Species- and organ-specific elemental profiles and biogeochemical indicators in *Lagochilus* taxa from gypsiferous mountain ecosystems of Central Asia

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Abstract. Medicinal plants inhabiting arid mountain ecosystems may display differences in elemental composition associated with species-specific characteristics and local environmental conditions. This study examined the elemental profiles of six *Lagochilus* taxa (*L. acutilobus, L. gypsaceus, L. proskorjakovii, L. inebrians, L. olgae,* and *L. vvedenskyi*) from gypsiferous habitats of the Zirabulak Mountains, Uzbekistan. Elemental concentrations in leaf and flower samples were determined by inductively coupled plasma optical emission spectrometry (ICP-OES). Standardized multielement data were explored using principal component analysis (PCA). The results showed variation in elemental composition among the analyzed samples. The leaves of *L. acutilobus* occupied an isolated position along PC1, consistent with comparatively high concentrations of Al, Fe, and several additional elements. However, leaves and flowers did not form consistently separated groups across all taxa. The PCA is therefore interpreted as an exploratory visualization of multielement variation rather than a formal test of organ-specific, taxonomic, or ecological differentiation. The findings provide a basis for future studies combining replicated plant sampling, substrate analyses, and formal statistical testing to investigate plant–substrate relationships in arid mountain ecosystems.

Keywords: Biogeochemistry, Elemental composition, Gypsiferous ecosystems, ICP-OES, Ionomics, *Lagochilus*, Principal Component Analysis, Species-specific elemental profiles.

1. Introduction

Arid and semi-arid ecosystems of Central Asia are characterized by high environmental heterogeneity and complex geochemical conditions that strongly influence vegetation structure and plant mineral metabolism (Yu et al., 2019). In Uzbekistan, the foothill and mountain regions of the Zirabulak range represent a geochemically distinctive territory formed by metamorphic rocks, polymetallic mineralization, and extensive gypsiferous outcrops (Azimov et al., 2015). Such substrates create specific edaphic conditions enriched with lithogenic and trace elements, which may substantially affect elemental accumulation patterns in native plant species (Palacio et al., 2022; Cera et al., 2023; Shi et al., 2023).

Plant communities inhabiting gypsum-rich landscapes often exhibit specialized physiological adaptations associated with ion regulation, mineral transport, and tolerance to elevated concentrations of calcium, sulfur, and trace metals. In arid environments, these adaptive mechanisms are particularly important for maintaining metabolic stability under conditions of limited water availability and mineral imbalance. Consequently, elemental profiling of endemic taxa growing on geochemically heterogeneous substrates provides valuable information for understanding ecological adaptation and species differentiation (Nguyen et al., 2022; Meng et al., 2024). Similar approaches have previously been applied to medicinal plants of Central Asian mountain ecosystems for evaluating phytochemical and ecological variability among geographically distinct populations (Aimenova et al., 2023).

Species of the genus *Lagochilus* Bunge ex Benth. (Lamiaceae) are widely distributed across the arid and mountainous regions of Central Asia and are known for their ecological plasticity and medicinal significance (Mamadalieva et al., 2021). Previous studies have also demonstrated substantial variability in the biochemical composition and population characteristics of *Lagochilus* species under different environmental conditions (Eshibaev et al., 2021). Several representatives of the genus are associated with rocky and gypsiferous habitats, where they may serve as sensitive indicators of local geochemical conditions. Previous studies have primarily focused on the phytochemistry and pharmacological properties of *Lagochilus* species, whereas their ionomic and biogeochemical characteristics remain insufficiently investigated, particularly in the Zirabulak Mountains. In addition, comparative information regarding species-specific elemental accumulation and organ-related mineral distribution in these taxa is still limited.

Elemental analysis combined with multivariate statistical approaches can support exploratory comparisons of multielement profiles in medicinal plants. In particular, principal component analysis can be used to visualize major patterns of variation among samples. Therefore, the present study aimed to characterize the elemental composition of six *Lagochilus*

taxa (*L. acutilobus, L. gypsaceus, L. olgae, L. proskorjakovii, L. vvedenskyi*, and *L. inebrians*) collected from the gypsiferous ecosystems of the Zirabulak Mountains, Uzbekistan, and to explore variation among taxa and plant organs using multivariate analysis. We hypothesized that multielement profiles would vary among the studied *Lagochilus* taxa and that leaf–flower differences could occur within individual taxa.

2.1. Study Area and Plant Sampling

The plant material was collected during the peak flowering stage (May–June 2024) from the northern foothills of the Zirabulak Mountains, Nurabad district, Samarkand region, Uzbekistan (Fig. 1). Six species of the genus *Lagochilus* were selected for the study: *Lagochilus acutilobus* (Ledeb.) Fisch. & C.A. Mey., *L. gypsaceus* Vved., *L. inebrians* Bunge, *L. olgae* Kamelin, *L. proskorjakovii* Ikramov, and *L. vvedenskyi* Kamelin & Tzukerv. Nomenclature follows World Flora Online (WFO, 2026).

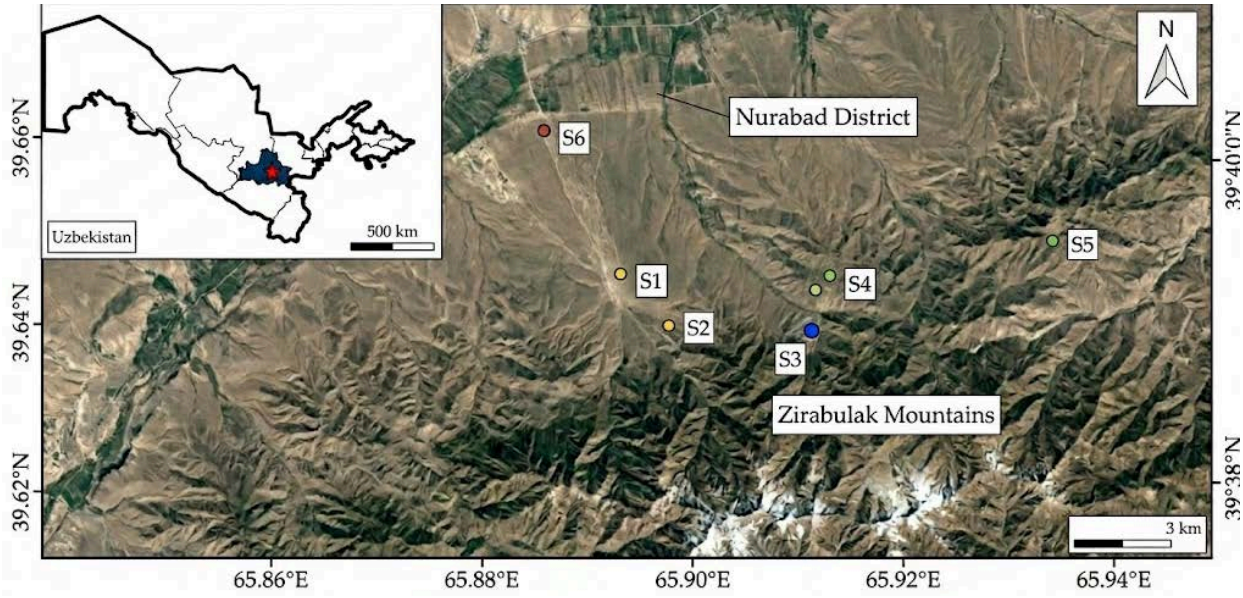


Figure 1. Sampling sites (S1–S6) of *Lagochilus* taxa in the Zirabulak Mountains, Nurabad district, Uzbekistan

This region is characterized by a sharply continental climate with arid conditions, typical of the Central Asian semi-desert zone. Sampling was performed during the peak flowering stage of the *Lagochilus* species to ensure consistent physiological status. Six distinct sampling sites (S1–S6) were selected to represent the diverse ecological niches of the studied species, with altitudes ranging from 433 to 561 m above sea level. The precise geographic coordinates and habitat characteristics for each site are detailed in Table 1. At each sampling site, aerial plant material from at least five mature individuals was collected and pooled into a composite sample for

subsequent elemental analysis. Leaves and flowers were separated prior to analysis; for each species–organ combination, the pooled material constituted one composite biological sample.

The precise geographic coordinates, altitudes, and habitat characteristics for each sampling site are provided in Table 1.

Table 1. Characteristics of the sampling sites in the Zirabulak Mountains

Site ID	Species (*Lagochilus*)	Coordinates	Altitude (m a.s.l.)	Habitat Description
S1	*L. inebrians*	39°38'24" N, 65°54'36" E	507.74	Foothill plain, loamy serozem soil
S2	*L. gypsaceus*	39°37'12" N, 65°52'48" E	436.67	Gypsiferous slopes, sparse vegetation
S3	*L. acutilobus*	39°37'48" N, 65°55'12" E	481.68	Stony-gravelly slopes, ephemeral herbs
S4	*L. olgae*	39°36'36" N, 65°52'12" E	426.94	Low hills, light serozem with gravel
S5	*L. proskorjakovii*	39°39'00" N, 65°55'48" E	561.18	Adyr zone, loamy-sandy soil
S6	*L. vvedenskyi*	39°37'12" N, 65°51'36" E	433.23	Rocky outcrops and saline patches

Note: m a.s.l. — meters above sea level. Coordinates were determined using a GPS Garmin eTrex 20x. Site ID (S1–S6) corresponds to the sampling locations within the Zirabulak Mountains, Navoi/Samarkand region, Uzbekistan. Habitat types follow the classification of arid ecosystems of Central Asia (adyr and foothill zones).

The studied species displayed distinct morphological adaptations to their environments. To illustrate the environmental plasticity of the genus, *L. inebrians* was documented in two contrasting habitats. Representative photographs show the plant *in situ* in the rugged terrain of the Zirabulak Mountains (Fig. 2A), where it forms a compact, densely pubescent shrub, and *ex situ* under the improved irrigation and soil conditions of the experimental plot in the Botanical Garden (Fig. 2B).

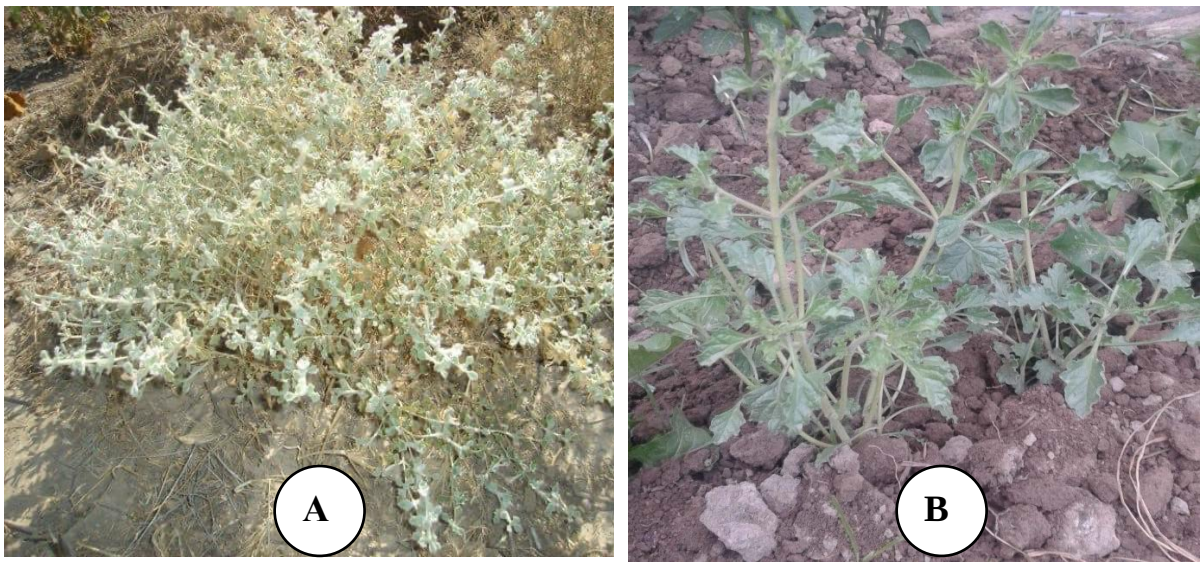


Figure 2. Morphological plasticity of *L. inebrians* under contrasting environmental conditions: (A) wild population from the arid habitat of the Zirabulak Mountains; (B) cultivated specimen grown under irrigated conditions in the Botanical Garden

2.2. Elemental Analysis

The elemental composition of the studied *Lagochilus* species was determined using Inductively Coupled Plasma Optical Emission Spectrometry (Khan et al., 2022).

2.3. Sample Preparation

A precise aliquot of 0.1000 g of air-dried, finely ground plant material (leaves and flowers) was quantitatively transferred into Teflon autoclaves. For sample digestion, 3 mL of purified concentrated nitric acid (HNO_3) and 2 mL of purified hydrogen peroxide (H_2O_2) were added. The digestion process was performed using a Berghof Speedwave Xpert microwave system. The wet digestion procedure lasted 35–45 minutes, with an automatic temperature ramp ranging from 50°C to a maximum of 230°C, and an internal pressure limit of 40 bar.

2.4. Analytical Procedure

Upon completion, the autoclaves were cooled to room temperature. The resulting mineralized solutions were quantitatively transferred into volumetric flasks (50 or 100 mL), rinsed with deionized water, and brought to volume. The solutions were analyzed using a PerkinElmer Avio 200 ICP-OES spectrometer. Element concentrations were calculated using the instrument software with correction for sample mass and dilution and were reported in ppb.

2.5. Quality Control

Quantification was performed against multi-element standard solutions containing macro- and microelements, heavy metals, and rare earth elements. Element concentrations were calculated from calibration curves using multi-element standard solutions, with correction for sample mass and dilution. The results are reported as mass concentrations in ppb (1 ppb = 1 μg kg^{-1}). Each composite sample was analyzed in triplicate as analytical replicates. Mean concentrations were used for subsequent analysis.

2.6. Statistical Analysis and Multivariate Data Processing

The PCA dataset consisted of mean concentrations obtained for 11 leaf and flower composite samples of the studied *Lagochilus* taxa. The leaf sample of *L. gypsaceus* was excluded because the original analytical dataset contained incomplete measurements. Forty-seven elemental variables were included in the analysis.

Because the concentrations of macro-, micro-, and trace elements varied across several orders of magnitude, all elemental variables were standardized by Z-score normalization prior to multivariate analysis. PCA is commonly used to reduce the dimensionality of multielement datasets and to visualize major patterns of variation among samples (Ibourki et al., 2022; Calixto et al., 2023). PCA was performed on the standardized dataset in Python version 3.12.14 using the scikit-learn package version 1.8.0 and singular value decomposition (SVD). The first two principal components, explaining 78.5% of the total variance, were used to visualize variation among the analyzed samples. PCA was interpreted as an exploratory descriptive method and was not used as a formal test of taxonomic, organ-specific, or ecological differentiation.

To assess the influence of the isolated *L. acutilobus* leaf sample on the ordination, an additional sensitivity PCA was performed after excluding this sample. The remaining ten samples were re-standardized, and PCA was recalculated using the same procedure. Both PCA analyses were interpreted descriptively because independent biological replication was not available.

3. Results and Discussion

3.1. Comparative Analysis of Elemental Composition

The elemental analysis of six *Lagochilus* species revealed a complex mineral profile consisting of macro-elements, essential micro-elements, and trace elements (including rare-earth elements). The quantitative distribution of these elements showed pronounced variation depending on species identity and plant organ (leaves vs. flowers). The complete data set of elemental concentrations is summarized in Table 2. In most species, leaves exhibited higher elemental intensities than flowers, particularly for lithogenic elements such as Mg, Al, and Fe.

Table 2. Concentration of major elements in the studied *Lagochilus* taxa

Species	Organ	Li	B	Na	Mg	Al	P	K	Ca	Fe
L. acutilobus	Flowers	3.07×10^4	1.78×10^5	3.29×10^7	2.62×10^7	2.57×10^6	1.58×10^8	5.59×10^7	3.76×10^5	3.28×10^6
	Leaves	2.80×10^5	2.90×10^5	3.91×10^7	6.48×10^7	5.63×10^7	2.10×10^8	6.01×10^7	4.88×10^5	3.38×10^6
L. gypsaceus	Flowers	4.89×10^4	1.32×10^5	1.79×10^7	1.97×10^7	4.59×10^6	1.01×10^8	2.65×10^7	2.24×10^5	3.69×10^7
L. olgae	Flowers	1.58×10^4	1.62×10^5	2.15×10^7	2.14×10^7	5.42×10^6	1.25×10^8	3.98×10^7	2.65×10^5	4.29×10^5
	Leaves	1.43×10^4	2.30×10^5	1.92×10^7	3.10×10^7	4.31×10^6	1.08×10^8	4.81×10^7	2.36×10^5	3.43×10^6
L. proskorjakovii	Flowers	1.62×10^4	2.16×10^5	3.16×10^7	1.78×10^7	3.23×10^6	1.68×10^8	3.53×10^7	4.7×10^5	4.04×10^5
	Leaves	2.16×10^4	2.30×10^5	4.65×10^7	3.13×10^7	4.42×10^6	2.28×10^8	1.90×10^7	4.58×10^5	3.61×10^6
L. vvedenskyi	Flowers	3.55×10^4	1.08×10^5	1.26×10^7	2.82×10^7	4.12×10^6	6.89×10^7	3.55×10^7	1.46×10^5	3.50×10^5
	Leaves	7.53×10^4	1.95×10^5	1.87×10^7	4.44×10^7	5.30×10^6	9.76×10^7	6.48×10^7	2.41×10^5	4.65×10^6
L. inebrians	Flowers	3.94×10^4	1.44×10^5	1.49×10^7	2.77×10^7	3.67×10^6	8.64×10^7	3.02×10^7	1.83×10^5	3.16×10^5
	Leaves	1.10×10^5	2.69×10^5	2.30×10^7	3.90×10^7	4.89×10^6	1.20×10^8	2.55×10^7	2.88×10^5	4.93×10^7

Note: Values are expressed in ppb. The leaf sample of *L. gypsaceus* was not included because the original analytical dataset contained incomplete measurements for this sample.

The distribution of essential micro-elements and heavy metals revealed marked variation among the studied taxa (Table 3). Several trace elements showed distinct concentration patterns among the analyzed samples. For instance, the highest concentrations of manganese (Mn) and strontium (Sr) were observed in *L. inebrians* leaves, whereas the highest zinc (Zn) concentration was observed in *L. acutilobus* leaves and the highest lead (Pb) concentration in *L. inebrians* leaves (Table 3).

Table 3. Concentrations of trace elements in the studied *Lagochilus* taxa

Species	Organ	Mn	Zn	Sr	Ba	Cu	Pb
L. acutilobus	Flowers	6.99×10^5	1.03×10^6	3.18×10^6	2.35×10^4	2.30×10^5	1.61×10^4
	Leaves	2.83×10^6	1.63×10^6	4.22×10^6	5.77×10^5	2.93×10^5	3.37×10^4
L. gypsaceus	Flowers	1.34×10^6	5.23×10^5	4.51×10^6	1.56×10^5	1.30×10^5	1.08×10^4
L. olgae	Flowers	1.22×10^6	9.54×10^5	5.54×10^5	2.70×10^4	2.69×10^5	8.28×10^3
	Leaves	1.78×10^6	7.52×10^5	6.44×10^5	2.54×10^4	5.60×10^5	9.68×10^3
L. proskorjakovii	Flowers	1.54×10^6	1.16×10^6	9.68×10^5	3.09×10^4	3.53×10^5	1.60×10^4
	Leaves	1.77×10^6	1.17×10^6	1.63×10^6	8.14×10^4	2.01×10^5	1.91×10^4
L. vvedenskyi	Flowers	1.99×10^6	4.18×10^5	2.80×10^6	2.62×10^4	8.70×10^4	8.97×10^3
	Leaves	3.00×10^6	5.54×10^5	3.68×10^6	2.90×10^5	8.22×10^4	1.40×10^4
L. inebrians	Flowers	1.35×10^6	4.50×10^5	1.34×10^7	1.05×10^6	1.15×10^5	7.74×10^3
	Leaves	2.22×10^6	5.11×10^5	1.49×10^7	1.26×10^6	1.36×10^5	6.07×10^4

Note: Values are expressed in ppb. The leaf sample of *L. gypsaceus* was not included because the original analytical dataset contained incomplete measurements for this sample.

3.2. Multivariate Analysis of Elemental Composition

PCA was applied to evaluate species- and organ-specific patterns of elemental accumulation among the studied *Lagochilus* taxa. The first two principal components explained 78.5% of the total variance, with PC1 and PC2 accounting for 63.4% and 15.1%, respectively (Fig. 3). The PCA biplot illustrated variation in elemental composition among the analyzed samples; however, leaves and flowers did not form consistently separated groups across the studied taxa.

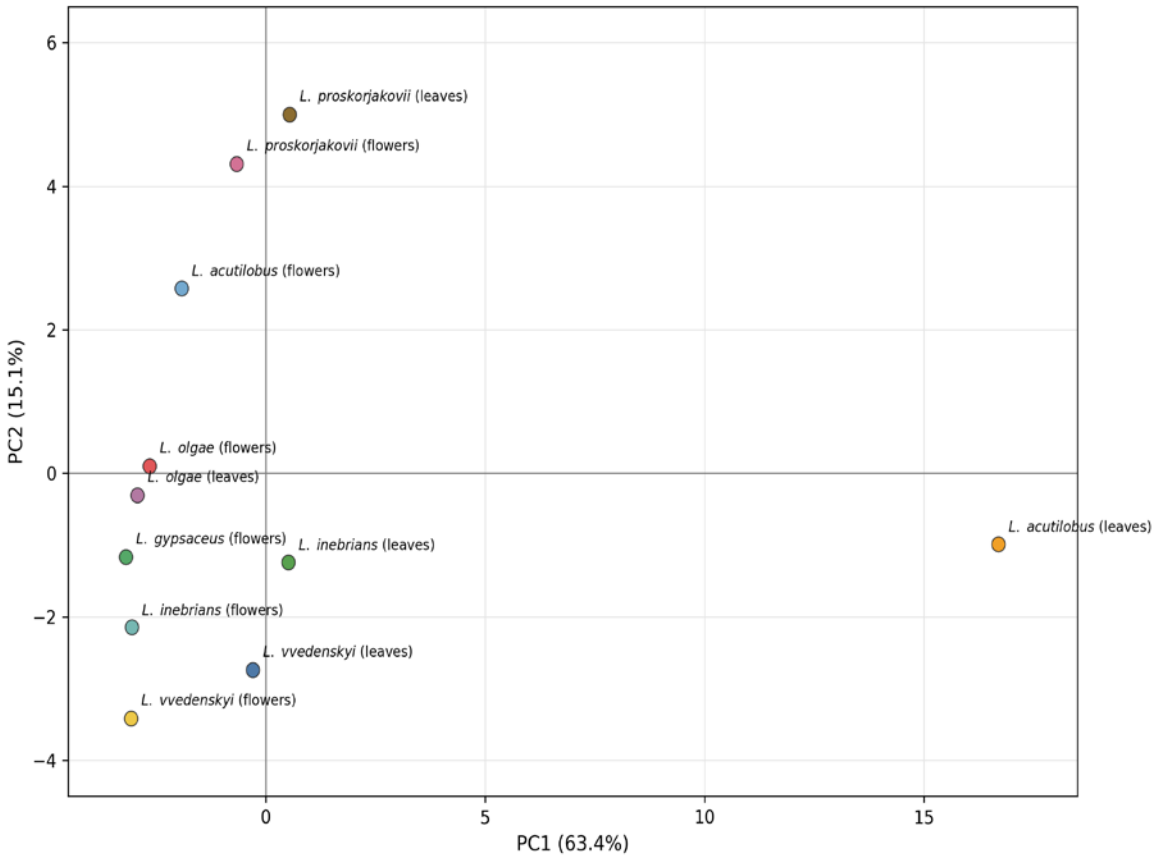


Figure 3. PCA score plot of *Lagochilus* leaf and flower samples based on standardized elemental concentrations.

Among the analyzed samples, *L. acutilobus* leaves occupied an isolated position along the positive direction of PC1. Re-examination of the original analytical dataset confirmed that this position reflects its multielement profile, including comparatively high concentrations of Al and Fe and elevated values for several additional elements included in the PCA. However, this pattern characterizes a single sample and should not be interpreted as a general separation between leaves and flowers. The samples of *L. proskorjakovii* were positioned mainly along PC2, indicating additional variation in elemental composition among the analyzed samples.

To evaluate the influence of the isolated *L. acutilobus* leaf sample, a sensitivity PCA was performed after excluding this sample. In the sensitivity analysis, PC1 and PC2 explained 47.8% and 25.2% of the total variance, respectively (72.9% cumulatively; Fig. App.1). The remaining samples still showed heterogeneous multielement profiles; however, leaf and flower samples did not form consistently separated groups. Therefore, both PCA analyses are interpreted as exploratory visualizations rather than formal evidence of species- or organ-specific differentiation.

The elemental composition of the studied *Lagochilus* taxa may reflect a combination of species-specific physiological traits and local environmental conditions in the Zirabulak Mountains. The occurrence of relatively high concentrations of lithogenic elements, including magnesium (Mg), calcium (Ca), iron (Fe), and aluminum (Al), may be associated with the mineral-rich geological setting of the region (Chaligava et al., 2025; Randé et al., 2023). However, because soil and substrate samples were not analyzed in the present study, this association should be interpreted cautiously. Similar plant–substrate relationships have been reported for plants inhabiting arid and metalliferous environments (Censi et al., 2017).

The comparatively high concentrations of Fe and Al in several samples may be compatible with variation in plant–environment interactions in the studied region. Although plant elemental patterns have been used to indicate mineralization in other settings, including Au and As concentrations in vegetation (Girling et al., 1978), the present data do not allow direct attribution of the observed patterns to mineralized rocky habitats. Similar ecological and biochemical variability has been reported for other representatives of the genus *Lagochilus* from Central Asia (Eshibaev et al., 2021). In the present study, *L. acutilobus* leaves showed a distinct multielement profile relative to the other analyzed samples.

Overall, the PCA provided an exploratory visualization of variation in multielement profiles among the analyzed *Lagochilus* samples. The main pattern in the ordination was associated with the isolated position of *L. acutilobus* leaves along PC1, whereas additional variation was observed along PC2. Given the limited number of samples, the PCA results are interpreted descriptively and are not used as a formal test of chemotaxonomic relationships, organ-specific differentiation, or ecological adaptation.

The observed multielement patterns, including the distribution of REEs, provide a preliminary basis for future investigations of plant–substrate relationships in arid mountain ecosystems (Dyakova, 2023; Sager & Wiche, 2024). Such studies should include replicated plant sampling, corresponding substrate analyses, and formal statistical testing.

4. Conclusion

This study characterized the elemental composition of leaf and flower samples from six *Lagochilus* taxa collected in the Zirabulak Mountains, Uzbekistan. The results showed variation in multielement profiles among the analyzed samples. In particular, *L. acutilobus* leaves displayed comparatively high concentrations of Al, Fe, and several additional elements, resulting in an isolated position along PC1 in the exploratory PCA score plot.

Leaf and flower samples did not form consistently separated groups across the studied taxa. In addition, because soil and geological substrate samples were not analyzed, the observed elemental patterns cannot be directly attributed to gypsiferous habitats or other substrate characteristics.

Overall, the study provides baseline elemental data for *Lagochilus* taxa from the Zirabulak Mountains. Future research should include replicated biological sampling, paired soil or substrate analyses, and formal statistical testing to evaluate plant–substrate relationships and possible species- or organ-related patterns.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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