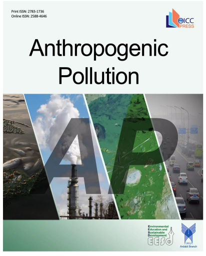

Volume 9, Issue 1, 092506 (1-9)

Anthropogenic Pollution (AP)

https://doi.org/10.57647/j.jap.2025.0901.06

Pollution-driven morphological adaptations in scorpions: insights from human-dominated landscapes

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Original Research

Received:
29 January 2025
Revised:
3 March 2025
Accepted:
6 March 2025
Published online:
1 July 2025

Abstract:

Pollution from human activities, such as industrialization and agriculture, has profound impacts on ecosystems and their inhabitants. This study investigates how environmental pollution influences morphological adaptations in scorpions, using them as bioindicators to assess ecological changes in human-dominated landscapes. Scorpions (*Androctonus crassicauda*; Buthidae family) were collected from regions in Isfahan Province, Iran, representing gradients of agricultural, urbanized, and industrialized areas. Morphological traits were measured and analyzed using multivariate statistical methods. Results revealed that over 70% of the variance in morphological traits was explained by a size gradient, with industrial pollution significantly associated with increased morphological variability ($\beta = 0.176$, $t = 2.019$, $p = 0.030$). In contrast, agricultural activities were linked to reduced morphological diversity ($\beta = -0.09$, $t = -2.739$, $p = 0.007$). These findings suggest that industrial pollution enhances morphological variability, likely through phenotypic plasticity in response to diverse stressors, while agricultural practices limit it, possibly due to environmental homogenization and pesticide pressures.

Keywords: Scorpion morphology; Land use effects; Bioindicators; Industrial pollution

1. Introduction

The Buthidae family represents the largest and most diverse group of scorpions globally, comprising 87 genera and 919 species (Guerrero-Vargas et al., 2015). This family accounts for a significant proportion of scorpion diversity worldwide, making it a critical focus for taxonomic and ecological studies. Buthidae scorpions are broadly categorized into two geographical groups: Old World and New World species. Old World scorpions, distributed across northern Africa, southern Europe, Asia, and the Middle East, include genera such as *Androctonus*, *Leiurus*, *Mesobuthus*, *Hemiscorpius*, and *Buthus*. In contrast, New World scorpions, primarily found in the Americas, are represented by distinct genera such as *Centruroides* and *Tityus* (Mendes et al., 2023). In Iran, the Old World Buthidae family exhibits remarkable diversity, with 44 documented species. Among these, *A. crassicauda* stands out due to its medical significance and widespread distribution across the Middle East (Fatemi et al., 2022). This species is prevalent in various regions of Iran, including the southern Zagros Mountains at elevations of approximately 2000 m above sea level, as well as the coastal areas of the Persian Gulf and Gulf of Oman (Fatemi et al., 2022).

Scorpions and other arthropods show notable changes in behavior, morphology, and physiology in polluted, human-dominated landscapes (Olivero et al., 2021). In such environments, species often encounter degraded habitats characterized by dysfunctional ecosystem components, such as harsh climatic conditions and poor vegetation cover (Mackay et al., 2017). These challenges force scorpions to develop adaptive responses to environmental pressures, primarily through variability in key anatomical traits. Their limited mobility restricts their ability to disperse over long distances, making morphological adaptations a critical element of their survival. This sensitivity to environmental changes positions scorpions as effective biomonitoring tools for assessing environmental pollution. For instance, Silkina et al. (2014) found that scorpions in polluted environments exhibit compromised immune status and elevated oxidative stress, which correlate with increased trait variability. Furthermore, studies have shown that scorpions thrive better in food-rich forested areas compared to urban environments (Feitosa et al., 2024) and agricultural regions (Murayama et al., 2023). Olivero et al. (2021) also observed significant morphological variations in scorpion populations subjected to prolonged urbanization pressures, concluding that scorpions exhibit high sensitivity to human-dominated and polluted landscapes.

Iran is a country characterized by a diverse range of climates (Hashemian et al., 2023), from arid deserts in the central regions to resource-rich mountainous areas in the north and west. The availability of water and other resources from these mountainous regions has enabled agricultural activities to flourish even in the arid central parts of the country (Mohammadi et al., 2023). However, these agricultural practices are predominantly traditional, relying heavily on the use of pesticides and herbicides (Shahradnia et al., 2022). This has led to significant pollution of the landscapes, posing severe risks to many arthropod species, including scorpions. In addition to agriculture, Iran's human-dominated landscapes are marked by compact industrial and urbanized areas, which are well-documented as major sources of pollution emissions (Asgarian et al., 2018; Qing et al., 2015). These land cover types are known to exert adverse effects on local biodiversity, disrupting ecosystems and threatening the survival of many species (Garrard et al., 2018; Hughes, 2017).

Despite the growing body of research on the impacts of human activities on arthropods, there remains a significant gap in understanding how these intense land use practices affect scorpions, particularly *A. crassicauda* in Iran. This species is recognized as a key biomonitoring species due to its high sensitivity to environmental changes, limited mobility, and reliance on specific microhabitats. Furthermore, its morphological and physiological responses to pollution and habitat degradation make it a valuable indicator of ecosystem health (Kassiri et al., 2020). However, the specific mechanisms by which agricultural and industrial activities influence scorpion populations in Iran are poorly understood. To address this gap, this study investigates the effects of land use on the morphology of *A. crassicauda*. Isfahan Province was selected as the study area due to its high diversity of human activities and distinct spatial patterns of land use. Specimens of *A. crassicauda* were collected from various locations, and their morphological characteristics were measured. A multivariate statistical analysis was employed to reduce the dimensionality of the morphometric data, and the resulting principal components were used as dependent variables. These variables were then analyzed to assess how the percentage of land use areas surrounding each sampling location influenced the variability of the species' morphological characteristics.

2. Material and methods

2.1 Sampling strategy and specimen collection

A total of 20 distinct locations were strategically selected across Isfahan Province for the collection of scorpion samples. These sites were chosen to encompass a diverse range of environmental and anthropogenic conditions, ensuring

Figure 1. Dorsal and ventral views of a representative male scorpion specimen collected during the study.

a comprehensive representation of the region's ecological variability. The sampling locations spanned from the periphery of Isfahan city, an area heavily influenced by agricultural and industrial activities, to the remote and pristine bare lands in the northern part of the province, which exhibit minimal evidence of human presence. At each of the 20 selected locations, one fully grown, healthy male scorpion specimen (figure 1) was collected to minimize confounding effects of sexual dimorphism and ensure consistency in the analysis of morphological, ecological, and behavioral traits. Sampling was conducted during the active nocturnal period of scorpions to maximize the likelihood of encounters. The collection period spanned two consecutive years: from April to September 2020 and from April to October 2021 to account for seasonal variations in scorpion activity and to ensure a robust dataset. All specimens were carefully handled, identified, and preserved according to standard entomological practices to maintain their integrity for subsequent analyses.

2.2 Morphometric analysis

Morphological characteristics of the collected scorpion specimens were measured following established taxonomic guidelines and methodologies described by Lamoral (1980) and Shewell (1971). All measurements were recorded in cm to ensure consistency and precision. The analysis focused on key morphological traits, including the carapace, metasomal segments, and other critical structures, which are essential for taxonomic identification and comparative studies. Accordingly, the following measurements were taken: carapace length (CL), carapace anterior width (CAW), and carapace posterior width (CPW). Additionally, distances between the anterior median eyes (X) and posterior median eyes (Y) were recorded. For the chelae, chela length (CHL) was measured, while the metasoma was analyzed through total metasoma length (ML) and the lengths of individual metasomal segments (MFL, TIL, TIH, TIW). The lengths, widths, and heights of the metatarsi (MTIL, MTIIL, MTIIIL, MTIVL, MTVL, MTIW, MTIIW, MTIIIW, MTIVW, MTVW, MTIH, MTIIH, MTIIIH, MTIVH, MTVH) were also measured to assess appendage proportions. Total body length (L), mesosoma length (MESO), and patella length (PAT) were recorded to provide a comprehensive overview of the specimen's morphology. These measurements were meticulously recorded to ensure accurate taxonomic identification and to facilitate comparative analyses of morphological variation across the sampled populations.

2.3 Principal component analysis of morphometric data

Given the interrelated nature of the measured morphological characteristics, Principal Component Analysis (PCA) was employed to reduce the dimensionality of the dataset and create dimensionless variables that effectively represent the entire set of measured variables. PCA is a multivariate statistical technique that transforms a large number of correlated variables into a smaller set of uncorrelated variables, known as principal components (PCs) (Jolliffe and Cadima, 2016). These PCs are linear combinations of the original variables and are ordered such that the first few components explain the majority of the variability in the dataset.
Prior to PCA, all measured variables were normalized to ensure that each variable contributed equally to the analysis, regardless of differences in scale or units. Normalization was achieved by scaling the data to have a mean of zero and a standard deviation of one. The normalized data were then introduced to PCA, which calculated the eigenvalues and eigenvectors of the covariance matrix to determine the principal components. The PCs were ranked based on the proportion of variance they explained, with the first PC accounting for the largest variance, the second PC for the next

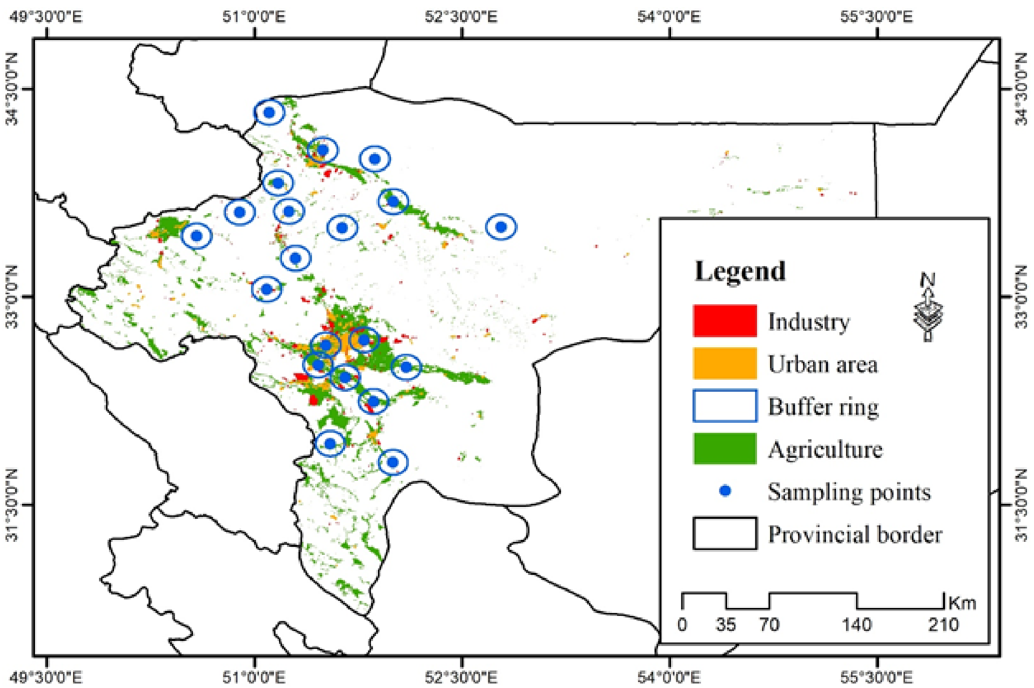

Figure 2. Spatial distribution of sampling locations and associated 10 km buffer rings across Isfahan Province.

largest, and so on. For further analysis, only those PCs that explained a majority of the variability in the dataset were retained to not only simplifies the interpretation of the data but also minimizes the loss of critical information.

2.4 Land use analysis and its influence on morphometric characteristics

To assess the potential influence of anthropogenic activities on the morphometric characteristics of the sampled scorpion species, a spatial analysis of land use was conducted. A buffer ring with a radius of 10 km was drawn around each of the 20 sampling locations (figure 2). Within each buffer zone, the percentage area of agricultural, urban, and industrial land use types was calculated and they were used as independent variables to evaluate their effects on the morphometric traits of the species. The land use data were obtained from the re-assessed dataset of the Isfahan Land Use Planning Report Archive. This dataset was initially compiled in early 2010 and subsequently updated after the beginning of 2020 to reflect recent changes in land use patterns. These land use percentages were then employed to determine whether anthropogenic activities, such as agriculture, urbanization, and industrialization, had a measurable impact on the species' morphology.

A statistical modeling approach was employed for this purpose. First, the autocorrelation among the three land use variables (agricultural, urban, and industrial percentages) was assessed using Variance Inflation Factor (VIF) analysis (Daoud, 2017). Variables with a VIF value higher than 3 were considered to exhibit significant multicollinearity and were excluded from further analysis to ensure the robustness of the model. Given that Principal Component Analysis (PCA) revealed that PC1 explained the majority of the variability in the morphometric characteristics, the scores assigned to each specimen along PC1 were used as the dependent variable in the statistical model. These scores represent a composite measure of the most influential morphometric traits, providing a comprehensive response variable for analysis.

The relationship between land use variables and PC1 scores was modeled using a Generalized Linear Model (GLM) in *R* (Dunn and Smyth, 2018), with the Gaussian family specified to account for the continuous nature of the dependent variable. The GLM framework allows for the examination of linear relationships between predictors (land use percentages) and the response variable (PC1 scores) while accommodating the assumptions of normality and homoscedasticity. The contribution of each land use variable to the model was assessed based on three key metrics: (1) the estimate, which indicates the direction (positive or negative) and magnitude of the effect; (2) the t-value, which measures the significance of the variable's contribution; and (3) the overall model performance, evaluated using the coefficient of determination (R^2), Root Mean Squared Error (RMSE), and Akaike Information Criterion (AIC). Additionally, the distribution of residuals was examined to ensure the model's assumptions were met and to validate its reliability.

3. Results

The morphometric characteristics of the sampled scorpion specimens are presented as mean values and standard deviations in figure 3. The CL averaged 10.425 ± 1.671 cm, with CAW and CPW measuring 6.913 ± 1.535 cm and 10.519 ± 1.549 cm, respectively. The distances between the anterior median eyes (X) and posterior median eyes (Y) were 5.512 ± 1.418 cm and 5.366 ± 1.472 cm, respectively. CHL averaged 15.772 ± 1.287 cm, while the total ML was 10.627 ± 1.131 cm. The lengths of individual metasomal segments varied, with MFL measuring 7.288 ± 0.635 cm and TIL averaging 9.044 ± 1.037 cm. TIH and TIW were 3.228 ± 0.442 cm and 3.460 ± 0.360 cm, respectively. For the metatarsi, the mean lengths were as follows: MTIL measured 6.014 ± 0.488 cm, MTIIL 6.720 ± 0.386 cm, MTIIIL 6.742 ± 0.934 cm, MTIVL 8.042 ± 0.331 cm, and MTVL 9.227 ± 0.671 cm. The mean widths were recorded as MTIW 6.055 ± 0.462 cm, MTIIW 6.671 ± 0.340 cm, MTIIIW 7.227 ± 0.395 cm, MTIVW 7.274 ± 0.902 cm, and MTVW 6.638 ± 0.400 cm. The mean heights of the metatarsi were MTIH 5.408 ± 0.351 cm, MTIIH 5.940 ± 0.452 cm, MTIIIH 6.647 ± 1.405 cm, MTIVH 6.531 ± 0.531 cm, and MTVH 4.915 ± 0.306 cm. L averaged 77.536 ± 22.801 cm, while MESO and PAT were 30.131 ± 8.519 cm and 9.772 ± 1.026 cm, respectively.

PCA was conducted to reduce the dimensionality of the morphometric dataset and identify the most influential variables. The cumulative explained variance (%) for the principal components was as follows: PC1 accounted for 70.547% of the total variance, PC2 for 84.1566%, PC3 for 94.7662%, PC4 for 98.5882%, and PC5 for 99.273% (figure 4 (a)). Given that PC1 explained the majority of the variability in the dataset, it was selected as the representative component for further modeling and analysis. The loadings of each morphometric variable on PC1, which accounted for 70.547% of the total variance, are presented in figure 4 (b). The highest loadings were observed for total body length (L, 0.9418) and mesosoma length (MESO, 0.952), indicating that these variables contributed most significantly to the variability captured by PC1. Other variables with strong contributions included carapace length (CL, 0.852), carapace posterior width (CPW, 0.8215), telson length (TIL, 0.9005), telson width (TIW, 0.832), and the lengths of the metatarsi (MTIL, 0.881; MTIIL, 0.8712; MTIVL, 0.8615; MTVL, 0.871). Variables such as the distances between the anterior median eyes (X, 0.406) and posterior median eyes (Y, 0.4255) showed relatively lower loadings, suggesting a weaker influence on PC1.

The percentage area of urban, agricultural, and industrial land use within the 10 km buffer rings around each sampling location was calculated to evaluate the variability in anthropogenic activities across the study area. Urban land use ranged from 0% to 43.62%, with a mean coverage of 10.6% (SD = 11.27) (Table 1). Agricultural land use exhibited the widest range, varying from 0% to 54.23%, with a mean of 11.5 ± 14.63%. Industrial land use showed the lowest coverage, ranging from 0% to 5.67%, averaging 1.25 ± 1.8%. The VIF values for urban, agricultural, and industrial land use were 2.14, 1.33, and 2.71, respectively. All

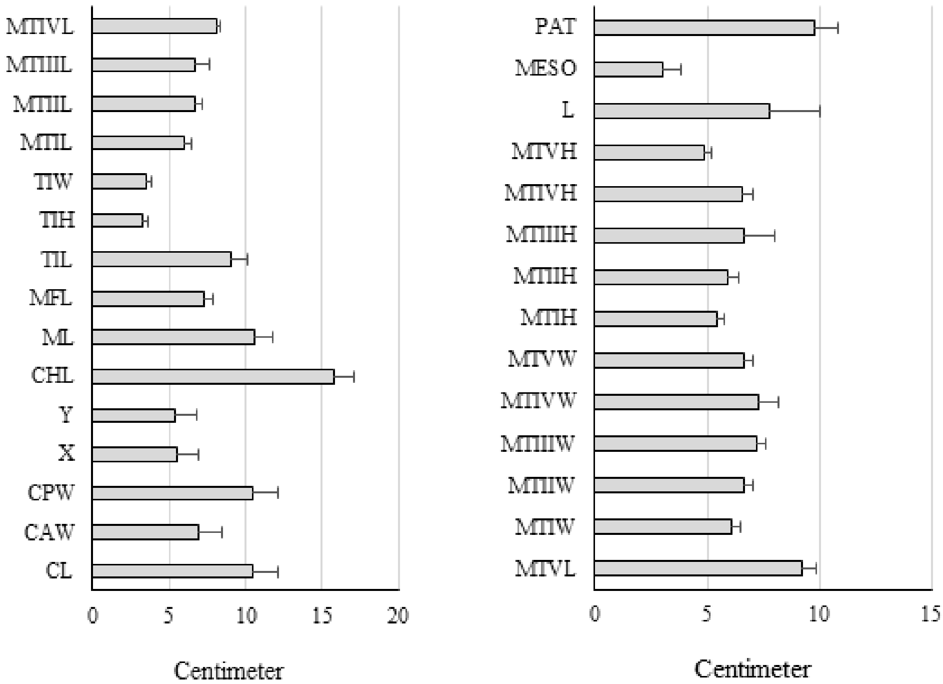

Figure 3. Morphometric characteristics of the sampled scorpion specimens. Total body length (L) and mesosoma length (MESO) are divided by 10 for better visualization and representation of the results.

VIF values were below the threshold of 3, indicating that multicollinearity among the variables was not significant, allowing all three land use variables to be included in the subsequent statistical modeling without compromising the robustness of the analysis.

The GLM model revealed significant relationships between land use variables and the morphometric characteristics represented by PC1 scores. The results indicated a satisfactory model fit, with an R^2 value of 0.617, explaining 61.7% of the variance in the morphometric characteristics represented by PC1 scores. The RMSE was found to be 1.993, reflecting a relatively low prediction error, and the AIC was 382.14, further supporting the model's robustness (Table 2). The intercept was statistically significant ($\beta = -0.285$, t $= -2.639$, p = 0.009), indicating a baseline effect on PC1 scores. Among the land use variables, agricultural land use showed a significant positive relationship with PC1 scores ($\beta = 0.09$, t = 2.739, p = 0.007), suggesting that increased agricultural activity is associated with reduced morphological variability in the sampled scorpion species. In contrast, industrial land use had a significant negative effect on PC1 scores ($\beta = -0.176$, t = -2.019, p = 0.030). This implies that industrial activities are linked to greater morphological variability. Urban land use, however, did not exhibit a significant relationship with PC1 scores ($\beta = 0.033$, t = 0.422, p = 0.339), indicating that urbanization had no measurable impact on the morphometric traits analyzed in this study (Table 3).

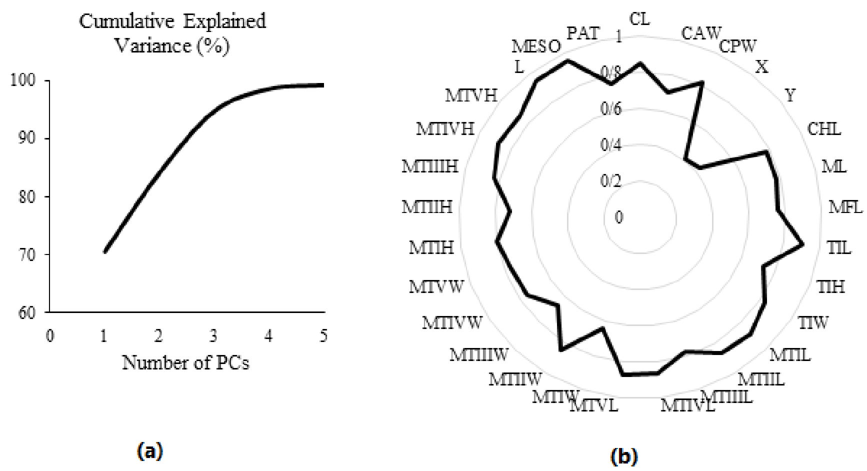

Figure 4. Results of Principal Component Analysis (PCA) applied to morphometric traits of *A. crassicauda.* (a) Cumulative explained variance (%) for the first five principal components. (b) Loadings of each morphometric variable on PC1.

Table 1. Descriptive statistics of percentage area for urban, agricultural, and industrial land use within 10 km buffer rings, along with their corresponding Variance Inflation Factor (VIF) values.

Land use	Percentage area				VIF
	Min	Max	Mean	SD	
Urban	0.00	43.62	10.60	11.27	2.14
Agriculture	0.00	54.23	11.50	14.63	1.33
Industry	0.00	5.67	1.25	1.80	2.71

4. Discussion

The measurements of the sampled scorpion specimens provided a detailed understanding of the morphological variability within the population in Isfahan Province. Morphometric analysis revealed both stability and variability in key scorpion traits. Consistent measurements of carapace, eye positions, and chela length suggest strong selective pressures maintaining essential functions. Conversely, significant variability in body length, mesosoma length, and metatarsi likely reflects adaptive responses to diverse environmental conditions within the sampled population. This stability and variability in key anatomical traits highlight a balance between functional constraints and adaptive responses to environmental pressures. This pattern is likely driven by the limited mobility of scorpions, rendering them particularly susceptible to environmental fluctuations and habitat loss (Bowden et al., 2015). Consequently, scorpions exhibit pronounced morphological adaptations to their specific environments rather than relying on long-distance dispersal to shift their ranges (Silva et al., 2018). These morphological adaptations are crucial for their survival and represent a key aspect of their evolutionary trajectory in this region.

In the PCA analysis, PC1 emerged as the dominant component, explaining a substantial proportion of the total variance. Most morphometric variables showed strong positive loadings on PC1, indicating that this component reflects a size gradient driving morphological variability. This finding aligns with Foerster (2025), who similarly observed that the strength and direction of trait correlations with PC1 can indicate a size gradient. This size gradient likely reflects a complex interplay of genetic, environmental, and ecological factors. Notably, this study highlights that anthropogenic activities, as measured by the percentage area of surrounding land uses, can also influence scorpion morphometric traits. This approach has proven effective in revealing morphological differences in various scorpion species exposed to varying levels of human impact, as demonstrated by Olivero et al. (2021), who found significant variations in scorpion populations subjected to high urbanization pressures over decades. In contrast to their findings, however, this study did not detect a significant relationship between urbanization and the developmental characteristics of scorpions. This discrepancy may stem from differences in the intensity or type of urbanization. Moreover, the resilience of scorpions to urban environments, as suggested by their ability to exploit microhabitats within human-altered landscapes (Motevalli Haghi et al., 2018), could explain the lack of significant urbanization effects in this study.

The results suggest that industrial activities may contribute to increased morphological diversity in scorpions, whereas agricultural activities appear to constrain it. This divergence likely reflects differences in environmental pressures and habitat modifications associated with these land use types. Specifically, industrial landscapes often create heterogeneous habitats through a mix of artificial structures, disturbed soils, and fragmented ecosystems (Prakash and Verma, 2022), which may drive morphological adaptations. As industrial activity intensifies, the morphological diversity of scorpion populations increases-a trend potentially linked to the unique selective pressures of these environments. However, industrial zones are also associated with environmental stressors such as pollution and habitat degradation, which impose significant physiological and ecological challenges. While some individuals may adapt to these conditions, others experience reduced fitness or survival rates, creating a trade-off between morphological diversity and population stability. This dynamic aligns with findings in other scorpion species exposed to industrial environments, where increased trait variability correlates with compromised immune status and elevated oxidative stress (Silkina et al., 2014). Such sensitivity to environmental stressors, combined with their sedentary nature and habitat specificity, positions scorpions as effective biomonitoring tools for assessing environmental pollution in industrial hotspots of central Iran.

In industrial zones, the observed morphological diversification likely stems from a suite of environmental pressures unique to these landscapes. For instance, chemical pollutants such as heavy metals or organic compounds, prevalent in industrial emissions (Qing et al., 2015), might select for variability in CHL to enhance prey capture efficiency under conditions of reduced prey availability or altered prey behavior due to contamination. Similarly, habitat fragmenta-

Table 2. Performance metrics of GLM in predicting morphometric characteristics represented by PC1 scores.

Deviance Residuals					AIC	R^2	RMSE
Min	1Q	Median	3Q	Max			
-8.383	-0.267	0.338	1.113	4.780	382.14	0.617	1.993

Table 3. Summary of GLM results showing the effects of urban, agricultural, and industrial land use on scorpion morphometric characteristics (PC1 scores).

Variable	Metrics			
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.285	0.108	-2.639	0.009
Urban	0.033	0.078	0.422	0.339
Agriculture	0.090	0.033	2.739	0.007
Industry	-0.176	0.087	-2.019	0.030

tion, characterized by disturbed soils and artificial structures (Prakash and Verma, 2022), could drive diversification in metatarsi lengths (e.g., MTIL, MTVL) to improve locomotion across patchy or unstable substrates. Larger or more variable ML might reflect adaptations for increased venom storage or delivery. Thermal fluctuations, another feature of industrial areas, could favor variability in carapace dimensions (CL, CPW) or total body length (L) to optimize thermoregulation under inconsistent microclimates. Unlike the more uniform pressures in agricultural zones, the multifaceted stressors in industrial landscapes likely promote a broader spectrum of adaptive responses, though experimental studies linking specific pollutants or habitat conditions to trait changes are needed to confirm these relationships.
The larger body sizes in agricultural areas are best attributed to environmental influences, such as enhanced food availability or milder microclimates, rather than genetic fixation. This interpretation aligns with the absence of data supporting genetic isolation, distinct genetic pools, or specific selection pressures in these landscapes. Instead, phenotypic plasticity likely drives these size differences, as scorpions respond to favorable conditions with increased growth rates. Genetic studies would be required to explore any heritable basis for these traits, but our findings suggest an environmentally mediated effect consistent with prior observations of plasticity in arthropods under resource-rich conditions (Feitosa et al., 2024). Moreover, the prominence of larger body parts in agricultural areas, such as the mesosoma or chela, may simply scale with the overall increase in body size (L), as PC1 predominantly captures a size gradient. This allometric effect could mask shape-specific adaptations that are biologically meaningful.
Standardizing morphometric traits-e.g., by computing ratios of individual measurements to total body length or deriving residuals from size regressions-would eliminate the bias of larger body sizes and highlight true differences in body part proportions. Such an analysis could reveal whether specific traits, like chela length or metasoma proportions, undergo independent adaptation to land use pressures, offering deeper insight into the functional significance of morphological variability beyond mere size scaling.
While this study provides valuable insights into the effects of land use on scorpion morphometric traits, several limitations should be acknowledged. First, the exclusive use of male specimens may restrict the broader applicability of our results, as females could exhibit distinct morphological responses to pollution due to differing ecological roles or physiological demands (e.g., reproduction). Future studies should compare both sexes to fully elucidate sex-specific adaptations. If PC1 captures a mix of size and shape variation, using it as a sole metric for size might introduce bias. To isolate size effects more accurately, future studies could employ allometry corrections, such as log-transforming variables or calculating residuals of size-standardized traits. The GLM model, although effective in capturing relationships between land use variables and morphometric traits, may not fully account for the biological significance of specific traits like chela length. Chela length, for instance, is often linked to feeding efficiency and reproductive success in scorpions, and its independent examination could reveal more nuanced patterns of adaptation to land use changes. Furthermore, the study's reliance on land use percentages as proxies for anthropogenic activities may oversimplify the complex interactions between scorpions and their environments. Future research could incorporate finer-scale environmental data, such as microhabitat characteristics or direct measurements of pollution levels, to better understand the mechanisms driving morphological changes.

5. Conclusion

This study provides compelling evidence of the divergent effects of land use on the morphometric characteristics of Androctonus crassicauda in Isfahan Province, Iran. Industrial activities drive increased morphological diversity, likely reflecting adaptive plasticity in response to heterogeneous and polluted habitats, while agricultural practices constrain variability, possibly due to habitat homogenization and pesticide-induced stressors. The dominance of PC1 as a size gradient underscores the importance of body size in mediating these responses, yet the lack of a significant urban effect suggests that *A. crassicauda* may tolerate moderate urbanization, potentially exploiting microhabitats within such areas. These findings affirm the sensitivity of scorpions as bioindicators, capable of revealing subtle ecological shifts in arid and semi-arid ecosystems under anthropogenic pressure. Beyond documenting morphological changes, this study highlights the need for integrated approaches-combining morphometric, physiological, and genetic analyses-to fully elucidate the mechanisms and long-term consequences of pollution-driven adaptations. Such insights are critical for informing conservation strategies and pollution mitigation efforts in human-dominated landscapes, ensuring the preservation of biodiversity and ecosystem functionality in regions like central Iran. The ecological consequences of these morphological changes remain nuanced and context-dependent. However, increased morphological diversity could confer a positive effect by enhancing *A. crassicauda's* adaptability to fragmented or polluted habitats. Conversely, the constrained morphological diversity in agricultural areas could negatively affect the ecosystem by reducing scorpion resilience to environmental fluctuations.

Funding
This research was funded by Islamic Azad University, Isfahan (Khorasgan) Branch, Isfahan, Iran.

Authors contributions
Yalda Montaser: Data curation, software, formal analysis. Atefeh Chamani: Resources, project administration, conceptualization, supervision. Rouhullah Dehghani: Validation, visualization. Hedieh Jafari: Methodology, review & editing.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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