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# Geometric morphometric analysis of head shape variation in *Hemidactylus turcicus* (Linnaeus, 1758) (Sauria: Gekkonidae) from the Aegean and Mediterranean regions of Türkiye

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**Abstract.** In this study, shape variation in the heads of 41 adult *Hemidactylus turcicus* specimens (17 males, 24 females) was investigated using geometric morphometric methods. To better understand geographic variation, an additional 21 juvenile specimens (12 Aegean, 9 Mediterranean) were analyzed, with separate analyses conducted for juvenile groups. For adults, landmark-based analyses revealed no evidence of sexual dimorphism ($F = 0.700$, $p > 0.5$). However, significant geographic variation was detected between adult groups (29 Aegean, 12 Mediterranean) ($F = 7.353$, $p < 0.01$). Similar results were obtained for juveniles (12 Aegean, 9 Mediterranean) ($F = 3.416$, $p < 0.01$). While strong positive correlations were observed between centroid size and linear measurements, the first principal component (PC1), which accounted for the largest portion of shape variation, showed no strong correlation with traditional morphometric traits. Variation in the anterior postmental plates of 37 adult specimens (14 males, 23 females; 27 Aegean, 10 Mediterranean) was assessed using an outline-based method to examine sexual and populational differences. Analyses revealed no sexual dimorphism in the anterior postmental plates; however, significant inter-population variation was detected in the right anterior postmental plate (Pillai's Trace = 0.355, $F(3, 31) = 5.697$, $p < 0.01$). Overall, the findings suggest the presence of geographic variation in head shape between the Aegean and Mediterranean groups in both adults and juveniles. This study represents a preliminary investigation of head morphology in *Hemidactylus turcicus* using geometric morphometric approaches. Since the present analysis included only specimens from the Aegean and Mediterranean regions, future research should apply these methods to larger samples representing all geographic regions of Türkiye.

**Keywords**: Mediterranean house gecko, sexual dimorphism, geographic variation, landmark-based methods, outline-based methods.

## Introduction

In many species, shape variation has traditionally been studied using classical morphometry, also known as multivariate morphometry, which relies on linear measurements, angles, and their ratios (Marcus 1990, Koca 2012, Adams et al. 2004). While numerous studies continue to employ these traditional methods (Sığırlı 2011), such measurements often fail to capture the full complexity of biological shapes (Rao 1948, Sığırlı 2011). In contrast, geometric morphometrics has emerged as a powerful approach for quantitatively analyzing shape and size changes in biological structures (Spani et al. 2025).

The origin of *Hemidactylus turcicus* has been the subject of multiple hypotheses (Rato et al.

2011). Carranza & Arnold (2006) proposed that the species originated in the Middle East, a region generally considered to include present-day Turkey. In contrast, more recent phylogeographic studies suggest that *H. turcicus* may have originated in Turkey and subsequently dispersed to Europe and North Africa (Rato et al. 2011). The species is primarily distributed throughout the Mediterranean basin, with populations extending along the Nile River to the Sudanese border (Rato et al. 2011, IUCN 2024, Mateus & Jacinto 2008, Sindaco & Jeremčenko 2008). Furthermore, human-mediated dispersal has enabled the species to establish populations beyond its native range (Farallo et al. 2009, Texas Invasive Species Institute 2014), with confirmed records from various regions including the United States, Mexico, Cuba, Russia, India, Pakistan, and the Canary Islands (Uetz et al. 2025). *H. turcicus* is distributed throughout the entire coastal regions of Türkiye (Bülbül et al. 2020, Baran et al. 2021, Budak & Göçmen 2008, Yaşar et al. 2021, Kaya et al. 2023). It has also been reported in inland areas such as Afyon, Şanlıurfa, and Kilis (Yıldız et al. 2007, Baran et al. 2021). This species occurs at altitudes of up to 1000 meters above sea level (Başoğlu & Baran 1977, Baran et al. 2021). In Türkiye, it is represented by a single subspecies, *H. turcicus turcicus* (Başoğlu & Baran 1977, Altunışık 2017).

Granatosky and Krysko (2014) reported sexual size dimorphism in head size and body length, favoring males, in *H. turcicus* populations from the southeastern USA. However, they suggested that this dimorphism may be linked to longitudinal rather than latitudinal variation. Topçu (2014), studying 36 specimens from Southwestern Anatolia, identified variation in some pholidosis traits, while Kanat & Tok (2015) found a positive correlation between age and snout–vent length in the same region. Using micro-CT–based geometric morphometrics, Paluh et al. (2018) showed that quadrate morphology varied ontogenetically but was not influenced by sexual dimorphism in USA and Turkish populations. Bülbül et al. (2020) reported slightly larger head dimensions in females compared to males across several Black Sea localities. Kurtul (2023) revealed morphological and osteological differences between Bozcaada and Ayvacık populations, while Kaya et al. (2023) demonstrated significant divergence in Büyükada and Heybeliada populations relative to others and recorded the first occurrence of *H. turcicus* in Büyükada.

A review of the literature indicates that the head morphology of *H. turcicus* populations in the Aegean and Mediterranean regions of Türkiye has not yet been extensively investigated using geometric morphometrics. Therefore, the present study aims to determine whether significant morphological variation exists between these populations.

## Materials and methods

Morphological variation in *H. turcicus* was investigated using 62 specimens from the Amphibians and Reptiles Collection (ÇOMU-ZLAR) of the Zoology Laboratory at Çanakkale Onsekiz Mart University, Çanakkale, Türkiye, comprising 41 adults and 21 juveniles. The adult specimens were from Osmaniye (4 males and 8 females) and Muğla (13 males and 16 females), while the juvenile specimens included 9 from Osmaniye, 6 from İzmir, and 6 from Muğla. Samples were placed on millimeter-scale graph paper and photographed orthogonally from a distance of 44 cm using a Canon EOS 2000D (24.1-megapixel APS-C sensor). Raw images were processed using RawTherapee (v.5.11) and exported as JPEGs. Measurements were taken using a digital caliper (0.01 mm precision). Given that head and body size vary with age (Kanat & Tok 2015) and that quadrate morphology differs between adults and juveniles (Paluh et al. 2018), all analyses were conducted separately for adults and juveniles.

In this study, several head length traits adapted from Tok (1993) and Topçu (2014) were used (Table 1). Consistent with the geometric analyses, length measurements were evaluated separately for adults and juveniles. The Shapiro–Wilk test was applied to assess the normality of the linear data (Shapiro & Wilk 1965), followed by Levene's test to determine homogeneity of variance and justify the use of parametric methods (Brown & Forsythe 1974). In adult *H. turcicus* specimens, the effects of sex, population, and their interaction on head morphometric features were analyzed using two-way ANOVA for normally distributed characters, and the Scheirer–Ray–Hare test, an extension of the Kruskal–Wallis test, for non-normally distributed characters (Sokal & Rohlf 1995). Since all head features of juveniles showed normal distribution, morphometric variations between juvenile populations were assessed using independent-samples t-tests.

In the landmark-based approach, the landmark configuration described by Zuffi et al. (2011) was modified (Figure 1, Table 2). Elliptic Fourier analysis, an outline-based method, was applied to examine the shape of the anterior postmental plates (Figure 2) (Kuhl & Giardina 1982). Generalized Procrustes Analysis (GPA) served as the superimposition method in the landmark-based geometric morphometry study (Rohlf & Slice 1990). Principal component analysis (PCA) was conducted for the landmark-based and outline-based datasets (Jolliffe 2002).

Table 1. Linear measurement traits used in analysis

| Trait | Abbreviation | Description |
|---|---|---|
| Head Length | HL | The distance from the tip of the rostrum (snout) to the posterior margin of the ear opening |
| Eye Diameter | ED | The length from the anterior to the posterior edge of the orbit |
| Head Width | HW | The maximum width of the head |
| Posterior Interorbital Width | PIO | The distance between the posterior margins of the orbits |
| Middle Interorbital Width | MIO | The shortest distance between the medial points of the orbits |
| Anterior Interorbital Width | AIO | The distance between the anterior margins of the orbits |
| Internasal Width | IN | The distance between the external nostrils |

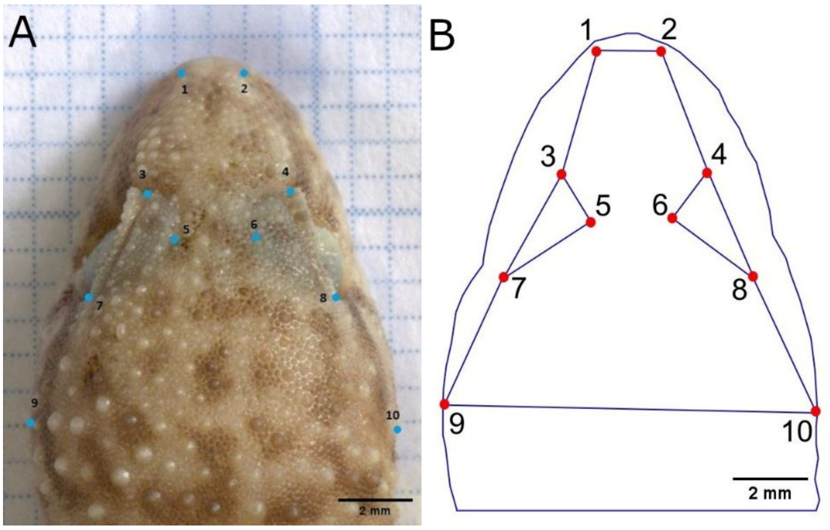

Figure 1. Landmark configuration of the head of *Hemidactylus turcicus*. (A) Dorsal view photograph of the head with landmarks indicated. (B) Schematic drawing of the same head showing the corresponding landmarks. Landmarks were digitized for geometric morphometric analysis.

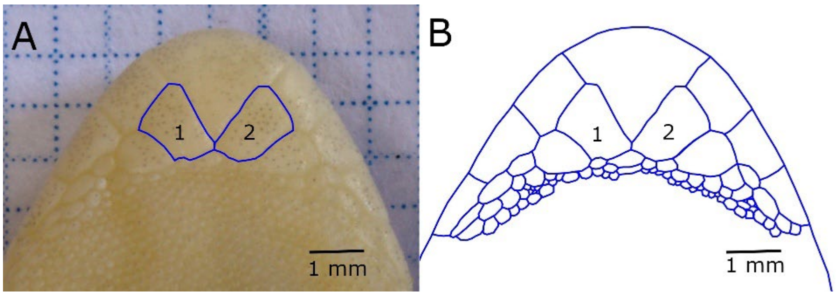

Figure 2. Postmental plates of *Hemidactylus turcicus*. (A) View of the postmental plates of the specimen. (B) Drawing of the specimen showing the right anterior postmental plate (1) and the left anterior postmental plate (2).

Table 2. Landmark numbers and descriptions

| Landmark | Description |
|---|---|
| 1 | Left nostril |
| 2 | Right nostril |
| 3 | Anterior edge of the left orbit |
| 4 | Anterior edge of the right orbit |
| 5 | Upper edge of the left orbit |
| 6 | Upper edge of the right orbit |
| 7 | Posterior edge of the left orbit |
| 8 | Posterior edge of the right orbit |
| 9 | Left side of the head width |
| 10 | Right side of the head width |

All analyses were conducted in R (version 4.4.3, R Core Team 2025). The Scheirer–Ray–Hare test was implemented using the rcompanion package (version 2.5.0, Mangiafico 2025). Landmark-based analyses were performed with geomorph (version 4.0.10, Baken et al. 2021, Collyer & Adams 2024, Adams et al. 2025), and graphical outputs were produced with ggplot2 (version 3.5.1, Wickham 2016). Procrustes ANOVA was applied to assess group differences in shape (Adams & Collyer 2007), based on 1000 permutations and Type I sums of squares (Rohlf & Slice 1990), using the "ProcD.lm" function (Adams et al. 2025). Outline analyses were performed with Momocs (Bonhomme et al. 2014). MANOVA was conducted on the first three principal components from the outline-based PCA (R Core Team 2025). In the landmark-based study, Pearson correlations were calculated between PC1, centroid size, and head length (Aldrich 2005). Regression plots of centroid size against head length were generated separately for adults and juveniles (Cohen et al. 2003, Bulut 2023, Demir 2024). Finally, the outline method was applied to analyze the anterior postmental plates in adults, as clear landmarks were not identifiable in this region (Dujardin et al. 2014). This analysis was restricted to adults because juvenile plates lacked extractable contours.

## Results

### Measurements

According to the two-way ANOVA results, head length (HL), posterior interorbital (PIO), anterior interorbital (AIO), and internasal (IN) lengths did not show any statistically significant effects of sex, population, or their interaction ($p > 0.05$; Supplementary Table S2). However, a statistically significant, borderline difference between populations was detected for head width (HW) ($F = 4.318$, $p < 0.05$; Supplementary Table S2), suggesting geographical variation in this trait among adults.

Since eye diameter (ED) and mid-interorbital length (MIO) were not normally distributed (Shapiro-Wilk test, $p < 0.05$), the nonparametric Scheirer–Ray–Hare test was applied. For ED, the results revealed no significant effects of sex, population, or their interaction ($p > 0.05$; Supplementary Table S3). In contrast, MIO exhibited significant variation between populations ($H = 11.223$, $p < 0.01$), while the other effects were not significant ($p > 0.05$; Supplementary Table S4).

Morphometric comparisons between juvenile geographic groups (Aegean: 12, Mediterranean: 9) were performed using independent samples t-tests (Supplementary Table S1). None of the examined head traits showed statistically significant differences between the two groups ($p > 0.05$).

<u>Landmark-based shape analyses</u>

Deformation grids and shape changes from the Aegean group to the Mediterranean group are shown in Figure 3. he first two principal components (PC1 and PC2) resulting from the Principal Component Analysis cumulatively explained 68.85% of the total shape variance, with PC1 accounting for 49.57% and PC2 for 19.28% (Figure 4). The PCA scatter plot by adult population (Figure 4) shows a partial separation along PC1: most specimens from the Mediterranean population, except two, are distributed on the negative side of PC1. This pattern is consistent with the Procrustes ANOVA results, which revealed significant shape variation among populations (Supplementary Table S5). The PCA scatter plot by sex (Figure 4) shows substantial overlap between male and female specimens, with no clear clustering along the first two principal components. This observation is consistent with the ANOVA and Procrustes ANOVA results, which indicated no significant effect of sex on shape (Supplementary Table S5). Procrustes ANOVA conducted on adult specimens revealed significant shape variations between populations (Aegean vs. Mediterranean) ($F = 7.353$, $p < 0.01$), whereas neither sex nor the sex × population interaction had a significant effect (Supplementary Table S5). Centroid size also did not differ significantly between sexes or between populations (Supplementary Table S6).

PCA plots for juvenile specimens (Figure 4) reveal a clear separation trend along PC1: most specimens from Osmaniye (Mediterranean) are distributed on the negative side of PC1 (8 out of 9), whereas the majority of specimens from İzmir and Muğla (Aegean) are positioned on the positive side (10 out of 12), with only one specimen from each Aegean locality falling on the negative side. Before performing the Procrustes ANOVA between the Aegean and Mediterranean juvenile groups, we tested whether the six İzmir and six Muğla specimens within the Aegean group could be considered a single population. The Procrustes ANOVA results for juveniles did not reveal significant variation in either shape ($F = 0.7346$, $p > 0.5$) or centroid size ($F = 0.181$, $p > 0.5$), and the effect sizes were also found to be low ($Z = -0.35178$ and $Z = -0.45443$, respectively). Therefore, the two groups were pooled and treated as a single Aegean juvenile group in subsequent analyses. The Procrustes ANOVA comparing the Aegean and Mediterranean juvenile populations indicated significant shape variation emerging at early developmental stages ($F = 3.4146$, $p < 0.01$; Supplementary Table S7), a finding consistent with the PCA results for juveniles. By contrast, Procrustes ANOVA for centroid size showed no significant variation between populations, similar to the results observed in adults ($F = 0.2325$, $p > 0.5$; Supplementary Table S8).

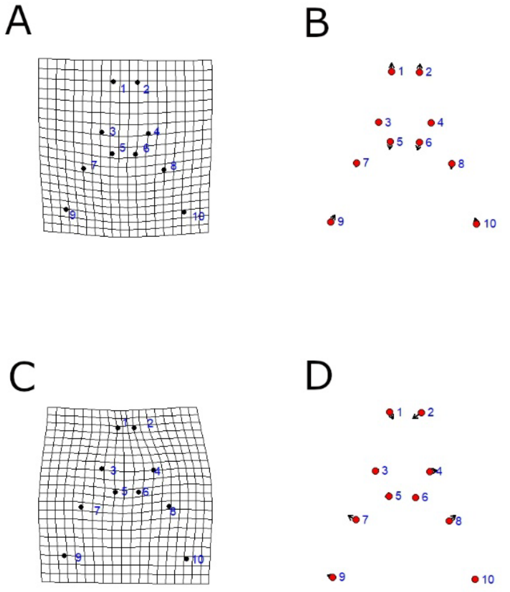

Figure 3. Variations in head shape between Aegean and Mediterranean groups. (A) TPS deformation grids for adults, (B) landmark displacement vectors for adults, (C) TPS deformation grids for juveniles, (D) landmark displacement vectors for juveniles.

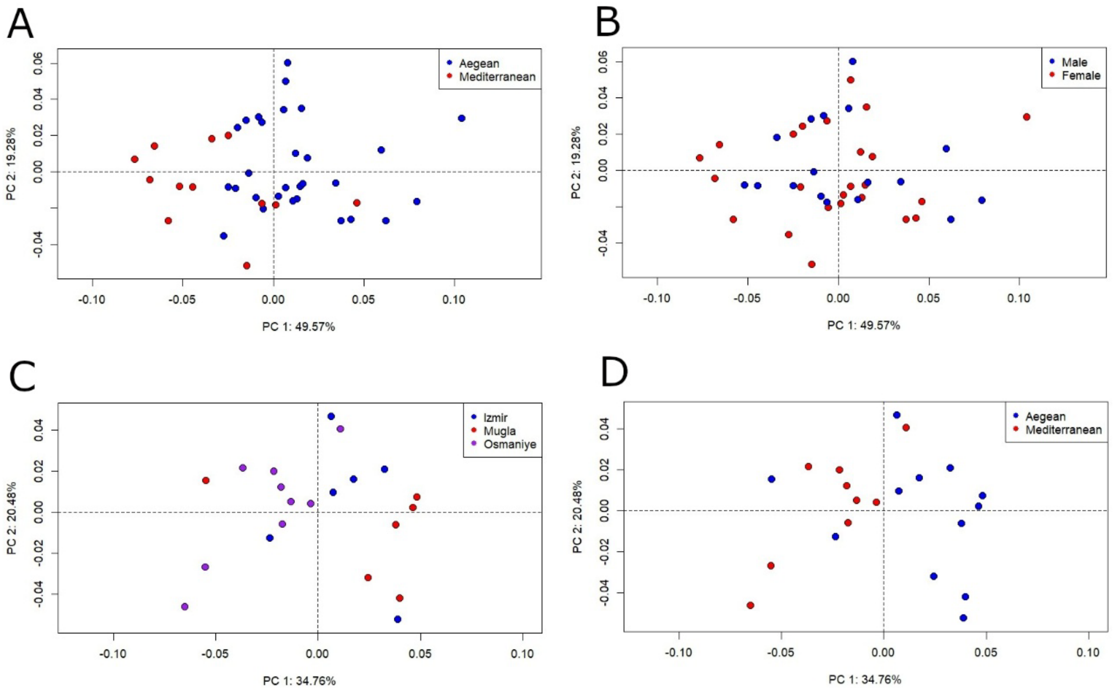

Figure 4. Principal Component Analysis (PCA) plots. (A) Geographic groups in adult populations, (B) sexual dimorphism, (C) variation among populations in juveniles, (D) variation between geographic groups in juveniles.

### Correlation and regression analyses

The correlation analyses revealed strong and statistically significant relationships between head length and centroid size (CS) in both adult and juvenile samples. In adults, HW, HL, AIO, and IN showed strong positive correlations with CS ($r > 0.70$, $p < 0.001$), indicating a strong association between CS and the head traits.

Among juveniles, very strong correlations were observed between CS and several measurements, particularly juvenile head width (JHW, $r = 0.94$), juvenile posterior interorbital width (JPIO, $r = 0.94$), juvenile middle interorbital width (JMIO, $r = 0.88$), and juvenile head length (JHL, $r = 0.87$). These results suggest a consistent pattern of increasing head size during early development. In contrast, correlations between linear measurements and PC1—the primary axis of shape variation—were generally weak or nonsignificant. Only a few traits, such as JPIO ($r = 0.56$, $p < 0.01$), JHW ($r = 0.56$, $p < 0.01$), and juvenile anterior interorbital width (JAIO, $r = 0.52$, $p < 0.05$), showed moderate correlations with PC1.

The centroid size–head length regression plots for adults and juveniles are presented in Figure 5. The regression models were significant for both adults and juveniles ($p < 0.001$).

### Outline-based shape analyses

MANOVA of the outline-based shape analysis of the anterior postmental plates showed that neither sex nor the sex × population interaction had a significant effect on shape ($p > 0.10$; Supplementary Tables S9 and S10). These findings indicate that there is no sexual dimorphism in the anterior postmental plates of this species. In contrast, significant shape variations were detected between geographical groups for the right anterior postmental plate (Pillai's Trace = 0.346, $F$ (3, 31) = 5.462, $p < 0.01$). For the left anterior postmental plate, no significant variation was found between geographical groups (Pillai's Trace = 0.210, $F$ (3, 31) = 2.745, $p > 0.05$).

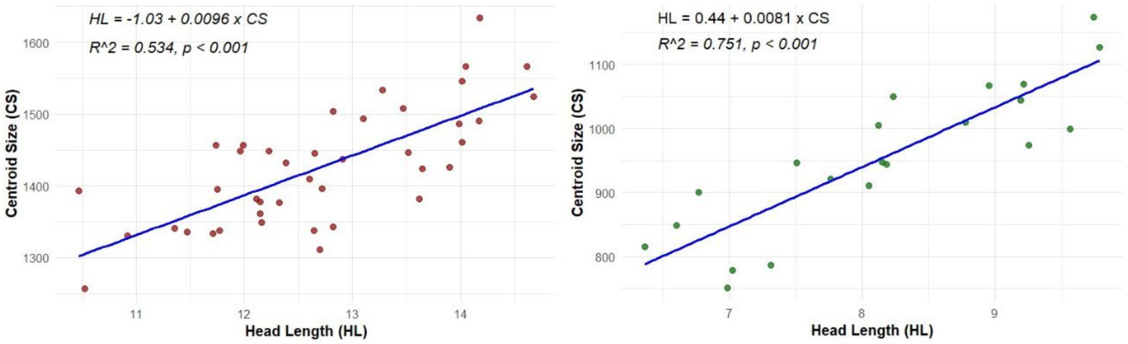

Figure 5. HL–CS relationship. Left: Adult specimens, right: Juvenile specimens.

## Discussion

Geometric morphometric analyses revealed no significant sexual dimorphism in the external head shape and size of *H. turcicus*. Similarly, Paluh et al. (2018) reported quadrate variation between juvenile and adult individuals but no sexual dimorphism in quadrate morphology. Taken together, both geometric morphometric studies highlight the absence of sexual dimorphism in this species.

Morphological variation among lizard populations has been reported across different habitats and conditions (Herrel et al. 2011, Jaffe et al. 2016, Chabaud et al. 2022), and in some species, such differences arise early in development (Pezaro et al. 2024). Length analyses revealed significant variation among geographical groups for HW and MIO ($p < 0.05$ and $p < 0.01$, respectively). These findings are consistent with those of Kaya et al. (2023), who found that the populations of Heybeliada and Büyükada differed from those in southern Anatolia. Similarly, our geometric morphometric analyses revealed significant shape variation between the Aegean and Mediterranean populations in both adults and juveniles. In particular, Procrustes ANOVA results showed that the two geographical groups differed in shape, with morphological variation evident from an early stage ($F = 3.4146$, $p < 0.01$).

The absence of significant variation between the juvenile populations of İzmir and Muğla suggests that these two Aegean groups are morphologically similar and can be considered as a single Aegean group. The observed shape variation between the Mediterranean group, comprising the Osmaniye population, and the Aegean group suggests that geographic factors drive morphological variation in the early developmental stages of the species.

In conclusion, the study demonstrated statistically significant shape variation between the Aegean and Mediterranean populations of *H. turcicus* in Türkiye using geometric morphometric approaches. According to the literature review, no previous studies have used geometric morphometric methods to evaluate shape variation in *H. turcicus* from Türkiye. Therefore, this study represents the first attempt to investigate head-shape variation among Turkish regional populations of this species using geometric morphometrics. Further morphometric studies covering *H. turcicus* populations across all geographical regions of Türkiye and accounting for variation in island populations (Kaya et al. 2023, Kurtul 2023) are important for understanding the evolutionary and ecological basis of this species's intraspecific variation. To better understand the intra-species variation of *H. turcicus*, increasing the sample size in geometric morphometry studies (Paluh et al. 2018) and evaluating specimens from the northern regions of Türkiye (Marmara and Black Sea regions) using the same methods, while considering the possibility of a "cline", will allow for a more accurate taxonomic evaluation of the populations (Thorpe & Baez 1987, Robbins & Hegdahl 2024).

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