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Species Diversity and Elevational Patterns of Saxicolous Lichens in the Eastern Pamir Plateau, China

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Abstract

Saxicolous lichens are crucial elements of alpine ecosystems and are involved in soil formation, rock weathering, nutrient cycling, and environmental monitoring. However, little is known about their distribution patterns and diversity on the eastern Pamir Plateau of China. This study looked at the variety and elevational distribution of saxicolous lichens in China's eastern Pamir Plateau's Taxkorgan Nature Reserve. Six transects spanning an elevational range of 3500–4500 m were used for field studies in July and August of 2025. Stratified sampling was used to gather lichen specimens, which were then identified by morphological, anatomical, chemical (thin-layer chromatography), and molecular investigations. Lichens communities' similarity across altitudes was evaluated using Sørensen's index, and diversity indices such as Simpson, Shannon–Wiener, and Pielou's consistency were computed. A total of 69 saxicolous lichen species from 12 families and 27 genera were identified. With 95.6% of all species, crustose lichens predominated, whilst foliose and fruticose forms were uncommon. Acarosporaceae and Megasporaceae were the most species-rich families, accounting for over half of total recognized species. In the study region, *Aspicilia* and *Acarospora* dominated at the genus level. Saxicolous lichen species richness exhibited a unimodal elevational pattern, peaking at 4101–4300 m with pronounced community turnover across altitudes, as supported by Sørensen similarity values (0.253–0.561). Additionally, substrate type affected lichen distribution, with siliceous rocks hosting richer lichen communities than calcareous substrates. In general, the richness and distribution of saxicolous lichens in the alpine ecosystems of the eastern Pamir Plateau are mostly determined by elevation and rock type. This work provides essential baseline data for lichen biodiversity in the region and highlights the potential use of lichens as bio-indicators for monitoring environmental change in high-mountain ecosystems.

Keywords: alpine ecosystems; biodiversity patterns; environmental bio-indicators; Northwest China

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1. Introduction

Lichens are distinct symbiotic organisms made up of one or more photosynthetic partners (photobionts), typically cyanobacteria or green algae, and a fungal partner (mycobiont). Because of their mutualistic relationship, lichens may live in a variety of conditions, including harsh ones like deserts, arctic areas, alpine ecosystems, and exposed rock surfaces [1]. Globally, lichens are estimated to comprise approximately 20,000 species [2].

Lichens occupy rocks as their substrates, generally known as saxicolous species (categorized into three types based on their growth forms: crustose, foliose, and fruticose) [3], and they represent one of the most ecologically significant groups within lichenized fungi [1].

Saxicolous lichens play an essential role in ecosystem functioning. They contribute to rock weathering, soil formation, and nutrient cycling [1,3]. Additionally, these lichens are significant bio-indicators of environmental conditions, especially habitat disturbance, air pollution, and climate change [4,5]. Numerous environmental conditions, including substrate type, microclimate, altitude, and geographic position, affect the diversity of saxicolous lichens, which are found in a wide range of climatic settings, from tropical mountains to polar deserts [6,7].

Research on saxicolous lichens has greatly increased during the last few decades, combining molecular phylogenetic methods, ecological studies, and conventional taxonomy methodologies. The diversity of saxicolous lichens is remarkable, particularly within crustose lichen communities that dominate rock surfaces. Crustose lichens are highly adapted to exposed substrates due to their tightly attached thalli and efficient water retention mechanisms [8]. Several genera are widely recognized as dominant components of saxicolous lichen communities. These include *Aspicilia* A. Massal., *Circinaria* Link, *Lobothallia* (Clauzade & Cl. Roux) Hafellner, *Rhizocarpon* Ramond ex DC., *Acarospora* A. Massal., *Lecanora* Ach., and *Xanthoparmelia* (Vain.) Hale. Research on saxicolous lichen diversity has historically relied on morphological and chemical characteristics, including thallus structure, reproductive structures, and secondary metabolites detected through thin-layer chromatography (TLC) [9]. However, recent studies have increasingly incorporated molecular phylogenetics to resolve taxonomic uncertainties and identify cryptic species. A global reassessment of lichenized fungi conducted by Robert Lücking and colleagues estimated that more than 28,000 lichen species may exist worldwide, many of which remain undescribed [2]. This estimate highlights the significant knowledge gap that still exists in lichen biodiversity research.

Tajikistan and China make up the majority of the Pamir Plateau. The eastern Pamir Plateau borders eastern Tajikistan, northeastern Afghanistan, and northern Pakistan. It is located in the southwest of China's Xinjiang Uygur Autonomous Region (Xinjiang). There is significant topographic variety because the average elevation is about 4000 m, with some peaks rising to 7000 m [10,11]. An exceptionally dry continental climate governs the eastern Pamir Plateau, which is located in the interior of the Eurasian continent. The extreme climate promotes the dominance of cushion and herbaceous plants that can withstand dryness and cold, particularly saxicolous lichens [12]. Biodiversity patterns may differ significantly from those of other mountain ecosystems due to the combined effects of difficult topography and harsh hydrothermal conditions, which restrict species dispersal and turnover processes [13,14].

Vascular plants are currently the primary focus of vegetation research in this area, and a prior study identified 963 species of seed plants (including cultivars) from 303 genera and 59 families [10,13]. The elevational distribution of plant species and phylogenetic diversity on the eastern Pamir Plateau were recently published by Wei et al. (2026) [13]. Nonetheless, incomplete surveys of the lichen flora have been conducted, and Abbas and Wu (1998) documented 37 lichen species [15]. However, the environmental factors influencing the diversity of lichens in the eastern Pamir Plateau are still poorly known, and the ecological response mechanisms have not yet been well examined. Furthermore, the eastern Pamir Plateau is currently experiencing biodiversity loss, a decline in the number of dominant species, and a growing danger of extinction as a result of global climate change and excessive human disturbance, all of which seriously impair ecosystem structure and function [10]. The preservation of biodiversity is a major component of

sustainable development and ecological monitoring in China, and it is currently one of the most pressing environmental protection issues globally. In the study of environmental succession and changes, lichens are an indispensable environmental sensor that reacts quickly to pollution and climatic change [16].

The aims of the present study were to characterize saxicolous lichen diversity and compare distribution characteristics at different elevations of the eastern Pamir Plateau, China.

2. Materials and Methods

2.1. Study Area

The majority of the eastern Pamir Mountains are found in Taxkorgan County, China (71.33°~77.02° E, 35.62°~38.67° N), which is also where the Chinese Tajik people were born and settled [17]. It has twisting valleys, towering glaciers, and an average elevation of 4000 m. Its delicate ecosystem is extremely sensitive to climate change, and its harsh desert environment is too cold to sustain forests [18]. Between 1990 and 2020, the Pamir Plateau experienced an average annual temperature of −5.79 °C and an average annual precipitation of 648 mm. In particular, the average annual temperature in the eastern region was −4.13 °C and the average annual precipitation was approximately 532 mm, whereas the average annual temperature in the western region was −6.38 °C and the average annual precipitation was approximately 689 mm [19]. This region is dominated by an open alpine vegetation landscape, and trees are present only in some valleys below 3400 m because of the local climate conditions [18,20].

2.2. Field Survey

The lichen survey was carried out by us at Taxkorgan Nature Reserve (74°27′21″~77°5′9″ E, 35°35′41″~37°30′21″ N), in the eastern Pamir Plateau, China, between July and August in 2025 using the stratified sampling method at an altitude of 3500 m to 4500 m (Figure 1).

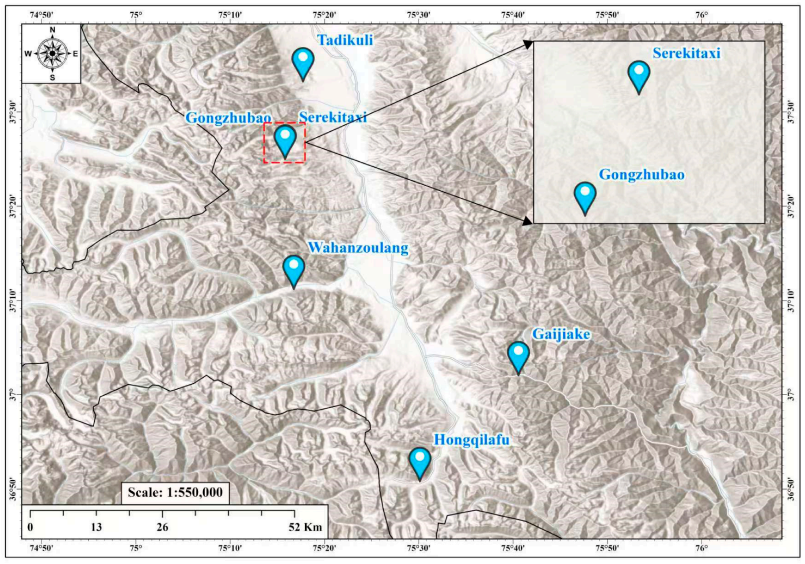


Figure 1. Sampling site distribution in China's eastern Pamir Plateau (map approval number: GS (2024) 0650). Notes: The red boxes in the figure represent the two transect belts, Gongzhubao and Serekitaxi.

Six transect belts including Gaijiake (GJ) transect, Gongwenbao (GWB) transect, Hongqilafu (HQ) transect, Serekitaxi (ST) transect, Tadikuli (TDK) transect, and Wahan

zoulang (WH) transect covering vertical vegetation zones across the study area were established (Figure 2).



Figure 2. Sampling transects: (**A**) Gaijiake, (**B**) Gongwenbao, (**C**) Hongqilafu, (**D**) Serekitaxi, (**E**) Tadikuli, (**F**) Wahan zoulang (photo by: Ainiwaer Tumier).

A wide environmental gradient typical of the Taxkorgan Nature Reserve was covered by the elevational transects. Mean annual temperatures (−0.6 °C), less wind exposure, more vegetation cover, and better developed soils around rock outcrops were the characteristics of lower-elevation locations (about 3500–3900 m a.s.l.). Mid-elevation transects (about 3901–4300 m a.s.l.) had more microhabitat variability, intermediate plant cover, higher moisture availability from seasonal snowmelt, and mean annual temperatures (−3.0 °C). The characteristics of higher-elevation sites (about 4301–4500 m a.s.l.) were mean annual temperatures (−7.2 °C), severe winds, frequent freeze–thaw cycles, intense sun radiation, shorter snow-free periods, sparse vegetation, and mostly exposed rock surfaces with little soil formation. To reduce variance linked to substrate type and assess the impact of elevation- related environmental changes on lichen diversity, sampling was limited throughout the study to saxicolous lichens found on natural rock substrates [21]. Hand lenses were used for observing lichens "in situ". Common lichen species were identified in the field using handheld magnifying glasses and color test methods. For those species that could not be identified in the field, samples were collected, using a knife or chisel/hammer, and placed in separate paper envelopes. We photographed the external morphology of lichen thalli with a digital camera in the field and recorded geographical coordinates and altitude of sampling sites with a Garmin GPS ETREX 329X(Garmin Corp, Olathe, KS, USA).

2.3. Lichen Species Identification

Lichens were identified in the Laboratory of the Arid Land Lichens Research Center of the College of Life Sciences and Technology, Xinjiang University, China, using relevant keys and references [15,22–24], and the nomenclature generally follows the Index Fungorum (https://speciesfungorum.org/, accessed on 23 April 2026). Lichens morphology was examined using a Nikon ECLIPSE E200 stereo-microscope (Nikon, Tokyo, Japan). Sections were hand-cut with a razor blade, mounted in water and iodine, and observed using a

Zeiss Axioskop two-plus light microscope (Zeiss, Oberkochen, Germany) to study thallus structure and hymenial characteristics. Photographs were taken with a Nikon Digital Camera D50 (Nikon Malaysia Sdn. Bhd, Shah Alam, Malaysia). Thin-layer chromatography (TLC) [9,25,26] was used to detect lichen secondary metabolites. Voucher specimens are deposited in the Lichen Herbarium of College of Life Science and Technology, Xinjiang University (XJU), China. Additionally, elevation and growth forms were recorded for each specimen.

Molecular and phylogenetic analyses were conducted on species that could not be identified through phenotypic analyses. First we blew off dust from the surface of lichen specimens with a rubber ear syringe. Forceps were used under a dissecting microscope to collect an appropriate amount of dried lichen thalli or apothecia and placed into a sterilized 2 mL EP centrifuge tube. Afterwards grinding steel beds were added to the tubes. The tubes were incubated at −20 °C for 1 h, and the samples were homogenized using a tissue grinder as previously described [27–29]. Total genomic DNA was extracted from the homogenized samples with the Sangon Ezup Column Fungal Genomic DNA Extraction Kit (Sangon Biotech Co., Ltd., Shanghai, China). The concentration of extracted DNA was quantified via a microplate spectrophotometer, and the purified DNA was preserved at −20 °C for subsequent experiments. ITS 1F and ITS 4 primers were used for PCR amplification in a 20 μL reaction system: 50–100 ng of genomic DNA, 10 μL of 2× Taq PCR Master Mix, 1 μL of each primer, and double-distilled water (ddH2O) to bring the total volume to 20 μL [27–29]. The following was the PCR thermal profile: 3 min of initial denaturation at 95 °C; 30 cycles of denaturation at 95 °C for 30 s, annealing at 55 °C for 30 s, and extension at 72 °C for 1 min; and a final extension at 72 °C for 10 min. Products that had been amplified were kept at 4 °C. Sangon Biotech Co., Ltd. (Shanghai, China) carried out bidirectional sequencing following PCR product verification using 1% agarose gel electrophoresis. DNA Star's SeqMan pro (11.1.0(59),419)was used to assemble bidirectional sequencing reads. To verify the identity of lichens, the resultant sequences were run through BLAST searches against the GenBank database. QUICK ClustalW or MUSCLE algorithms were used in MEGA X (10.2.6) to align sequences that were downloaded from GenBank and self-sequenced. Using Figtree v.1.4.4 software, maximum likelihood (ML) phylogenetic analysis was carried out using 1000 bootstrap replicates to create a phylogenetic tree [27–29].

2.4. Data Analysis

In this study, the study area was divided into five altitude zones according to each sampling transect, with a vertical interval of 200 m between zones, and a complete set of a presence/absence of lichen species data matrix through altitude was prepared. This is a macro-scale study where the definition of species richness is the total number of lichen species occurring in each altitude zone covering the entire elevational range of Taxkorgan Nature Reserve. We calculated the diversity of saxicolous lichens across different elevational bands based on their coverage values. Lichen coverage was calculated as the percentage of grids occupied by each lichen species relative to the total number of grids in the quadrat [21]. We calculated α-diversity (Shannon–Wiener diversity and Simpson's diversity), Pielou's evenness indices and β-diversity (Sørensen's similarity index) across five altitude zones based on amalgamated species data from six sampling transects [30]. Additionally, saxicolous lichen diversity and evenness indices at different altitude zones were calculated using PAST version 3.17 [31].

α and β-diversity indices were calculated using the following equations:

H—Shannon–Wiener diversity index [31].

$$H = -\sum_{i=1}^{S} P_i log_2 P_i$$

S—Species richness (number of species), P_i—proportion of species i.

$$P_i = \frac{n_i}{N}$$

n_i—abundance of species i, N—total abundance.
D—Simpson's diversity index [31].

$$D = 1 - \sum_{i=1}^{S} P_i^2$$

S—Species richness, P_i—proportion of species i.
J—Pielou's evenness index.

$$J = H/H_{\max} \qquad H_{\max} = \log_2 S$$

H = Shannon–Wiener diversity index, S = number of species.
Sørensen's similarity index [31].

$$Ss = 2a/(2a + b + c)$$

where Ss = Sørensen similarity index, a = the number of species common to both sites, b = the number of species present in one of the altitude zones, and c = the number of species present in the other altitude zone.

3. Results

3.1. Saxicolous Lichen Species Composition

The study revealed the 149 specimens of 69 saxicolous lichen species belonging to 27 genera and 12 families in the area (Appendix A). Among these lichens, 66 species (95.6% of total species) were crustose (including squamulose), 2 species (2.89% of total species) were foliose, and 1 species (1.44% of total species) was fruticose (Appendix A).

The species richness at the family level shows that there are two most diverse families such as Acarosporaceae and Megasporaceae containing 35 species (50.7% of total species). These are followed by the families Lecanoraceae and Teloschistaceae, which have 13 species (18.8% of total species). Their families Caliciaceae, Psoraceae and Tephromelataceae each contain one genus and one species (Table 1). In terms of generic diversity, the top three families are Teloschistaceae, Acarosporaceae and Megasporaceae, which collectively encompass 13 genera, accounting for 48.1% of the total genera. Among these families, Teloschistaceae contains five genera, representing 18.5% of all genera and being the family with the highest generic richness. Acarosporaceae and Megasporaceae each have four genera, accounting for 14.8% of the total genera respectively (Table 1).

Table 1. Statistical results of genera and species in the lichen family in the research area.

	Name of Family	Number of Genera Contained	Proportion of the Total Number of Genera (%)	Number of Species	Proportion of the Total Number of Species (%)
Dominant families (≥10 species)	Acarosporaceae	4	14.8	20	29.0
	Megasporaceae	4	14.8	16	23.2
Polytypic families (5 ≤ species < 10)	Lecanoraceae	3	11.1	7	10.1
	Teloschistaceae	5	18.5	5	7.2

Table 1. *Cont.*

	Name of Family	Number of Genera Contained	Proportion of the Total Number of Genera (%)	Number of Species	Proportion of the Total Number of Species (%)
Oligotypic families (2 ≤ species < 5)	Physciaceae	3	11.1	4	5.8
	Lecideaceae	1	3.7	4	5.8
	Rhizocarpaceae	1	3.7	4	5.8
	Candelariaceae	1	3.7	3	4.3
	Verrucariaceae	2	7.4	3	4.3
Monotypic families (species = 1)	Psoraceae	1	3.7	1	1.4
	Tephromelataceae	1	3.7	1	1.4
	Caliciaceae	1	3.7	1	1.4
Total		27		69	

3.2. The Saxicolous Lichens Species Diversity at Different Elevations

The α-diversity differed among altitudes, the highest diversity (H = 3.928, D = 0.978) occurring at 4101–4300 m, followed by that at 3901–4100 m (H = 3.385, D = 0.963) and the lowest diversity at 3500–3700 m (H = 2.831, D = 0.839) (Table 2). Transects with high species diversity exhibited low evenness indices. On the contrary, the maximum evenness indices were found in transects with low species diversity.

Table 2. The diversity index of saxicolous lichens at different altitude zones.

	Elevation (m)				
	3500–3700	**3701–3900**	**3901–4100**	**4101–4300**	**4301–4500**
Simpson index (H)	0.839	0.895	0.963	0.978	0.891
Shannon–Wiener index (D)	2.831	3.023	3.385	3.925	2.94
Evenness index (J)	1.351	1.23	1.027	1.126	1.13

Significant differences were observed in the β-diversity indices among the five altitude zones. In general, sampling sites with similar elevations exhibited higher species similarity and a lower species turnover rate. By contrast, transects with large elevation differences showed the lowest species similarity and a relatively high species turnover rate. The results of this study indicate that *Candelariella oleifera* H. Magn.; *Lecidea tessellata* Flörke; *Rusavskia elegans* (Link) S.Y. Kondr. & Kärnefelt occur at every elevational gradient and exhibit an extremely wide distribution range. In addition, there are obvious differences in dominant species across different elevational gradients, such as 3500–3700 m: *C. oleifera* H. Magn., *A. badiofusca* (Nyl.) Th. Fr., *C. aurella* (Hoffm.) Zahlbr., *Rinodina demissa* (Körb.) Arnold, *Tephromela atra* (Huds.) Hafellner; 3701–3900 m: *Acarospora rosulata* (Th. Fr.) H. Magn., *Calogaya biatorina* (A. Massal.) J. Steiner and *Pleosporidium gobiensis* (H. Magn.) Hafellner; 3901–4100 m: *Dermatocarpon vellereum* Zschacke, *Calogaya biatorina* (A. Massal.) J. Steiner, *Aspicilia oleifera* (H. Magn.) J.C.Wei, *Lecidella carpathica* Körb., *Rhizoplaca melanophthalma* (DC.) Leuckert & Poelt; 4101–4300 m: *Physconia grisea* (Lam.) Poelt, *Kuettlingeria erythrocarpa* (Pers.) I.V. Frolov; 4301–4500 m: *Aspicilia oleifera* (H. Magn.) J.C.Wei, *Acarospora invades* H. Magn., *Protoblastenia areolata* H. Magn., *A. hartliana* (Sthr.) Hue. The average Sørensen similarity between altitudes was 0.324, with a range of 0.253 to 0.561 (Table 3). The environment changes as the altitude increases from 3500 to 4500 m, leading to a notable turnover of lichen species and a subsequent decline in overall similarity.

Table 3. The Sørensen's similarities between different altitude zones.

Elevation (m)	3701–3900	3901–4100	4101–4300	4301–4500
3500–3700	0.269	0.367	0.253	0.256
3701–3900		0.313	0.258	0.315
3901–4100			0.561	0.351
4101–4300				0.302

3.3. The Relationship Between Species Richness and Elevation

Along the elevational gradient, the species diversity of saxicolous lichens in the reserve showed a unimodal trend. Within the altitude zone of 3500 m to 4300 m, lichen species richness increased with rising elevation, and subsequently declined above 4301 m (Figure 3). A total of 45 species were recorded at 4101–4300 m, representing the maximum value across all altitude zones. By contrast, the minimum species richness values of 14 and 15 were observed at low (3500–3700 m) and high elevations (4301–4500 m), respectively.

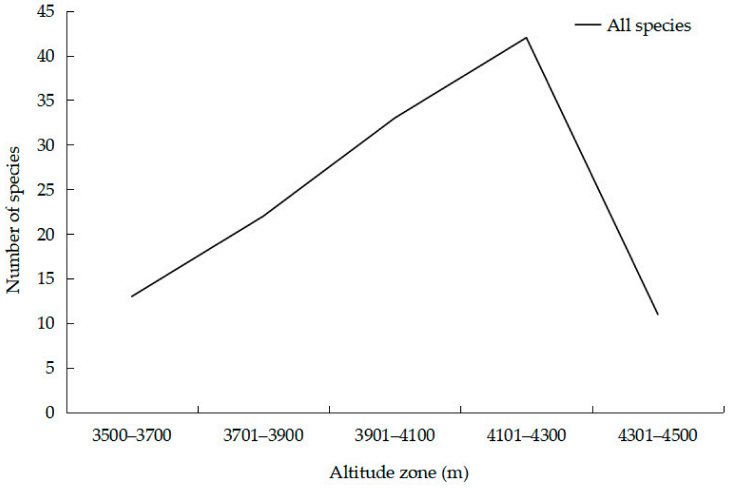


Figure 3. Elevation and the quantity of lichen species.

Acarosporaceae and Megasporaceae, two of the most prevalent families in the research region, showed a bimodal pattern over the elevational gradient (Figure 4a). The family Lecanoraceae saw a rise in species richness starting at 3700 m, peaking between 4100 and 4300 m, and then declining at higher elevations. Within Teloschistaceae, the species richness of lichens displayed a non-significant bimodal distribution (Figure 4b).

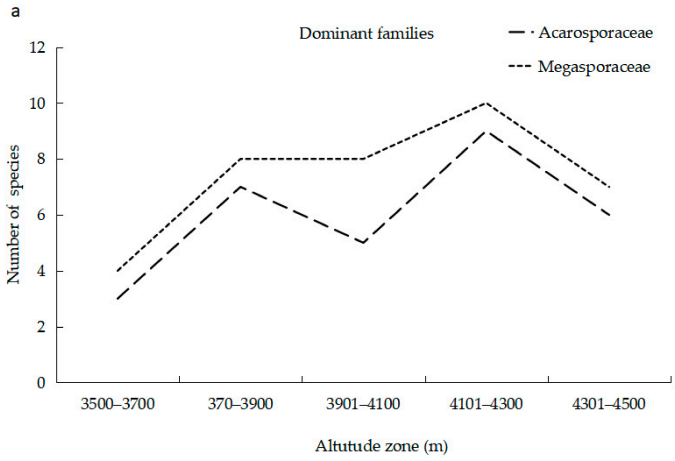


Figure 4. *Cont.*

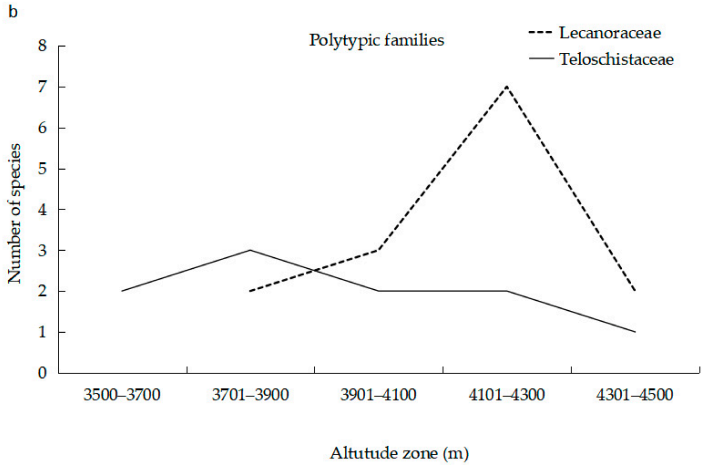


Figure 4. Lichen families have an elevational richness pattern. Notes: (**a**) Species number of dominant families along elevational belts; (**b**) Species number of polytypic families along elevational belts.

3.4. The Connection Between Rock Types and Species Richness

Siliceous rock, the most common rock type in the area, supported 41 species, while 16 species grew on calcareous rock and 12 species were distributed on both siliceous and calcareous rocks (Appendix A: Table A1). Regarding abundant families, 20 *Acarospora* species, 14 were collected on siliceous rock, 2 on calcareous rock and 4 on both siliceous and calcareous rocks. Among the 16 Megasporaceae species, 8 species grew on siliceous rock, 5 on calcareous rock and 3 on both siliceous and calcareous rocks (Appendix A: Table A1).

4. Discussion

The current study makes a contribution to our knowledge of the variety of saxicolous lichens in alpine habitats along an elevational gradient. Most lichen species found in this study were pioneers in extreme environments where vascular plant cover is scarce, showing a saxicolous lichen distribution pattern in Taxkorgan Nature Reserve similar to Mexican drylands [32]. There was a comparatively high diversity of rock-dwelling lichens in the study region, with 69 species found in 27 genera and 12 families. The ecological fit of alpine habitats for lichens, where severe weather, little competition from vascular plants, and a variety of microhabitats encourage lichen colonization and persistence, is reflected in this great diversity [33]. The current study's overwhelming dominance of crustose lichens (95.6%) is in line with findings from numerous alpine and arctic habitats, where crustose forms are the most effective life strategy on exposed rock substrates. Crustose lichens can colonize bare rock surfaces where other growth forms cannot easily survive because of their strong substrate adhesion and excellent endurance to desiccation, temperature fluctuations, and intense solar radiation [34]. Conversely, foliose and fruticose lichens typically grow in more stable or humid microhabitats and are more susceptible to environmental stress [35,36]. Acarosporaceae and Megasporaceae accounted for over half of all known species, making them the leading groups at the family level, followed by the Lecanoraceae and Teloschistaceae. Because many of their species are well suited to harsh ecological circumstances, these families are widely acknowledged as essential elements of saxicolous lichen communities in desert and alpine habitats. Particularly well-known for their ability to withstand extreme UV light and temperature changes, species of the genera *Acarospora* and *Aspicilia* are able to thrive in exposed mountain environments [25,37]. The most species-rich genus in the current study was *Acarospora*, which was followed by *Aspicilia*. Due to their ecological adaptability and wide substrate tolerance, these taxa often dominate saxicolous lichen communities in other mountainous regions, where similar patterns have been documented [38]. In this study, we also identified three families,

namely Caliciaceae, Psoraceae and Tephromelataceae, which have only a single species. Among them, species of *Dimelaena* and *Tephromela* were found only at higher elevations in the current survey, and they were mostly connected to exposed siliceous rock substrates. However, rather than representing their general ecological or biogeographical ranges, these observations should be understood as indicating their local distribution within the eastern Pamir Plateau. According to earlier research, *Dimelaena oreina* is found across a much wider elevational gradient, including lower elevations where appropriate siliceous substrates are present [15,39,40]. Therefore, judgments about the tight elevational specialization or endemicity of these taxa are not supported by our data. Rather, local habitat availability, substrate properties, and regional environmental variables are probably reflected in the observed dispersion patterns. Comparative research covering a greater geographic and environmental range would be necessary to draw broader conclusions on the ecology and arealogical patterns of these taxa.

The findings showed that species diversity varied significantly over the elevational gradient. Lower diversity values were found at both lower and higher elevations, with the highest α-diversity occurring between 4101 and 4300 m. In mountain ecosystems, this pattern is consistent with the mid-elevation peak or unimodal diversity pattern. This pattern could be explained by a number of ecological mechanisms. Mid-elevations frequently offer ideal climatic conditions, such as an optimal temperature, enough moisture availability, and a variety of microhabitats that support the coexistence of several species [41–43]. Higher elevations, on the other hand, are characterized by harsher climatic conditions like lower temperatures, stronger winds, and shorter growth seasons that limit species establishment, while lower elevations may face greater competition with vascular plants and increased anthropogenic disturbances, such as grazing [44].

It's interesting to note that evenness values were lower at sites with higher species richness, indicating that a small number of dominant species may have a significant impact on community structure. In alpine lichen communities, analogous trends have also been observed across habitats where stress-resistant taxa prevail under distinct environmental conditions [33]. Significant species turnover throughout the elevational gradient is shown by the comparatively low Sørensen similarity values (0.253–0.561) found among elevation zones.

Because climatic conditions change with elevation, affecting species distribution and community composition, species turnover is a prevalent feature of mountain ecosystems [45]. While greater elevation differences result in more ecological filtration and community divergence, higher similarity across neighboring elevations indicates that environmental parameters stay generally comparable over short elevational distances. In alpine regions of Europe and Asia, where altitude-related environmental gradients significantly impact species replacement patterns, this phenomenon has also been reported in lichen research [33].

The mid-domain hypothesis and environmental gradient theory, which contend that biodiversity frequently peaks at intermediate elevations as a result of overlapping ecological niches and advantageous environmental conditions, are further supported by the unimodal relationship between species richness and elevation found in this study [36]. More environmental stress is probably the cause of the species richness drop over 4300 m. Reduced oxygen levels, strong sun radiation, low temperatures, and limited nutrient availability are characteristics of high-altitude ecosystems that can restrict lichen development and reproduction [35,46]. It's interesting to note that along the elevational gradient, the main groups Megasporaceae and Acarosporaceae showed bimodal distribution patterns. The number of species of Lecanoraceae, one of the most abundant families, exhibited a unimodal pattern and Teloschistaceae showed a non-significant bimodal pattern. Mi-

croclimatic variation in the mountain terrain, substrate availability, and species-specific ecological preferences may all be reflected in these patterns [47].

The mineral composition, surface chemistry, pH, porosity, and water-holding capacity of the substrate have a significant impact on the formation of thallus's and the long-term durability of saxicolous lichen communities [2,48–53]. There was a strong substrate-associated pattern in species richness in our study, with siliceous rocks supporting more species (53 species) than calcareous substrates (28 species). Similar substrate preferences have been documented from other alpine and arid mountain ecosystems, where siliceous substrates, as opposed to carbonate rocks, often offer more favorable microhabitats for diverse crustose lichen communities due to their greater surface stability, heterogeneous micro-topography, and fewer chemical constraints [27]. However, the makeup of the local lichen community is probably shaped by the interaction of substrate type with other environmental parameters, such as elevation, microclimate, and moisture availability [54,55]. Many saxicolous lichens have strong substrate preferences, which are further highlighted by the dominance of *Acarospora* species on siliceous rocks. According to earlier research, many Acarosporaceae species prefer siliceous substrates, while some taxa can also be found on calcareous rocks [56]. Saxicolous lichens were more commonly found on siliceous than calcareous rock surfaces in the transects that were surveyed. These findings should be seen as field-based distribution patterns rather than proof of substrate-driven mechanisms because rock physicochemical characteristics (such as pH, mineral composition, and metal availability) were not assessed in this investigation. To ascertain how substrate chemistry shapes lichen diversity throughout the eastern Pamir Plateau, more research involving in-depth geochemical analysis is required.

Overall, the results demonstrate that elevation and substrate type are two significant environmental factors affecting the distribution and richness of saxicolous lichens in alpine habitats. Because saxicolous lichens are extremely sensitive bio-indicators of environmental change, changes in their distribution along elevational gradients may offer early warning signs of ecological reactions to climate change [57]. However, substrate properties also play a significant role in mediating these elevational patterns. Due to differences in mineral composition, surface texture, pH, water retention capacity and microhabitat characteristics, lichen communities on siliceous and calcareous rocks differ markedly in community composition and species richness [58–61]. The establishment, growth, and persistence of lichens are influenced by these substrate-related characteristics, which also interact with meteorological variables along the elevational gradient to form the composition of communities. Thus, in the eastern Pamir Plateau, elevation and substrate type should be regarded as important biological drivers of saxicolous lichen diversity.

Our knowledge of the mechanisms governing lichen diversity in high-mountain habitats would be improved by more research using microclimatic data, substrate chemistry, and long-term monitoring.

5. Conclusions

The variety and growth form of saxicolous lichens along an elevational gradient in an alpine ecosystem are highlighted in this study. High lichen diversity was found in the research region, with a total of 69 species from 27 genera and 12 families identified. The predominance of crustose growth forms shows how well they have adapted to the severe alpine climate, which includes intense solar radiation, low temperatures, and low precipitation. The saxicolous lichen communities were significantly shaped by families Acarosporaceae and Megasporaceae. Because of their ecological adaptability and resistance to harsh environments, the genera *Acarospora* and *Aspicilia* were especially prevalent.

Elevation zones differed greatly in species diversity, with mid-elevations (4101–4300 m) showing the greatest diversity.

According to this unimodal pattern, intermediate elevations offer a variety of microhabitats and ideal environmental conditions for lichen colonization. Increased environmental stress and scarce resources are probably the causes of lower species richness at higher elevations; in low-elevation zones, conditions are primarily associated with anthropogenic disturbances (e.g., grazing), as well as limited rock-type variation and low habitat heterogeneity. Significant species turnover over the elevational gradient is indicated by the observed beta diversity, highlighting the impact of environmental filtering on community composition. The kind of substrate had a major impact on lichen distribution patterns as well. Siliceous rocks supported the most species due to their favorable surface characteristics and microhabitat conditions. On the other hand, fewer species were discovered on calcareous substrates, most likely due to their chemical composition and smoother surfaces. These findings demonstrate that elevation and rock type are two significant ecological factors influencing the diversity of saxicolous lichens.

The findings offer important baseline data for comprehending the ecology of lichens in alpine settings. The recorded diversity patterns may aid in tracking ecological reactions to climate change because lichens are sensitive markers of environmental change. Improving our knowledge of lichen biodiversity in high-mountain habitats requires ongoing study that incorporates microclimatic factors, substrate chemistry, and long-term monitoring.

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Abbreviations

The following abbreviations are used in this manuscript:

TLC	Thin-Layer Chromatography
XJU	Xinjiang University
GJ	Gaijiake Transect
GWB	Gongwenbao Transect
HQ	Hongqilafu Transect
ST	Serekitaxi Transect
TDK	Tadikuli Transect
WH	Wahan Zoulang Transect

Appendix A

Table A1. Elevational ranges of saxicolous lichens in Taxkorgan Nature Reserve, their families and growth forms.

S.No.	Name of Lichen Species	Family	Photobiont	Growth Form	Rock Type	Elevational Range (m)	
1	*Acarospora aeginaca* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	3669	4168
2	*A. badiofusca* (Nyl.) Th. Fr.	Acarosporaceae	Gr	Cr	Siliceous	3669	4347
3	*A. bohlinii* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4001	4441
4	*A.boulderensis* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4028	
5	*A. brevilobata* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	3704	
6	*A. bullata* Anzi	Acarosporaceae	Gr	Cr	Calcareous	4001	
7	*A. glypholecioides* H. Magn.	Acarosporaceae	Gr	Cr	Calcareous	4052	4332
8	*A. heppii* Nägeli ex Körb.	Acarosporaceae	Gr	Cr	Siliceous	4001	
9	*A. interrupta* (Ehrenb.) Vain.	Acarosporaceae	Gr	Cr	Calcareous, Siliceous	3704	3900
10	*A. irregularis* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	3704	
11	*A. invades* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4001	4316
12	*A. molybdina* (Wahlenb.) Trevis.	Acarosporaceae	Gr	Cr	Siliceous	3900	
13	*A. pulvinata* H. Magn.	Acarosporaceae	Gr	Cr	Calcareous, Siliceous	4242	4291
14	*A. rosulata* (Th. Fr.) H. Magn.	Acarosporaceae	Gr	Cr	Calcareous, Siliceous	3704	4137
15	*A. superans* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4052	4347
16	*A. verruculosa* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4347	
17	*Anaptychia ulothricoides* (Vain.) Vain.	Physciaceae	Gr	Sh	Calcareous	3745	
18	*Aspicilia asiatica* (H. Magn.) Oxn.	Megasporaceae	Gr	Cr	Calcareous	4137	4280
19	*A. bohlinii* (H. Magn.) J.C.Wei	Megasporaceae	Gr	Cr	Calcareous	3669	4441
20	*A. cinerea* (L.) Körb.	Megasporaceae	Gr	Cr	Siliceous	4232	4280
21	*A. cupulifera* (H. Magn.) Oxner	Megasporaceae	Gr	Cr	Siliceous	4232	4280
22	*A. hartliana* (Sthr.) Hue	Megasporaceae	Gr	Cr	Calcareous	4316	4347
23	*A. oleifera* (H. Magn.) J.C.Wei	Megasporaceae	Gr	Cr	Calcareous, Siliceous	3900	4454
24	*A. subalbicans* (H. Magn.) J.C.Wei	Megasporaceae	Gr	Cr	Calcareous	4052	
25	*A. sublaqueata* (H. Magn.) J.C. Wei	Megasporaceae	Gr	Cr	Siliceous	4052	
26	*A. verrucigera* Hue	Megasporaceae	Gr	Cr	Siliceous	4454	
27	*Calogaya biatorina* (A. Massal.) J. Steiner	Teloschistaceae	Gr	Cr	Calcareous	3900	4332
28	*Caloplaca anularis* Clauzade & Poelt	Teloschistaceae	Gr	Cr	Calcareous	3704	

Table A1. *Cont.*

S.No.	Name of Lichen Species	Family	Photobiont	Growth Form	Rock Type	Elevational Range (m)	
29	*Candelariella aurella* (Hoffm.) Zahlbr.	Candelariaceae	Gr	Cr	Calcareous, Siliceous	3669	
30	*C. blastidiata* Yakovch.	Candelariaceae	Gr	Cr	Calcareous	4347	
31	*C. oleifera* H. Magn.	Candelariaceae	Gr	Cr	Calcareous, Siliceous	3517	4454
32	*Circinaria contorta* (Hoffm.) A. Nordin, Savić & Tibell	Megasporaceae	Gr	Cr	Calcareous	4332	4347
33	*C. maculata* (H. Magn.) Q. Ren	Megasporaceae	Gr	Cr	Calcareous, Siliceous	4332	4347
34	*C. ochraceoalba* (H. Magn.) Q. Ren	Megasporaceae	Gr	Cr	Calcareous, Siliceous	3517	4454
35	*C. tortuosa* (H. Magn.) Q. Ren	Megasporaceae	Gr	Cr	Siliceous	4001	
36	*C. transbaicalica* (Oxner) Q. Ren	Megasporaceae	Gr	Cr	Siliceous	3704	4347
37	*Dermatocarpon vellereum* Zschacke	Verrucariaceae	Gr	Fl	Calcareous	4012	
38	*Dimelaena oreina* (Ach.) Norman	Caliciaceae	Gr	Cr	Siliceous	3704	4332
39	*Glypholecia scabra* (Pers.) Müll. Arg.	Acarosporaceae	Gr	Cr	Siliceous	4001	4441
40	*Kuettlingeria erythrocarpa* (Pers.) I.V. Frolov	Teloschistaceae	Gr	Cr	Calcareous	4012	4245
41	*Lecanora argopholis* (Ach.) Ach.	Lecanoraceae	Gr	Cr	Siliceous	4347	
42	*L. marginata* (Schaer.) Hertel & Rambold	Lecanoraceae	Gr	Cr	Siliceous	4298	
43	*L. oreinoides* (Körb.) Hertel & Rambold	Lecanoraceae	Gr	Cr	Siliceous	4330	
44	*L. pachysoma* B.D. Ryan & Poelt	Lecanoraceae	Gr	Cr	Siliceous	4347	
45	*L. polytropa* (Hoffm.) Rabenh.	Lecanoraceae	Gr	Cr	Siliceous	4235	4347
46	*Lecidea atrobrunnea* (DC.) Schaer.	Lecideaceae	Gr	Cr	Siliceous	4347	
47	*L. auriculata* Th. Fr.	Lecideaceae	Gr	Cr	Siliceous	4001	4454
48	*L. suberratica* J. Lowe	Lecideaceae	Gr	Cr	Siliceous	4347	
49	*L. tessellata* Flörke	Lecideaceae	Gr	Cr	Siliceous	3669	4441
50	*Lecidella carpathica* Körb.	Lecanoraceae	Gr	Cr	Calcareous, Siliceous	4001	4347
51	*Lobothallia alphoplaca* (Wahlenb.) Hafellner	Megasporaceae	Gr	Cr	Siliceous	4052	4287
52	*Myriolecis fugiens* (Nyl.) Sliwa	Lecanoraceae	Gr	Cr	Siliceous	3704	
53	*Physconia grisea* (Lam.) Poelt	Physciaceae	Gr	Fl	Calcareous	4232	4287
54	*Pleosporidium gobiensis* (H. Magn.) Hafellner	Acarosporaceae	Gr	Cr	Calcareous, Siliceous	3704	
55	*Protoblastenia areolata* H. Magn.	Psoraceae	Gr	Cr	Calcareous, Siliceous	4332	4347
56	*Rhizocarpon disporum* (Nägeli ex Hepp) Müll. Arg.	Rhizocarpaceae	Gr	Cr	Siliceous	3704	
57	*R. eupetraeoides* (Nyl.) Blomb. & Forssell	Rhizocarpaceae	Gr	Cr	Siliceous	4252	4290
58	*R. geographicum* (L.) DC.	Rhizocarpaceae	Gr	Cr	Siliceous	3704	4332

Table A1. *Cont.*

S.No.	Name of Lichen Species	Family	Photobiont	Growth Form	Rock Type	Elevational Range (m)	
59	*R. macrosporum* Räsänen	Rhizocarpaceae	Gr	Cr	Siliceous	4316	
60	*Rhizoplaca melanophthalma* (DC.) Leuckert & Poelt	Lecanoraceae	Gr	Sq	Siliceous	3900	4332
61	*Rinodina demissa* (Körb.) Arnold	Physciaceae	Gr	Cr	Calcareous	3669	4441
62	*R. straussii* J. Steiner	Physciaceae	Gr	Cr	Calcareous	3669	
63	*Rusavskia elegans* (Link) S.Y. Kondr. & Kärnefelt	Teloschistaceae	Gr	Cr	Calcareous, Siliceous	3669	4454
64	*Sarcogyne gyrocarpa* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	4454	
65	*S. soliteria* H. Magn.	Acarosporaceae	Gr	Cr	Siliceous	3669	4454
66	*Staurothele clopima* (Wahlenb. ex Ach.) Th. Fr.	Verrucariaceae	Gr	Cr	Siliceous	4347	
67	*S. rufa* (A. Massal.) Lettau	Verrucariaceae	Gr	Cr	Siliceous	3704	4347
68	*Tephromela atra* (Huds.) Hafellner	Tephromelataceae	Gr	Cr	Siliceous	3517	3704
69	*Xanthoria sorediata* (Vain.) Poelt	Teloschistaceae	Gr	Cr	Siliceous	3517	4168

Notes: Photobiont: *Gr*: green algae; Growth form: *Cr*: crustose; *Fl*: foliose; *Sq*: squamulose; *Sh*: Shrubby.

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