1.55	1.95	2.63	1	0.35	1.03	0.47
Max.		3.83	3.5	1.61	3.97	2.84	8.22	3	0.84	1.43	1.02

Table 3 (continued)

Mean squares and *P* values										
Source of variation	*df	**COW(mm)**	**COL(mm)**	**LLW(mm)**	**LLL(mm)**	**ULW(mm)**	**ULL(mm)**	**LGHT**	**CROMA**	**HUE**
Mean squares between locations	**88**	0.035	-	0.025	-	0.012	0.038	54.207	-	270.173286
P value		0.001[1]	0.004[2]	0.001[1]	0.004[2]	0.064[1]	0.001[1]	<0.0001[1]	0.002[2]	<0.001[1]
Error Mean Squares	335	0.017	-	0.014	-	0.012	0.018	0.606	-	1.296
Test statistic (F_{Anova}/χ^2 KW)		4.280	22.265	4.512	22.850	2.088	4.557	7.240	24.365	9.296
In-location		**Mean±Standard Deviation**								
DZ***	55	1.06±0.11c	1.84±0.09b	0.51±0.055c	0.87±0.07b	0.91±0.05	0.98±0.09c	45.24±3.62e	26.64±1.57b	102.6±5.33bcd
AL	44	1.29±0.9ab	2.11±0.06ab	0.72±0.117ab	1.09±0.09a	1.00±0.04	1.18±0.06ab	47.11±2.06cde	26.7±2.02b	117.3±1.32a
UL	55	1.28±0.11ab	2.26±0.08a	0.74±0.04a	1.13±0.08a	1.04±0.05	1.25±0.06a	49.60±2.13abcde	30.98±3.97ab	103.0±6.65bcd
CM	55	1.14±0.09bc	2.11±0.1ab	0.63±0.10abc	0.96±0.06ab	0.998±9.07	1.04±0.06bc	51.78±3.71abcd	33.64±1.75a	106.5±4.33abc
CR	55	1.2±0.07abc	2.05±0.11ab	0.61±0.06abc	0.98±0.08ab	1.07±0.09	1.09±0.07abc	52.74±1.57abc	29.89±4.43ab	93.97±6.55d
TK	55	1.26±0.06ab	2.12±0.1ab	0.63±0.06abc	1.12±0.1a	1.02±0.08	1.15±0.09abc	54.27±2.12a	36.3±1.16a	111.5±1.51ab
AD	55	1.25±0.07abc	2.23±0.13a	0.67±0.07ab	1.08±0.1a	1.03±0.11	1.13±0.04abc	53.41±1.37ab	31.22±5.22ab	99.88±7.64 cd
PH	55	1.21±0.12abc	2.1±0.12ab	0.57±0.067bc	0.96±0.12ab	1.01±0.07	1.00±0.06bc	46.28±2.59de	31.26±2.32ab	113.7±3.30ab
OL	55	1.34±0.03a	2.18±0.13ab	0.65±0.06abc	1.01±0.05ab	1.07±0.02	1.11±0.09abc	48.29±3.89bcde	26.53±3.88b	99.39±6.85 cd
All Locations mean±sd		1.23±0.11	2.11±0.15	0.64±0.10	1.02±0.11	1.02±0.08	1.11±0.12	49.92±4.02	30.43±4.34	105.07±8.60

Table 3 (continued)

Mean squares and *P* values									
Min.	0.93	1.75	0.46	0.77	0.85	0.73	42.32	22.15	86.09
Max.	1.39	2.41	0.84	1.24	1.21	1.32	57.99	37.64	118.39

[1]Analysis of variance (ANOVA), [2]Kruskal Wallis H (KW) test were used.*df: degree of freedom. The different lowercase letters throughout the column indicate statistical significance ($p<0.05$).** LW: Leaf width, LL: Leaf length, PETL: Petiole length, SW: Spike width, SL: Spike length, PEDL: Flower stalk length, CFN: Circular flower number, CW: Calyx width, CL: Calyx length, CTL: Calyx tooth length, COW: Corolla width, COL: Corolla length, LLW: Lower lip width, LLL: Lower lip length, ULW: Upper lip width, ULL: Upper lip length, LGHT: Lightness, CROMA: Chroma value and HUE: Leaf Hue angle.***DZ: Düzlerçamı, AL: Alcasu, UL: Ulupinar, CM: Çamyuva, CR: Cirali, TK: Tekirova, AD: Adrasan, PH: Phaselis, OL: Olympos

Table 4 Analysis of variance of *P. chimerae* populations in terms of edaphic characters between populations

Mean squares and *P* values															
Source of variation	*df	**pH	LIME (%)	SALT (%)	SOSAT (%)	OM	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Mean squares between locations	8	-	-	0.001	-	10.36	-	-	529.71	188133.19	191475.47	320.98	680.69	-	-
P values		0.27[2]	0.003[2]	0.01[1]	0.024[2]	0.12[1]	0.220[2]	0.11[2]	0.001[1]	0.19[1]	0.001[1]	0.034[1]	0.01[1]	0.11[2]	0.038[2]
Error Mean Squares	35	-	-	<0.0001	-	0.39	-	-	2.10	55.76	40.61	1.95	2.63	-	-
Test statistic (F(Anova)/ χ^2 (KW))		9.837	23.430	3.064	17.662	1.756	10.682	13.018	4.556	1.504	4.220	2.413	3.126	13.082	16.359
In-location		**Mean±Standard Deviation**													
***DZ	4	6.82±0.22	1.30±a	0.0108±0.003b	63±16.17b	4.314±1.644	0.19±0.11	1.82±1.31	30.26±3.71b	634.78±156.66	486±147.64b	35.11±10.44abc	32.51±11.01ab	1.27±0.59	1±0.13ab
AL	3	7.1±0.28	1.475±ab	0.0215±0.002ab	67±4.69b	3.305±0.775	0.11±0.01	1.47±0.6	47.67±12.69ab	574.05±152.73	792.20±181.59ab	37.36±12.15abc	30.39±10.89ab	0.95±0.23	1.13±0.12ab
UL	4	6.98±0.39	3.76±ab	0.0164±0.007ab	76±17.1ab	6.38±3.16	0.27±0.1	2.46±1.04	31±4.455b	1141.58±720.36	473.18±313.34b	46.42±17.38ab	22.66±7.460b	1.06±0.51	0.8±0.24b
CM	4	6.9±0.35	3.48±b	0.242±0.003ab	79.8±26.24ab	5.71±3.07	0.23±0.13	3.27±1.62	35.56±4.45b	793.40±419.18	672.32±213.12ab	47.63±12.62ab	29.67±20.45ab	1.74±0.89	1.1±0.16ab
CR	4	6.92±0.18	1.44±ab	0.0124±0.003a	77.6±3.13ab	5.87±2.19	0.28±0.1	2.08±0.76	62.64±10.72a	764.56±69.06	1012.04±198.70a	51.98±14.01a	58.50±18.73a	1.41±0.59	1.44±0.17a
TK	4	7±0.19	1.64±ab	0.0142±0.04ab	62.6±14.08b	4.18±2.63	0.2±0.1	1.49±0.62	35.06±12.16b	668.86±246.96	539.94±84.11b	34.50±11.50bc	27.53±11.83ab	0.7±0.38	1.35±1.57ab
AD	4	6.86±0.26	1.74±ab	0.0226±0.008ab	58.2±6.98b	4.68±0.77	0.23±0.11	3.47±3	41.7±10.42ab	666.14±222.0	350.70±72.95b	35.60±6.407abc	47.75±11.62ab	1.9±0.5	1.11±0.31ab
PH	4	6.88±0.13	1.74±ab	0.0204±0.008ab	89.8±22.13a	7.84±3.74	0.3±0.14	3.03±1.37	37.06±12.32b	1015.44±337.22	550.84±120.69b	49.04±8.569ab	44.01±21.02ab	1.73±1.47	1.17±0.37ab
OL	4	7.2±0.14	1.42±a	0.0178±0.007ab	58.6±7.06b	3.6±1.64	0.17±0.1	1.39±0.22	47.9±12.80ab	599.48±358.93	678.10±374.72ab	29.22±6.237c	28.67±12.36ab	1.01±0.43	1.15±0.38ab
All Locations mean±sd		6.96±0.26	2.01±1.68	0.02±0.01	70.36±17.41	5.14±2.59	0.22±0.11	2.29±1.50	40.83±13.9	765.4±369.86	613.28±269.36	40.84±12.96	35.87±17.43	1.32±0.76	1.14±0.56
Min		6.5	0.6	0.01	42	0.66	0.09	0.74	17.5	191.1	127.3	17	9.67	0.12	0.39
Max		7.5	9.2	0.04	121	12.33	0.44	7.98	80.4	2304.1	1304.7	69.9	76.9	4.24	4.15

[1]Analysis of variance (ANOVA), [2]Kruskal Wallis H (KW) test were used. *df: degree of freedom. The different lowercase letters throughout the column indicate statistical significance ($p<0.05$).

** pH: Common logarithm of hydrogen ion concentration, LIME (% calcimetric), SALT (% salinity), SOSAT (% soil saturation): <30%: sand, 30–50%: loam, 50–70%: clay loam, 70–110%: clay, >110%: heavy clay (Richards 1954), OM: Organic matter (%-TS8336), N: Total nitrogen (Kjeldahl), P: Plant-available phosphorus (kg K_2O/ha) (Acetate-ICP), K: Plant-available potassium (kg K_2O/da), Ca: Extractable calcium (kg CaO/da) (A.Acetate-ICP), Mg: Extractable magnesium (kg MgO/da), Fe: Plant-available iron (ppm), Mn: Plant-available manganese (ppm), Zn: Plant-available zinc (ppm), Cu: Plant useful copper (ppm)

*** DZ: Düzlerçamı, AL: Alcasu, UL: Ulupinar, CM: Çamyuva, CR: Cirali, TK: Tekirova, AD: Adrasan, PH: Phaselis, OL: Olympos

statistically significant correlations with vegetative and floral traits ($p < 0.05$). These results indicate structured relationships.

Multivariate structure of morphological and edaphic variation

Individual-Level Principal Component Analysis

Principal component analysis (PCA) was conducted using 39 morphological and edaphic variables measured across 44 individuals (excluding ecological variables such as slope, aspect, and elevation).

A total of six principal components were extracted. The first principal component explained 50.18% of the total variance, while the second accounted for 49.82%. Together, these two components represented the majority of the variation observed among individuals (Fig. 5).

Factor loadings indicated that the first component was primarily associated with edaphic variables, including organic matter (OM), total nitrogen (N), soil saturation (SOSAT), iron (Fe), zinc (Zn), manganese (Mn), and salinity (SALT) (Table 5).

The second component was mainly related to floral morphological traits, including lower lip length (LLL), corolla length (COL), lower lip width (LLW), upper lip width (ULW), upper lip length (ULL), corolla width (COW), spike length (SL), and calyx length (CL).

Individuals from Ulupınar, Olympos, Çamyuva, Adrasan, and Alacasu populations were distributed distinctly along the principal component axes. In particular, individuals coded UL2, UL3, CM4, AD4, AL1, AL2, and OL5 showed separation from the main cluster of individuals.

Population-level principal component analysis

Population-level PCA was performed using mean values of the same 39 morphological and edaphic variables.

The first principal component explained 56.10% of the total variance, and the second explained 29.96%. Together, the first three components accounted for 98.71% of the total variance.

The first principal component was primarily associated with plant size parameters, including plant height (PHAVE, PHMIN, PHMAX), canopy diameter (PDAVE, PDMAX), and leaf dimensions (LL, LW). The second principal component was associated mainly with soil-related variables, including organic matter (OM), salinity (SALT), iron (Fe), manganese (Mn), and magnesium (Mg).

Ulupınar population showed clear separation from other populations along the primary component axis. Çıralı and Phaselis populations also displayed differentiation relative to the remaining populations (Fig. 6).

Cluster analysis (UPGMA)

Hierarchical cluster analysis was performed using the unweighted pair-group method with arithmetic mean (UPGMA) based on the same dataset.

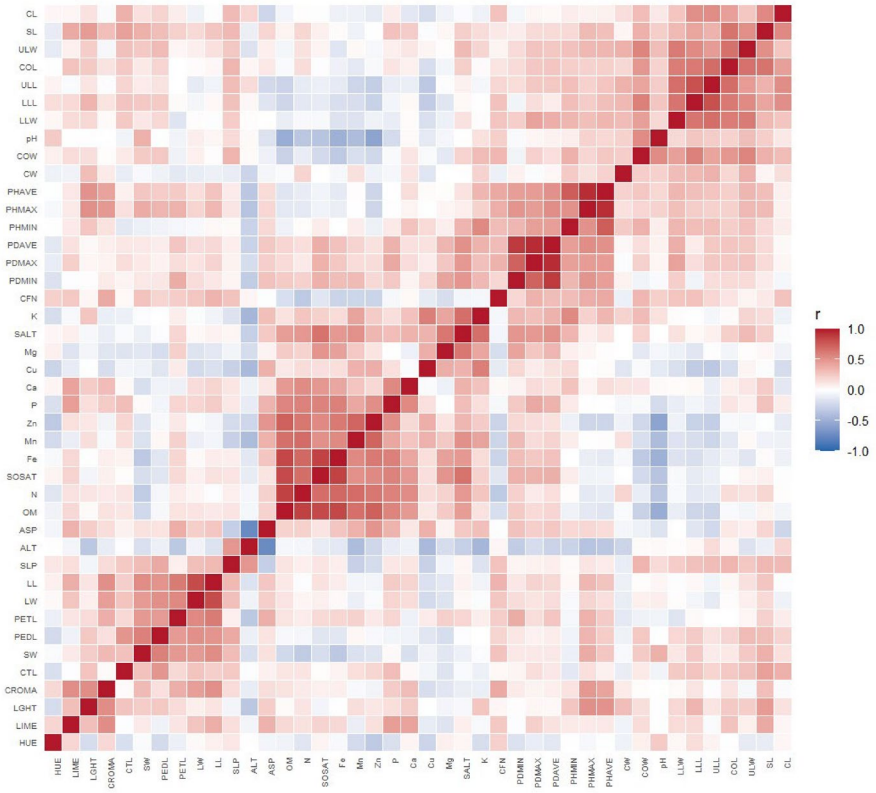

Fig. 4 Correlation heatmap of morphological, ecological and edaphic characters of the population. *SLP: Slope, ALT: Altitude, ASP: Aspect, PHMIN: Plant height minimum, PHMAX: Plant height maximum, PHAVE: Plant height average, PDMIN: Plant distribution area diameter minimum, PDMAX: Plant distribution area diameter maximum, PDAVE: Plant distribution area diameter average, LW: Leaf width, LL: Leaf length, PETL: Petiole length, SW: Spike width, SL: Spike length, PEDL: Flower stalk length, CFN: Circular flower number, CW: Calyx width, CL: Calyx length, CTL: Calyx tooth length, COW: Corolla width, COL: Corolla length, LLW: Lower lip width, LLL: Lower lip length, ULW: Upper lip width, ULL: Upper lip length, LGHT: Lightness, CROMA: Chroma value, HUE: Leaf Hue angle, pH: Common logarithm of hydrogen ion concentration, LIME (% calcimetric), SALT (% salinity), SOSAT (% soil saturation): <30%: sand, 30–50%: loam, 50–70%: clay loam, 70–110%: clay, >110%: heavy clay (Richards 1954), OM: Organic matter (%-TS8336), N: Total nitrogen (Kjeldahl), P: Plant-available phosphorus (kg K_2O/ha) (Acetate-ICP), K: Plant-available potassium (kg K_2O/da), Ca: Extractable calcium (kg CaO/da) (A.Acetate-ICP), Mg: Extractable magnesium (kg MgO/da), Fe: Plant-available iron (ppm), Mn: Plant-available manganese (ppm), Zn: Plant-available zinc (ppm), Cu: Plant useful copper (ppm)

At the individual level, the dendrogram revealed three major clusters with an average similarity index of 1.75 (Fig. 7). The first cluster contained 42 individuals, whereas two individuals formed separate clusters. Individuals UL2 and OL5 were positioned distinctly from the main cluster.

At the population level, cluster analysis grouped the nine populations into four clusters with an average similarity index of 0.75 (Fig. 8). Six populations were grouped within the first cluster, while Ulupınar formed a distinct cluster separate from all other populations. Çıralı and Phaselis also exhibited partial separation within the dendrogram structure.

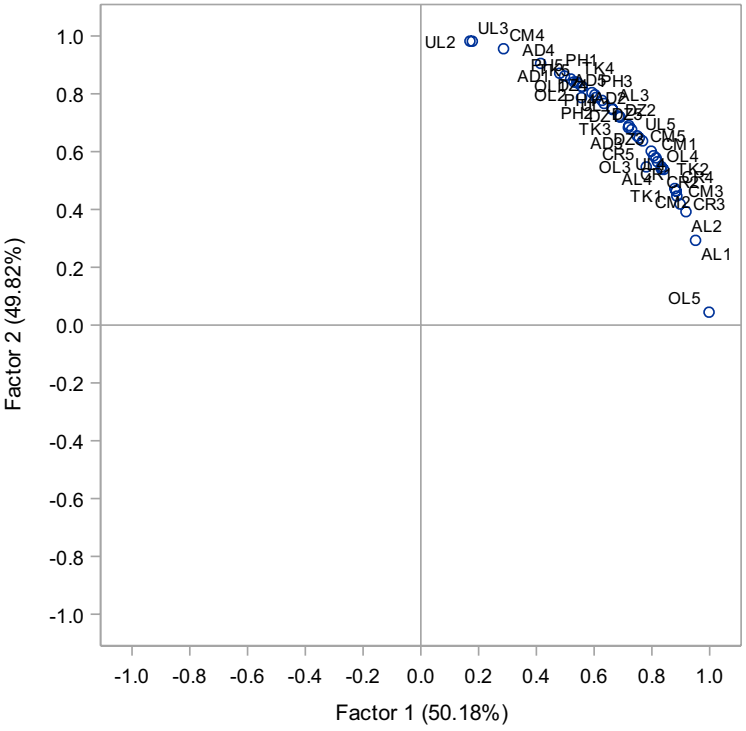

Fig. 5 Individual-level principal component analysis of 39 measured morphological and edaphic characters. *Spatial distribution graph—rotated factor pattern, horizontal column factor 1 (50.18%), vertical column factor 2 (49.82%) (Individual codes: UL1:Ulupınar1, UL2: Ulupınar2, UL3: Ulupınar3, UL4: Ulupınar4, UL5: Ulupınar5, PH1: Phaselis1, PH2:Phaselis2, PH3:Phaselis3, PH4:Phaselis4, PH5:Phaselis5, TK1: Tekirova1, TK2: Tekirova2, TK3: Tekirova3, TK4: Tekirova4, TK5: Tekirova5, AL1: Alacasu1, AL2: Alacasu2, AL3: Alacasu3, AL4: Alacasu4, OL1: Olimpos1, OL2: Olimpos2, OL3: Olimpos3, OL4: Olimpos4, OL5: Olimpos5, DZ1: Düzlerçamı1, DZ2: Düzlerçamı2, DZ3: Düzlerçamı3, DZ4: Düzlerçamı4, DZ5: Düzlerçamı5, AD1: Adrasan1, AD2: Adrasan2, AD3: Adrasan3, AD4: Adrasan4, AD5: Adrasan5, CR1: Çıralı1, CR2: Çıralı2, CR3: Çıralı3, CR4: Çıralı4, CR5: Çıralı5, CM1: Çamyuva1, CM2: Çamyuva2, CM3: Çamyuva3, CM4: Çamyuva4, CM5: Çamyuva5)

These multivariate analyses indicate clear differentiation patterns among individuals and populations based on combined morphological and edaphic characteristics.

Discussion

Topographic gradients and morphological differentiation

The distribution pattern of *P. chimerae* across slope and aspect gradients suggests an association between topographic heterogeneity and morphological differentiation. The predominance of individuals on east- to southwest-facing slopes suggests that microclimatic variation related to solar radiation exposure and moisture regimes may contribute to phenotypic differentiation. Comparable slope-aspect effects on woody Mediterranean vegetation

Table 5 Factor loadings of the principal component analysis at the individual level for the 39 measured morphological and edaphic characteristics *OM: Organic matter (%-TS8336), N: Total nitrogen (Kjeldahl), SOSAT (% soil saturation): <30%: sand, 30–50%: loam, 50–70%: clay loam, 70–110%: clay, >110%: heavy clay (Richards 1954), Fe: Plant-available iron (ppm), Zn: Plant-available zinc (ppm), Mn: Plant-available manganese (ppm), SALT (% salinity), P: Plant-available phosphorus (kg K_2O/ha) (Acetate-ICP), pH: Common logarithm of hydrogen ion concentration, LLL: Lower lip length, COL: Corolla length, LLW: Lower lip width, ULW: Upper lip width, ULL: Upper lip length, COW: Corolla width, SL: Spike length, CL: Calyx length, PDAVE: Plant distribution area diameter average, PDMIN: Plant distribution area diameter minimum, PDMAX: Plant distribution area diameter maximum, PHAVE: Plant height average, PHMAX: Plant height maximum, PHMIN: Plant height minimum, Mg: Extractable magnesium (kg MgO/da), LL: Leaf length, PETL: Petiole length, PEDL: Flower stalk length, SW: Spike width, LW: Leaf width, CTL: Calyx tooth length, CW: Calyx width, LIME (% calcimetric), Ca: Extractable calcium (kg CaO/da) (A.Acetate-ICP), CROMA: Chroma value, CFN: Circular flower number, K: Plant-available potassium (kg K_2O/da), LGHT: Lightness, Cu: Plant useful copper (ppm), HUE: Leaf Hue angle

Rotated Factor Pattern												
	**Factor1		Factor2		Factor3		Factor4		Factor5		Factor6	
***OM**	93	*	.		.		.		.		.	
N	87	*	.		.		.		.		.	
SOSAT	87	*	.		.		.		.		.	
Fe	82	*	.		.		.		.		.	
Zn	81	*	.		.		.		.		.	
Mn	68	*	.		.		.		.		42	*
SALT	63	*	.		52	*	.		.		.	
P	47	*	.		.		.		46	*	.	
ph	-48	*	33	*	.		.		33		.	
LLL	.		84	*	.		.		.		.	
COL	.		82	*	.		.		.		.	
LLW	.		76	*	.		.		.		.	
ULW	.		75	*	.		.		.		.	
ULL	.		75	*	.		.		.		.	
COW	.		71	*	.		.		.		.	
SL	.		66	*	.		40	*	.		.	
CL	.		62	*	.		.		.		.	
PDAVE	.		.		88	*	.		.		.	
PDMIN	.		.		84	*	.		.		.	
PDMAX	.		.		78	*	.		.		.	
PHAVE	.		.		70	*	.		.		43	*

Table 5 (continued)

Rotated Factor Pattern												
	**Factor1		Factor2		Factor3		Factor4		Factor5		Factor6	
PHMAX	.		.		65	*	.		.		38	*
PHMIN	.		.		58	*	.		32		40	*
Mg	.		.		47	*	.		-45	*	.	
LL	.		.		.		73	*	36	*	.	
PETL	.		.		32		73	*	.		.	
PEDL	.		33	*	.		73	*	.		.	
SW	.		36	*	.		65	*	.		.	
LW	.		.		.		63	*	.		.	
CTL	.		43	*	.		54	*	.		.	
CW	.		37	*	.		-41	*	.		.	
LIME	.		.		.		.		86	*	.	
Ca	35	*	.		.		.		82	*	.	
CROMA	.		.		.		50	*	51	*	.	
CFN	-33		.		32		32		34	*	.	
K	.		.		36	*	.		.		66	*
LGHT	.		32		.		.		31		64	*
Cu	.		.		.		.		.		51	*
HUE	.		.		.		.		.		-43	*

Printed values have been multiplied by 100 and rounded to the nearest ten. Values greater than 0.33142 are marked with '*'. Values less than 0.3 are not specified.
The cut-off value of 0.33142 was automatically generated by the SAS statistical software. In PROC FACTOR, SAS calculates the threshold for significant loadings based on the sample size ($p < 0.05$ level) using the formula $|\text{loading}| \approx 2/\sqrt{(n-2)}$.

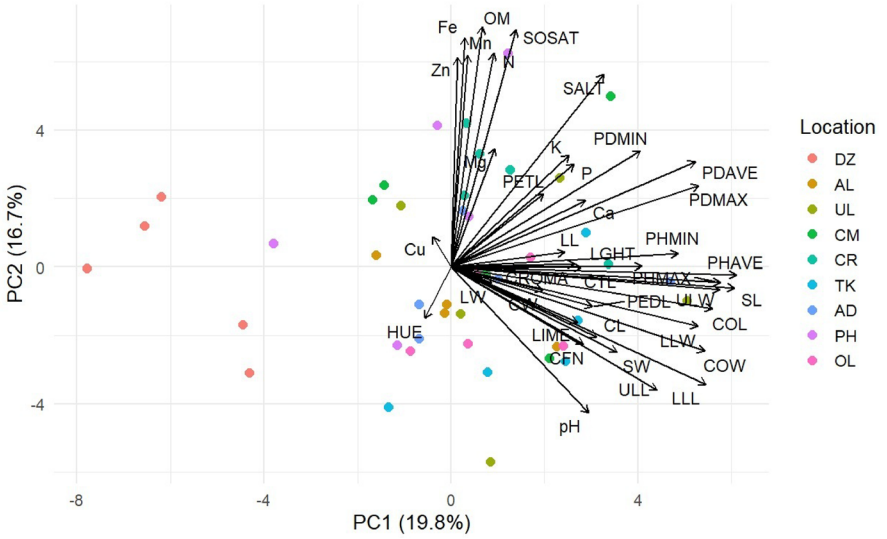

Fig. 6 Biplot of principal component analysis (PCA). *OM: Organic matter (%-TS8336), N: Total nitrogen (Kjeldahl), SOSAT (% soil saturation): <30%: sand, 30–50%: loam, 50–70%: clay loam, 70–110%: clay, >110%: heavy clay (Richards 1954), Fe: Plant-available iron (ppm), Zn: Plant-available zinc (ppm), Mn: Plant-available manganese (ppm), SALT (% salinity), P: Plant-available phosphorus (kg K_2O/ha) (Acetate-ICP), pH: Common logarithm of hydrogen ion concentration, LLL: Lower lip length, COL: Corolla length, LLW: Lower lip width, ULW: Upper lip width, ULL: Upper lip length, COW: Corolla width, SL: Spike length, CL: Calyx length, PDAVE: Plant distribution area diameter average, PDMIN: Plant distribution area diameter minimum, PDMAX: Plant distribution area diameter maximum, PHAVE: Plant height average, PHMAX: Plant height maximum, PHMIN: Plant height minimum, Mg: Extractable magnesium (kg MgO/da), LL: Leaf length, PETL: Petiole length, PEDL: Flower stalk length, SW: Spike width, LW: Leaf width, CTL: Calyx tooth length, CW: Calyx width, LIME (% calcimetric), Ca: Extractable calcium (kg CaO/da) (A.Acetate-ICP), CROMA: Chroma value, CFN: Circular flower number, K: Plant-available potassium (kg K_2O/da), LGHT: Lightness, Cu: Plant useful copper (ppm), HUE: Leaf Hue angle. **DZ: Düzlerçamı, AL: Alcasu, UL: Ulupinar, CM: Çamyuva, CR: Cirali, TK: Tekirova, AD: Adrasan, PH: Phaselis, OL: Olympos

structure and biomass have been documented in semiarid ecosystems (Åström et al. 2007; Sternberg and Shoshany 2001; Zhang et al. 2022).

Elevation was negatively correlated with plant height, a pattern consistent with previously reported altitudinal declines in maximum plant stature (Mao et al. 2016; Xu et al. 2017). Reduced plant size at higher elevations may reflect environmental constraints associated with temperature regimes and soil development. The clear separation of the Ulupınar population—located at the highest altitudinal range—in multivariate analyses further supports the structuring role of elevation gradients.

Topographic variation is widely recognized as a driver of habitat differentiation and community structuring in Mediterranean systems (Åström et al. 2007; Sternberg and Shoshany 2001). In this context, the morphological divergence observed among *P. chimerae* populations likely reflects responses to fine-scale environmental heterogeneity within its restricted geographic range.

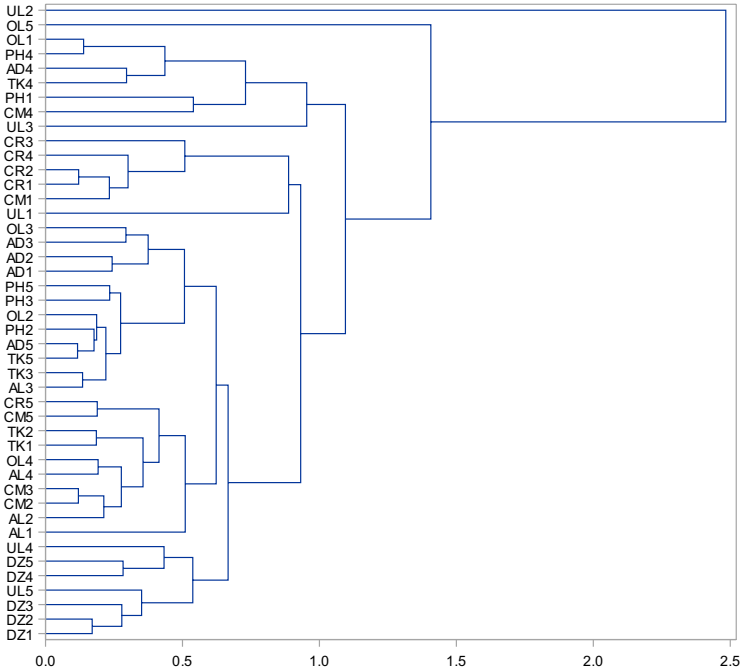

Fig. 7 Cluster analysis of 39 measured morphological and edaphic characters. *Basic component analysis Vertical columns define the average distance between clusters (average distance between clusters). The unweighted pair group method with arithmetic mean (UPGMA) dendrogram was created (Individual codes: UL1:Ulupınar1, UL2: Ulupınar2, UL3: Ulupınar3, UL4: Ulupınar4, UL5: Ulupınar5, PH1: Phaselis1, PH2:Phaselis2, PH3:Phaselis3, PH4:Phaselis4, PH5:Phaselis5, TK1: Tekirova1, TK2: Tekirova2, TK3: Tekirova3, TK4: Tekirova4, TK5: Tekirova5, AL1: Alacasu1, AL2: Alacasu2, AL3: Alacasu3, AL4: Alacasu4, OL1: Olimpos1, OL2: Olimpos2, OL3: Olimpos3, OL4: Olimpos4, OL5: Olimpos5, DZ1: Düzlerçamı1, DZ2: Düzlerçamı2, DZ3: Düzlerçamı3, DZ4: Düzlerçamı4, DZ5: Düzlerçamı5, AD1: Adrasan1, AD2: Adrasan2, AD3: Adrasan3, AD4: Adrasan4, AD5: Adrasan5, CR1: Çıralı1, CR2: Çıralı2, CR3: Çıralı3, CR4: Çıralı4, CR5: Çıralı5, CM1: Çamyuva1, CM2: Çamyuva2, CM3: Çamyuva3, CM4: Çamyuva4, CM5: Çamyuva5)

Edaphic heterogeneity and phenotypic plasticity

Soil analyses revealed substantial variation in lime content, salinity, and nutrient availability among populations. Edaphic factors are known to influence plant morphology and trait integration (Cousins and Murren 2017; Horst et al. 2018). The positive associations detected between potassium, magnesium, and plant size parameters are consistent with the role of macronutrients in supporting vegetative growth and structural development.

Negative correlations between certain floral traits and iron and zinc concentrations suggest that micronutrient variability may influence reproductive morphology. Similar soil-driven trait variation has been reported in morphometric and population-level analyses (Dey et al. 2006; Zhang et al. 2015).

The occurrence of *P. chimerae* across clay–loam to heavy clay soils indicates broad edaphic tolerance. Comparable ecological flexibility has been documented for other *Phlomis* taxa in Türkiye (Temel and Yıldız 2015) and in regional morphological surveys of

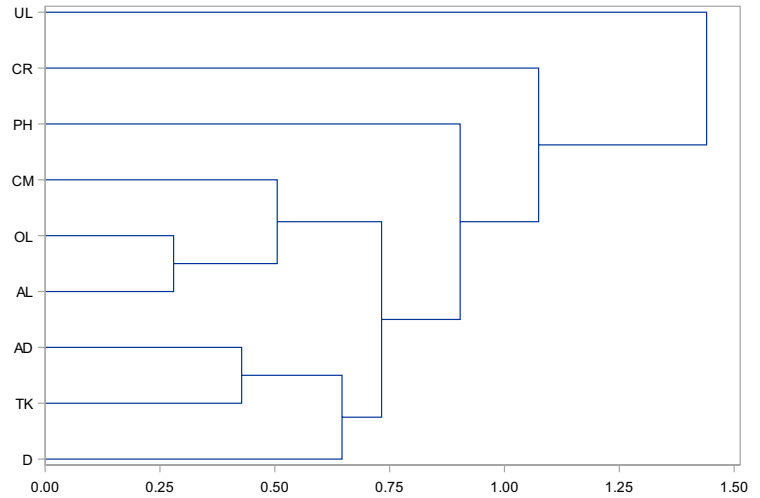

Fig. 8 Dendrogram of the cluster analysis performed among populations based on 39 measured morphological and edaphic characteristics. *Vertical columns represent individuals, horizontal columns represent the average distance between clusters.) The dendrogram created using the unweighted pair group method with arithmetic mean (UPGMA) (Population codes: AL: Alacasu, DZ: Düzlerçamı, TK: Tekirova, CM: Çamyuva, CR: Çıralı, OL: Olimpos, PH: Phaselis, UL: Ulupınar, D: Düzlerçamı

native *Phlomis* species (Sarıkaya and Fakir 2016). Such findings reinforce the view that soil heterogeneity contributes to intraspecific differentiation in Mediterranean shrub taxa.

Intraspecific variation and genetic resource potential

The substantial morphological differentiation detected among populations indicates notable intraspecific variability. Natural plant populations function as reservoirs of genetic diversity and adaptive potential (Gray 1996; Chung et al. 2023). Although morphological traits may be environmentally influenced, they remain valuable indicators of genetic structure and breeding potential (Hien et al. 2007; Kumar et al. 2025).

The distinct positioning of individuals such as UL2 and OL5 in PCA and cluster analyses suggests the presence of unique trait combinations within certain populations. Similar patterns of morphological divergence have been documented in Mediterranean shrubs and Lamiaceae species (Karaguzel and Girmen 2009; Selim and Kahraman 2021), as well as in recent comparative morphological assessments of *Phlomis* species in Türkiye (Sarikaya and Ilhan 2025).

Habitat heterogeneity has long been recognized as a key driver of morphological differentiation within the genus *Phlomis* (Dadandı 2002). The multivariate separation observed in the present study may therefore reflect both environmental responsiveness and underlying genetic structuring within this geographically restricted endemic species.

Implications for conservation and ornamental utilization

The integration of endemic species into ornamental horticulture represents an increasingly recognized strategy for biodiversity conservation and sustainable landscape design (Kri-

gas et al. 2021; Pipinis et al. 2022). Native Mediterranean taxa adapted to local climatic and edaphic conditions offer ecological stability and reduced maintenance requirements (Kayıkçı and Güzel 2023; Papafotiou et al. 2017).

The positive correlations observed between plant height and floral dimensions suggest that plant height may serve as an indirect selection criterion in breeding programs. Similar relationships between vegetative vigor and ornamental floral traits have been reported in ornamental crop species (Gómez et al. 2009; Han et al. 2025). Furthermore, significant variation in leaf color parameters among populations highlights additional aesthetic selection potential, consistent with criteria emphasized in ornamental breeding frameworks (Datta 2022).

Previous propagation studies on *P. chimerae* have demonstrated its responsiveness to vegetative rooting treatments (Selim and Kahraman), indicating practical feasibility for domestication and ex situ conservation. When considered together with the documented morphological and edaphic differentiation presented here, these findings provide a foundation for structured selection programs that preserve intraspecific diversity while enabling sustainable ornamental utilization.

Given its restricted distribution and increasing anthropogenic pressure in Mediterranean coastal habitats, conservation strategies for *P. chimerae* should prioritize integrated in situ protection complemented by carefully planned ex situ propagation and selection approaches. The identification of morphologically distinct populations and individuals represents an essential first step toward conserving adaptive diversity while facilitating responsible horticultural introduction.

Conclusion

This study demonstrates that although *P. chimerae* has a restricted distribution in Antalya, it exhibits substantial morphological variation among its natural populations. Such variability represents an important resource for conservation and future breeding programs. Variance and cluster analyses identified the Adrasan, Ulupınar, and Olympos populations as promising candidates for initial selection efforts due to their larger plant size and distinctive leaf and flower traits. Notably, individuals UL2 and OL5 showed marked morphological differentiation and should be prioritized in future research to preserve intraspecific diversity.

Ecological analyses revealed that the species prefers neutral to slightly alkaline clay–loam soils and occurs from sea level to approximately 500 m elevation. Increasing clay content, phosphorus, and potassium levels were positively associated with plant growth, whereas higher iron concentrations corresponded to reduced spike width. Plant height decreased with elevation but was strongly correlated with flower size, suggesting its potential use as an indirect selection criterion.

Overall, the documented morphological and ecological differentiation highlights both the adaptive potential of *P. chimerae* and the importance of integrating habitat-based conservation strategies with its sustainable ornamental utilization.

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book. We would like to thank taxonomist Prof. Dr. İ. Gökhan Deniz for his contributions to the field works and species identification.

Author contributions M.A. conducted the field surveys, collected plant material, performed morphological measurements, and contributed to data interpretation.C.S. conceptualized and designed the study, supervised the research process, contributed to data analysis and interpretation, and wrote the original draft of the manuscript. E.B.K. performed the statistical analyses, including variance analysis, PCA, cluster analysis, and correlation analyses, and contributed to the interpretation of statistical results. P.Z.A. contributed to ecological assessments, literature review, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare that they have no competing interests.

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References

Amor IL-B, Boubaker J, Sgaier MB, Skandrani I, Bhouri W, Neffati A, Kilani S, Bouhlel I, Ghedira K, Chekir-Ghedira L (2009) Phytochemistry and biological activities of Phlomis species. J Ethnopharmacol 125(2):183–202. https://doi.org/10.1016/j.jep.2009.06.022

Åström M, Dynesius M, Hylander K, Nilsson C (2007) Slope Aspect Modifies Community responses to clear-cutting in boreal forests. Ecology 88(3):749–758. https://doi.org/10.1890/06-0613

Başer KHC (2000a) Bulletin of medicinal and aromatic plants. Anadolu university medicinal and aromatic plant and drug research center (TBAM), 15, 20–33. (in Turkish)

Baytop T (2015) Dictionary of Turkish Plant Names, 4th edn. Ankara: Turkish Language Association. (in Turkish)

Celik S, Suleyman Gokturk R, Flamini G, Luigi Cioni P, Morelli I (2005) Essential oils of *Phlomis leucophracta, Phlomis chimerae* and *Phlomis grandiflora* var. grandiflora Turk Biochem Syst Ecol 33(6):617–623. https://doi.org/10.1016/j.bse.2004.11.010

Chung MY, Merilä J, Li J, Mao K, López-Pujol J, Tsumura Y, Chung MG (2023) Neutral and adaptive genetic diversity in plants: An overview. Front Ecol Evol. 11https://doi.org/10.3389/fevo.2023.1116814

Cousins EA, Murren CJ (2017) Edaphic history over seedling characters predicts integration and plasticity of integration across geologically variable populations of *Arabidopsis thaliana*. Am J Bot 104(12):1802–1815. https://doi.org/10.3732/ajb.1700220

Dadandı MY (2002) The revision of the genus phlomis l. (lamiaceae) of turkey. Gazi university, institute of natural sciences, department of biology, doctorate thesis. Ankara, Türkiye

Datta SK (2022) Breeding of ornamentals: success and technological status. Nucleus 65(1):107–128. https://doi.org/10.1007/s13237-021-00368-x
Davis PH, Cullen J, Coode MJE (eds) (1965) Flora of Turkey and the East Aegean Islands, vol 1, 1st edn. Edinburgh University
Deniz İG, Aykurt C (2016) Antalya Endemik ve Nadir Çiçekleri. Kutlu & Avcı Ofset
Dey SS, Singh AK, Chandel D, Behera TK (2006) Genetic diversity of bitter gourd (*Momordica charantia* L.) genotypes revealed by RAPD markers and agronomic traits. Sci Hort 109(1):21–28. https://doi.org/10.1016/j.scienta.2006.03.006
Ekim T, Koyuncu M, Vural M, Duman H, Aytaç Z, Adıgüzel N (2000) Red data book of Turkish plants (Pteridophyta and Spermatophyta). Türkiye Tabiatını Koruma Derneği, Van 100.Yıl Üniversitesi
Gao J, Huang W, Gielis J, Shi P (2023) Plant morphology and function, geometric morphometrics, and modelling: decoding the mathematical secrets of plants. Plants 12(21):3724. https://doi.org/10.3390/plants12213724
Gómez JM, Abdelaziz M, Muñoz-Pajares J, Perfectti F (2009) Heritability and genetic correlation of corolla shape and size in *Erysimum mediohispanicum*. Evolution 63(7):1820–1831. https://doi.org/10.1111/j.1558-5646.2009.00667.x
Gray A (1996) Genetic diversity and its conservation in natural populations of plants. Biodivers Lett 3(3):71. https://doi.org/10.2307/2999720
Güner A, Aslan S, Ekim T, Vural M, Babaç MT (2012). Türkiye Bitkileri Listesi (Damarlı Bitkiler). – Nezahat Gökyiğit Bot. Bahçesi Yayınları , Flora Dizisi 1, pp. 240–242.
Han Y, Yu P, Jiang Y, Chen N, Gong T, Kong X, Gao L, Jia G (2025) Genetic variation in ornamental and growth traits in hybrid populations of *Lilium davidii* var. unicolor Plants 14(5):656. https://doi.org/10.3390/plants14050656
Hien NL, Sarhadi WA, Oikawa Y, Hirata Y (2007) Genetic diversity of morphological responses and the relationships among Asia aromatic rice (*Oryza sativa* L.) cultivars. Tropics 16(4):343–355. https://doi.org/10.3759/tropics.16.343
Horst TZ, Dalmolin RSD, Caten A, ten, Moura-Bueno JM, Cancian LC, Pedron F, de A, Schenato RB (2018) Edaphic and topographic factors and their relationship with dendrometric variation of *Pinus taeda* L. in a high altitude subtropical climate. Revista Brasileira de Ciência Do Solo 42(0). https://doi.org/10.1590/18069657rbcs20180023
Kamel MS, Mohamed KM, Hassanean HA, Ohtani K, Kasai R, Yamasaki K (2000) Iridoid and megastigmane glycosides from *Phlomis aurea*. Phytochemistry 55(4):353–357. https://doi.org/10.1016/S0031-9422(00)00331-9
Karaguzel O, Girmen B (2009) Morphological variations of chaste tree (*Vitex agnus-castus*) genotypes from southern Anatolia, Turkey. New Z J Crop Hortic Sci 37(3):253–261. https://doi.org/10.1080/01140670909510271
Kayıkçı S, Güzel Y (2023) Evaluation of local wild plants, including recently discovered endemics, as ornamentals: the EXPO-2021 Hatay, Türkiye Example. ANADOLU J Aegean Agricultural Res Inst 33(1):95–108. https://doi.org/10.18615/anadolu.1300188
Krigas N, Tsoktouridis G, Anestis I, Khabbach A, Libiad M, Megdiche-Ksouri W, Ghrabi-Gammar Z, Lamchouri F, Tsiripidis I, Tsiafouli MA, Haissoufi E, Bourgou M, S (2021) Exploring the potential of neglected local endemic plants of three mediterranean regions in the ornamental sector: value chain feasibility and readiness timescale for their sustainable exploitation. Sustainability 13(5):2539. https://doi.org/10.3390/su13052539
Kumar SS, Prasad S, Wani OA, El-Hendawy S, Mattar MA, Salem A (2025) Genetic diversity and agro-morphological characterization of cassava varieties provides insight for breeding and crop improvement. Sci Rep 15(1):17498. https://doi.org/10.1038/s41598-025-02527-5
Mao L, Chen S, Zhang J, Zhou G (2016) Altitudinal patterns of maximum plant height on the Tibetan Plateau. J Plant Ecol. https://doi.org/10.1093/jpe/rtw128. rtw128
Mathiesen C, Scheen AC, Lindqvist C (2011) Phylogeny and biogeography of the lamioid genus Phlomis (Lamiaceae). Kew Bulletin 66(1): 83–99. https://doi.org/10.1007/s12225-011-9257-0
Papafotiou M, Bertsouklis KF, Martini AN, Vlachou G, Akoumianaki-Ioannidou A, Kanellou E, Kartsonas ED (2017) Evaluation of the establishment of native Mediterranean plant species suggested for landscape enhancement in archaeological sites of Greece. Acta Hortic 1189:177–180. https://doi.org/10.17660/ActaHortic.2017.1189.35
Pipinis E, Hatzilazarou S, Kostas S, Bourgou S, Megdiche-Ksouri W, Ghrabi-Gammar Z, Libiad M, Khabbach A, El Haissoufi M, Lamchouri F, Koundourakis E, Greveniotis V, Papaioannou E, Sakellariou MA, Anestis I, Tsoktouridis G, Krigas N (2022) Facilitating conservation and bridging gaps for the sustainable exploitation of the tunisian local endemic plant marrubium aschersonii (Lamiaceae). Sustainability 14(3):1637. https://doi.org/10.3390/su14031637
Richards LA (1954) Diagnosis and improvement saline and alkaline soils. U.S. Dep. Agr. Handbook, pp.60

Sarikaya AG, Ilhan B (2025) Morphological and volatile profiles of *Phlomis russeliana* and *Phlomis armeniaca* from Uludağ. Türkiye BioResources 20(3):5301–5314. https://doi.org/10.15376/biores.20.3.5301-5314

Sarıkaya AG, Fakir H (2016) The morphological and distribution areas characteristics of native *Phlomis* L. (Lamiaceae) taxa in the Lakes district, Turkey. Turkish Journal of Forestry. 2016;17:85–93. https://doi.org/10.18182/tjf.45620

Selim C, Kahraman E (2021) Effects of different IBA (Indole-3-Butyric Acid) doses on rooting of endemic *Phlomis chimerae* Boiss. cuttings. J Bartin Fac Forestry 23(1):1–8. https://doi.org/10.24011/barofd.784412 (in Turkish)

Sokovic MD, Marin PD, Simic D, Vukcevic JK, Vajs V, Petrovic S (2002) Antimutagenic activity of essential oil and crude extract of *Phlomis fruticosa*. Pharm Biol 40(4):311–314. https://doi.org/10.1076/phbi.40.4.311.8466

Sternberg M, Shoshany M (2001) Influence of slope aspect on Mediterranean woody formations: Comparison of a semiarid and an arid site in Israel. Ecol Res 16(2):335–345. https://doi.org/10.1046/j.1440-1703.2001.00393.x

Temel M, Yıldız Ü (2015) Morphological, anatomical and ecological properties of *Phlomis armeniaca* Willd. (Lamiaceae). Kafkas Üniversitesi Fen Bilimleri Enstitüsü Dergisi 8(1):18–29 (in Turkish)

Turkish State Meteorological Service (2023) Republic of Turkey Ministry of Environment, Urbanization, and Climate Change

Valant-Vetschera KM, Roitman JN, Wollenweber E (2003) Chemodiversity of exudate flavonoids in some members of the Lamiaceae. Biochem Syst Ecol 31(11):1279–1289. https://doi.org/10.1016/S0305-1978(03)00037-1

Xu M, Ma L, Jia Y, Liu M (2017) Integrating the effects of latitude and altitude on the spatial differentiation of plant community diversity in a mountainous ecosystem in China. PLoS ONE 12(3):e0174231. https://doi.org/10.1371/journal.pone.0174231

Zhang Y, Wang Z-Z (2008) Comparative analysis of essential oil components of three Phlomis species in Qinling Mountains of China. J Pharm Biomed Anal 47(1):213–217. https://doi.org/10.1016/j.jpba.2007.12.027

Zhang Q, Jia Z, Meng C, Ti CW, Wang YL (2015) Diversity and population structure of a dominant deciduous tree based on morphological and genetic data. AoB Plants 7:plv103. https://doi.org/10.1093/aobpla/plv103

Zhang S, Huang W, Huang Y, Zhang C (2020) Plant species recognition methods using leaf image. Overv Neurocomputing 408:246–272. https://doi.org/10.1016/j.neucom.2019.09.113

Zhang Q, Fang R, Deng C, Zhao H, Shen M-H, Wang Q (2022) Slope aspect effects on plant community characteristics and soil properties of alpine meadows on Eastern Qinghai-Tibetan plateau. Ecol Ind 143:109400. https://doi.org/10.1016/j.ecolind.2022.109400

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