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Diversity and Distribution Patterns of Lichens in Different Ecological Conditions in the Garhwal Himalaya, Uttarakhand

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ABSTRACT

Present study investigates the distribution and diversity of lichens across different elevational zones in the Madhyamaheshwar Valley, Garhwal Himalaya. A total of 77 lichen species from 22 families and 52 genera were recorded across three altitudes: lower (1600 - 2300 m a.s.l), middle (2600 - 3100 m a.s.l), and higher (3200 - 3600 m a.s.l). Lichen diversity increased with elevation, with 48 species recorded at higher elevation sites, Madhyamaheshwar and Budha Madhyamaheshwar; 17 at middle elevation sites, Maikhamba-Chatti and Koonchatti; and 12 at lower elevation sites, Goundar Village, Lower Bantoli, Upper Bantoli, Khadarakhal, and Nanuchatti. Temperature and humidity were identified as significant factors influencing lichen diversity, with cooler conditions at higher elevations supporting more diverse lichen communities. Slope and cardinal

directions aspect also influenced species distribution, with gentler slopes and southern cardinal direction aspects supporting higher diversity. Lichens demonstrated a preference for tree bark as a substrate, with certain species exhibiting greater host specificity. These findings underscore the crucial role of environmental factors in shaping the distribution of lichen communities across the elevational gradients of the valley.

1. INTRODUCTION

Lichens, as complex symbiotic systems, are globally distributed and serve as reliable indicators of ecological conditions, particularly in relation to atmospheric and climatic variability. Recent scientific investigations have deepened insight into their physiological and distributional responses to changing climate patterns, reinforcing their role as critical bioindicators in ecological monitoring and environmental assessment (Stanton et al. 2023).Elevation gradients are regarded as one of the most significant patterns in biogeography (Lomolino 2001). The atmospheric conditions on a mountain change with altitude, resulting in variability in both the number of different species present and the specific types of species found (Körner 2007). Lichens, comparable to various other creatures, have been demonstrated to react to elevation-dependent parameters, which is well recognized (Vetaas et al. 2019). Consequently, altitude is a key factor that affects the abundance, composition, and variety of lichen ecosystems (Baniya et al. 2010; Vittoz et al. 2010; Bässler et al. 2016; Rodríguez et al. 2017; Cleavitt et al. 2019). Lichens are adaptable organisms capable of surviving in a variety of environments, with their population patterns being shaped by factors like moisture, temperature, air quality, and nutrient availability (Geiser et al. 2021). Their spatial distribution is strongly influenced by climatic factors, especially temperature and humidity. Additionally, studies show that the abundance of species varies significantly across different altitudinal zones (Abas & Din 2021).The distribution of lichen communities are influenced by key environmental elements such as sunlight, humidity, temperature, and slope (Shrestha et al. 2012). Lichen communities are sensitive to variations in abiotic conditions, including temperature, pollution levels, rainfall, and light availability. Steeper slopes tend to support fewer lichen species, suggesting that terrain significantly affects their distribution. Additionally, microhabitat features like slope and light exposure contribute to shaping lichen diversity, influencing both their richness and abundance across different environments (Cung et al. 2021). Latitude-dependent factors like aspect (primarily north-south) and slope are also crucial, as they impact the amount of solar radiation received. Alongside altitude, these factors determine incident solar radiation (insolation) and the extent of evapotranspiration (Pentecost 1979; Kidron & Termina

2010; Rodríguez et al. 2017). Therefore, in the southern hemisphere, areas facing south have a cooler temperature and higher levels of humidity as opposed to areas that face north (Körner 1995, 2007). Lichen communities are strongly influenced by elevation, with species richness and composition exhibiting variation along altitudinal gradients (Pinokiyo et al. 2008). Numerous studies have highlighted the exceptional diversity of lichens found at high-altitude locations across Europe, Asia, and India (Baniya et al. 2010; Vittoz et al. 2010; Rashmi & Rajkumar 2019; Abas & Din 2021).

In our previous work (Prabhakar et al., 2024), we provided valuable insights into the lichen flora of the Madhyamaheshwar Valley, documenting over 60 lichen species, representing 33 genera and 21 families, across 8 sites along the trekking route from Goundar village to Budha Madhyamaheshwar. However, the scope of that study was confined to a limited number of key locations along the trekking path. The present study significantly broadens this scope by investigating previously unexplored regions within the valley. In contrast to our earlier research, this study incorporates additional ecological factors, including aspect, temperature, humidity, slope, and altitudinal gradients, thereby offering a more comprehensive understanding of species distribution. Moreover, several additional species were identified that were not recorded in our previous work. These novel findings provide enhanced insights into the ecological and biodiversity patterns of the region, thereby advancing our understanding of lichen distribution across this ecologically sensitive Himalayan gradient.

2. MATERIALS AND METHODS

2.1. Site description

The study area Madhyamaheshwar Valley, located in the Rudraprayag District of the Garhwal Himalayan region in Uttarakhand, is a part of the Kedarnath Wildlife Sanctuary. Spans approximately 262 km^2. Lichens were collected from altitudinal ranges of 1600 to 3600 m a.s.l, covering an area of about 13.92 km^2. This area lies between latitudes 30°36'22" N and 30°37'59" N, and longitudes 79°11'12" E and 79°12'46" E (Fig. 1).

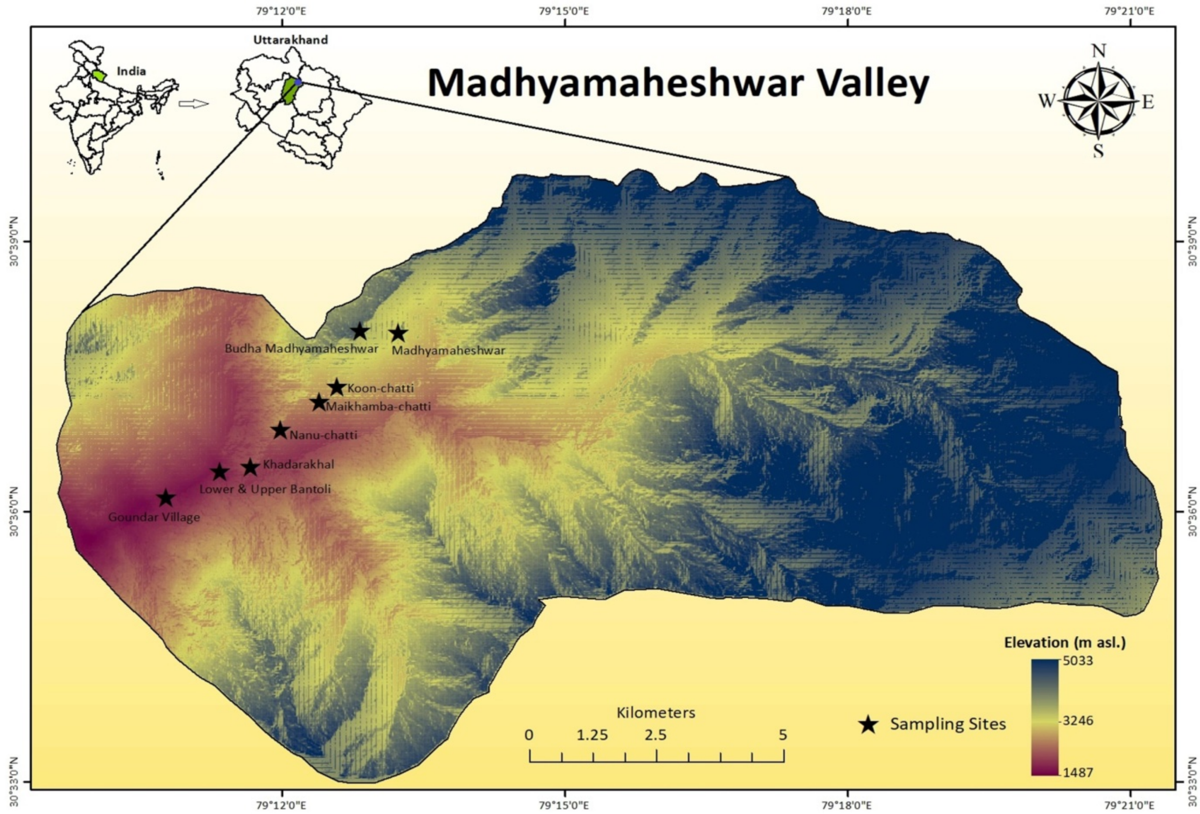

Fig. 1: Geographical map of the study area.

2.2. Lichen sampling and collection of environmental variables

The lichen samples were collected during May 2024 from Goundar Village, Lower Bantoli, Upper Bantoli, Khadarakhal, Nanuchatti, Maikhamba-Chatti, Koonchatti, Madhyamaheshwar, and Budha Madhyamaheshwar area of Madhyamaheshwar valley. These sites were categorized into three elevational zones: lower (1600 - 2300 m a.s.l), middle (2600 - 3100 m a.s.l) and higher (3200 - 3600 m a.s.l). Lichen samples were collected from various substrates including tree barks, twigs, mosses, rocks and soil. The data on elevation, slope, cardinal direction aspect, temperature and humidity are recorded at the collection sites to ensure a thorough analysis of the environmental variables influencing lichen distribution. The study areas display a distinct elevation gradient, with Goundar villageat1600 m a.s.l.,, Lower and Upper Bantoliranging from1700 - 1800 m a.s.l., Khadarakhalat2100 m a.s.l., Nanu-Chattiat2300 m a.s.l., Maikhamba-Chattiat2600 m a.s.l., Koon-Chattiat2900 m a.s.l., Madhyamaheshwarat3200 m a.s.l., and the highestpoint,Budha Madhyamaheshwar, at3400 m a.s.l.,This gradient reflects a progressive increase in elevation across the sites.

2.3. Identification of lichens

The lichen samples were identified based on their morphological, anatomical and chemical characteristics, following the methods described by Nayaka (2014) and following relevant literature (Awasthi 1991, 2007; Lücking et al. 2009; Singh & Sinha 2010; Singh &Arya 2019).The samples were confirmed and authenticated at the Lichenology Laboratory CSIR-National Botanical Research Institute in Lucknow. The identified lichen samples were deposited at the herbarium of H.N.B. Garhwal University (GUH) as well as at the herbarium of the NBRI, Lucknow (LWG). The statistical analysis was carried out using software/tools to accurately measure environmental variables: altitude was recorded with a barometric altimeter, slope was measured using a digital clinometer, aspect was determined with a compass, and humidity and temperature were quantified using a digital hygrometer. For spatial analysis and visualization, QGIS was utilized to process, analyze, and map the collected data, ensuring a comprehensive and scientifically rigorous assessment of the environmental parameters.

3. RESULTS

A total of 77 lichen species belonging to 22 families and 52 genera were documented. These included 28 crustose, 28 foliose, and 21 fruticose lichens (Table 1, Fig. 2 and 3).

Table 1: Distribution of lichen taxa across different elevations, slopes, aspects, temperature ranges and humidity levels in the Madhyamaheshwar Valley.

Lower elevation (1600 - 2300 m a.s.l.)					
Sites - Goundar village, Lower Bantoli, Upper Bantoli, Khadarakhal and Nanu-chatti					
Family	**Lichen taxa**	**Slope**	**Aspect**	**Temperature (Min-max)**	**Humidity (Min-max)**
Teloschistaceae	*Caloplaca flavorubescens* (Huds.) J.R. Laundon	38.6°	NE	11.3°C to 32.1°C	34% - 59%
Chrysotrichaceae	*Chrysothrix candelaris* (L.) J.R. Laundon	63.7°	NE		
Cladoniaceae	*Cladonia fruticulosa* Kremp.	24.7°	SE		
	Cladonia subulata (L). F.H. Wigg.	11.1°	SE		
Verrucariaceae	*Dermatocarpon miniatum* (L) W. Mann	46.0°	SE		
Parmeliaceae	*Flavoparmelia caperata* (L.) Hale	48.2°	E		
Physciaceae	*Heterodermia diademata* (Taylor) D.D. Awasthi	20.8°	SE		

Collemataceae	*Leptogium delavayi* Hue	44.2°	E		
Lobariaceae	*Lobaria retigera* (Bory) Trevis.	40.2°	SE		
Parmeliaceae	*Parmotrema reticulatum* (Taylor) M. Choisy	57.0°	S		
	Parmotrema tinctorum (Despr. ex Nyl.) Hale	40.0°	W		
Pertusariaceae	*Pertusaria velata* (Turner) Nyl.	22.4°	SW		
Middle elevation (2600 - 3100 m a.s.l.)					
Sites - Maikhamba-chatti and Koon-chatti					
Cladoniaceae	*Cladonia coccifera* (L.) Willd.	22.8°	NW	11.3°C to 24.8°C	54% - 77%
	Cladonia corniculata Ahti and Kashiw	22.7°	NW		
	Cladonia ramulosa (With.) J. R. Laundon	29.6°	N		
Graphidaceae	*Graphis* sp.2	14.3°	SE		
Parmeliaceae	*Hypotrachyna cirrhata* (Fr.) Divakar et al.	52.5°	SW		
Collemataceae	*Leptogium askotense* D.D. Awasthi	51.4°	N		
	Leptogium burnetiae C.W. Dodge.	41.2°	S		
	Leptogium trichophorum Müll. Arg.	50.6°	S		
Lobariaceae	*Lobaria kurokawae* Yoshim	40.3°	S		
Parmeliaceae	*Parmotrema nilgherrensis* (Nyl.) Hale	21.0°	E		
Peltigeraceae	*Peltigera polydactylon* (Neck.) Hoffm.	28.6°	S		
Physciaceae	*Polyblastidium microphyllum* (Kurok) Kalb.	45.1°	SE		
Ramalinaceae	*Ramalina sinensis* Jatta	25.6°	SW		
Parmeliaceae	*Sulcaria sulcata* (Lév) Bystrek ex Brodo and D. Hawksw	27.7°	W		
	Usnea subfloridana Stirt.	47.5°	S		
	Usnea orientalis Motyka	62.1°	S		
Umbilicariaceae	*Umbilicaria vellea* (L.) Ach.	46.3°	S		
Higher elevation (3200 - 3600 m a.s.l.)					
Sites - Madhyamaheshwar and Budha Madhyamaheshwar					
Megasporaceae	*Aspicilia cinerea* (L.) Körb	32.9°	N	7.2°C to 20.6°C	29% - 66%
	Aspicilia dwaliensis Räsänen	36.9°	NE		
Parmeliaceae	*Bryoria himalayana* (Motyka) Brodo. & D. Hawksw.	52.9°	N		
Caliciaceae	*Buellia himalayensis* (S.R. Singh and D.D. Awasthi) A. Nordin	27.4°	NE		

	Calicium adspersum subsp. *Himalayense* G.Pant & D.D. Awasthi	23.4°	W		
Cladoniaceae	*Cladonia fimbriata* (L.) Fr.	30.2°	W		
	Cladonia laii S. Stenroos	28.5°	N		
	Cladonia pocillum (Ach.) Grognot	44.2°	NW		
	Cladonia pyxidata (L.) Hoffm	39.7°	W		
	Cladonia squamosa Hoffm.	10.5°	E		
Coccocarpiaceae	*Coccocarpia erythroxyli* (Spreng.) Swinscow & Krog	27.5°	E		
Verrucariaceae	*Dermatocarpon vellereum* Zsaschke	35.9°	S		
Parmeliaceae	*Dolichousnea longissima* (Ach.) Articus	36.6°	S		
Graphidaceae	*Graphis cfr. duplicata* Ach.	67.8°	NE		
	Graphis furcata Fée	21.2°	N		
	Graphis scripta (L.) Ach.	23.1°	S		
	Graphis sp.1	25.4°	N		
	Graphis sp.3	18.6°	N		
Physciaceae	*Heterodermia japonica* (Sato) Swinsc. & Krog.	42.6°	NW		
Parmeliaceae	*Hypotrachyna nepalensis* (Taylor) Divakar et al.	38.6°	S		
Lecanoraceae	*Lecanora caesiorubella* Ach.	42.3°	NW		
	Lecanora fimbriatula Stirt.	14.2°	S		
	Lecanora interjecta Müll. Arg.	13.7°	W		
	Lecidella carpathica Körb.	15.1°	W		
	Lecidella elaeochroma (Ach.) M. Choisy	24.8°	NW		
	Lecidella euphorea (Flörke) Kremp	25.0°	W		
Pertusariaceae	*Lepra leucosorodes* (Nyl.) I. Schmitt, B.G. Hodk and Lumbsch	16.8°	E		
Teloschistaceae	*Loplaca pindarensis* (Räsänen) Poelt and Hinter.	60.2°	N		
Parmeliaceae	*Nephromopsis laii* (A. Thell and Randlane) Saag and A. Thell	14.2°	N		
Ochrolechiaceae	*Ochrolechia subpallescens* Verseghy	58.0°	NE		
Parmeliaceae	*Parmelia masonii* Essl. & Poelt.	28.4°	E		
	Parmelinella wallichiana (Taylor) D.D. Awasthi	43.8°	S		
	Parmotrema thomsonii (Stirt.) A. Crespo, Divakar and Hawksw	36.4°	S		

Peltigeraceae	*Peltigera canina* (L.) Willd.	21.6°	SW		
	Peltigera membranaceae (Ach.) Nyl	29.3°	N		
Pertusariaceae	*Pertusaria composita* Zahlbr.	48.6°	S		
Acarosporaceae	*Pleopsidium flavum* (Trevis) Körb.	38.1°	E		
Lecideaceae	*Porpidia crustulata* (Ach.) Hertel and Knoph	62.3°	S		
	Porpidia macrocarpa (DC.) Hertel and A.J Schwab	43.2°	S		
Ramalinaceae	*Ramalina conduplicans* Vain	33.6°	N		
	Ramalina himalayensis Räsänen	22.9°	E		
	Ramalina intermedia (Delise ex Nyl.) Nyl.	46.3°	E		
Rhizocarpaceae	*Rhizocarpon geographicum* (L.) DC	44.3°	NW		
Stereocaulaceae	*Stereocaulon foliolosum* var. *strictum* (C. Bab.) I.M. Lamb	57.1°	SW		
	Stereocaulon myriocarpum Th. Fr	69.0°	S		
Lobariaceae	*Sticta henryana* Müll. Arg.	72.0°	S		
Umbilicariaceae	*Umbilicaria indica* Frey	51.9°	S		
Teloschistaceae	*Xanthoria elegans* (Link)Th. Fr.	20.6°	NW		
Total family - 22	**Total number of lichen species – 77**				

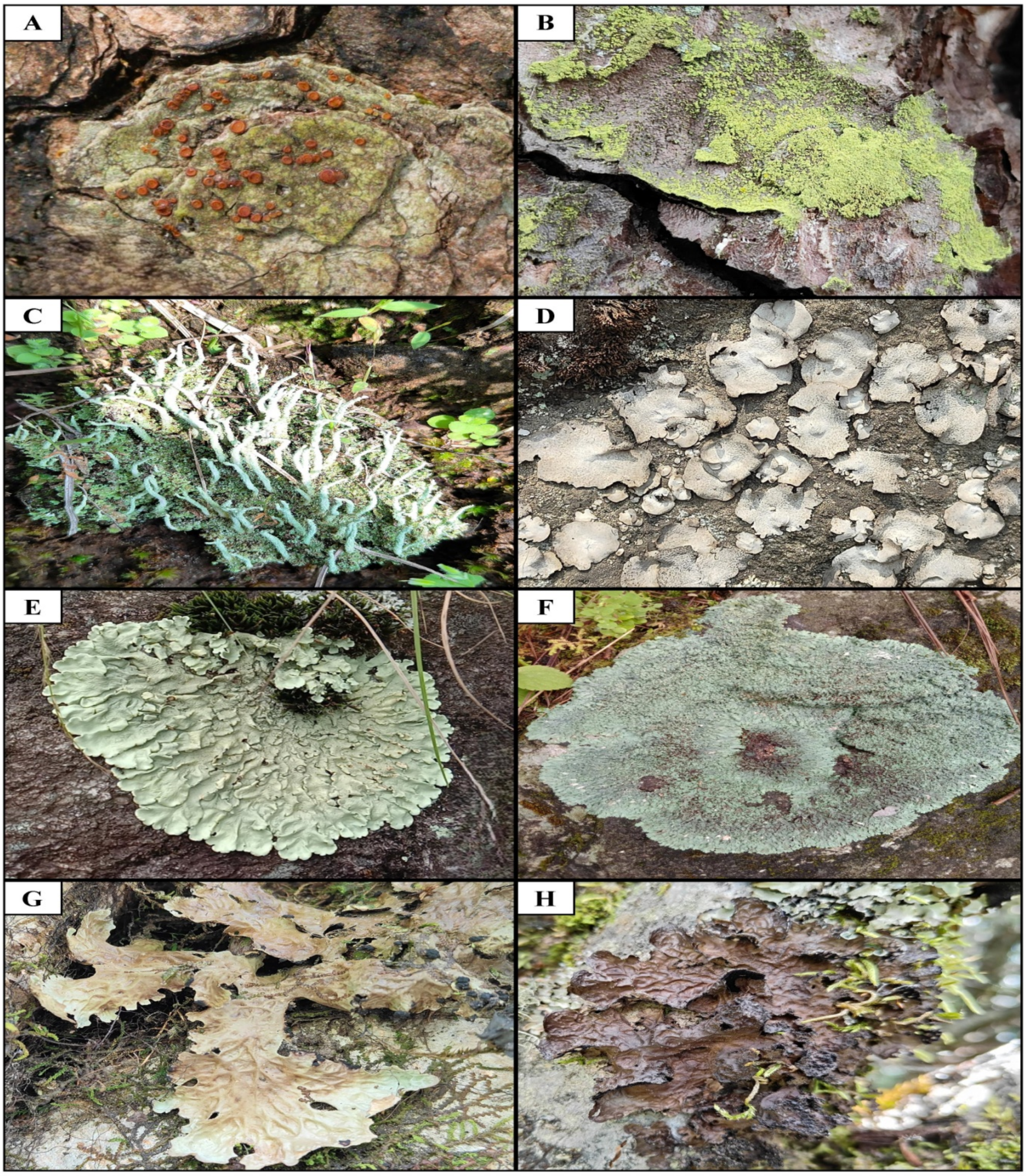

Fig. 2: Lichen species distribution across various substrates in the Madhyamaheshwar Valley **(A-H) - A.** *Caloplaca flavorubescens*, **B.** *Chrysothrix candelaris*, **C.** *Cladonia subulata*, **D.** *Dermatocarpon miniatum*, **E.** *Flavoparmelia caperata*, **F.** *Heterodermia diademata*, **G.** *Leptogium delavayi*, **H.** *Lobaria retigera*

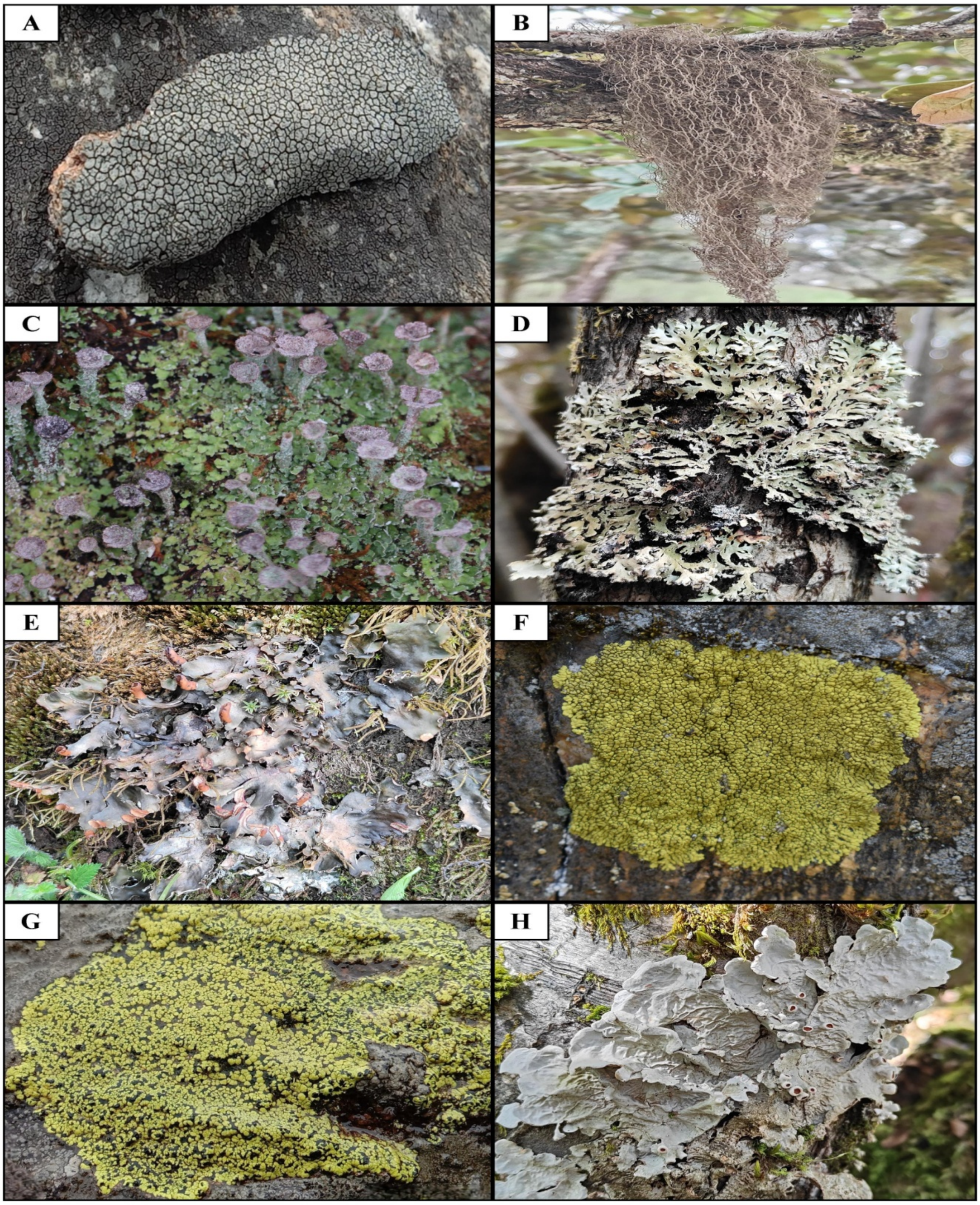

Fig. 3: Lichen species distribution across various substrates in the Madhyamaheshwar Valley **(A-H) - A.** *Aspicilia dwaliensis*, **B.** *Bryoria himalayana*, **C.** *Cladonia pocillum*, **D** .*Heterodermia japonica*, **E.** *Peltigera canina*, **F.** *Pleopsidium flavum*, **G.** *Rhizocarpon geographicum*, **H.** *Sticta henryana*

3.1. Lichen diversity, temperature, and humidity across different elevation zones

3.1.1. Lower elevation (1600-2300 m a.s.l.)

A total of 12lichen species were found, belonging to 9 families and 10 genera (3 crustose, 7 foliose, 2 fruticose). Parmeliaceae was the dominant family. Temperatures ranged from 11.3°C to 32.1°C and relative humidity from 34% to 59% (Table 1, Fig. 4, 7, 8). These climatic conditions likely create distinct ecological niches, influencing the distribution, growth, and survival of lichen species. Some species thrived in warmer, drier conditions, while others adapted to moderate temperature and humidity ranges.

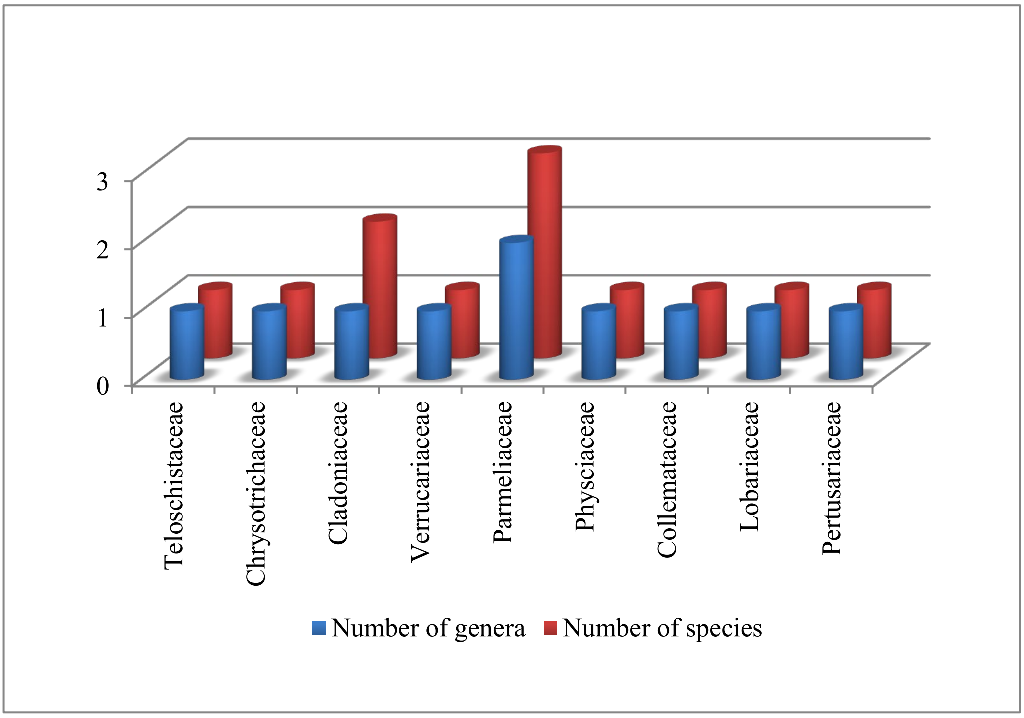

Fig. 4: Distribution of lichen families with respect to abundance of their species in lower elevation (1600 - 2300 m a.s.l.)

3.1.2. Middle elevation (2600-3100 m a.s.l.)

A total of 17species were recorded from 9 families and 12 genera (1 crustose, 9 foliose, 7 fruticose). Parmeliaceae dominated, followed by Cladoniaceae and Collemataceae. Temperatures ranged from 11.3°C to 24.8°C, with humidity between 54% and 77% (Fig. 5). These moderate temperatures and higher humidity conditions likely supported greater species richness compared to lower elevations. The more stable climatic conditions fostered a broader range of species with varying levels of tolerance to both temperature and humidity, promoting a diverse and stable ecological environment.

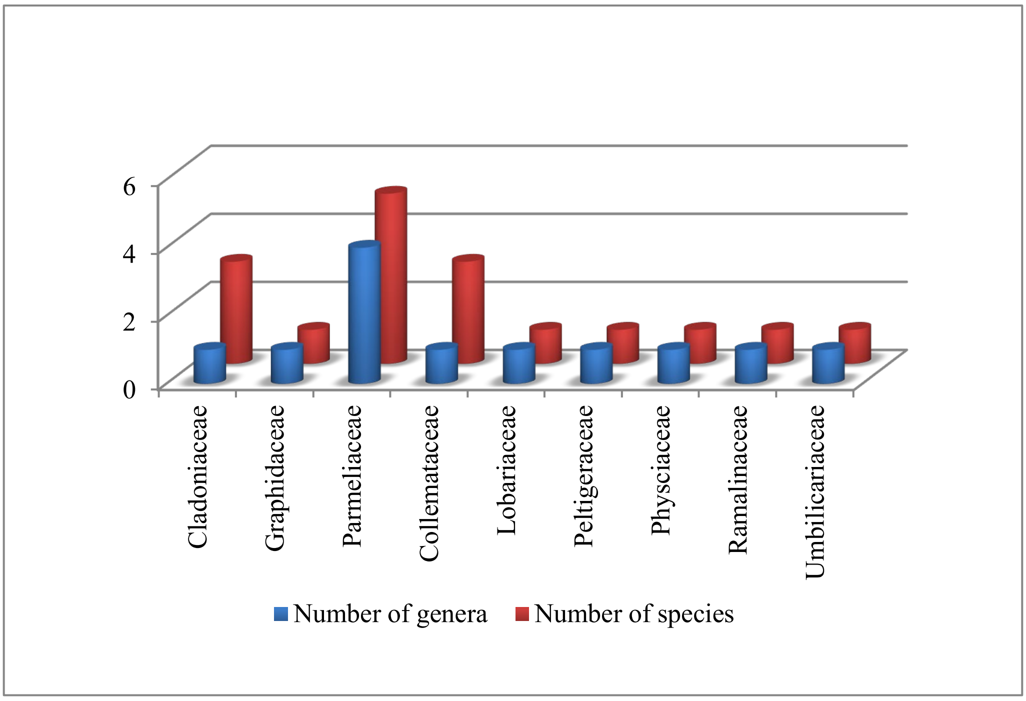

Fig. 5: Distribution of lichen families with respect to abundance of their species in middle elevation (2600 - 3100 m a.s.l.)

3.1.3. Higher elevation (3200-3600 m a.s.l.)

A total of 48species were recorded from 20 families and 30 genera (24 crustose, 12 foliose, 12 fruticose). Parmeliaceae was the most represented family, followed by Lecanoraceae, Cladoniaceae, and Graphidaceae. Temperatures ranged from 7.2°C to 20.6°C and humidity from 29% to 66% (Fig. 6). These cooler temperatures and variable humidity levels supported a highly diverse lichen community. Some species thrived in cooler, less humid conditions, while others were resilient to lower humidity levels. These climatic factors, along with the specific adaptations of lichen species, played a critical role in shaping the lichen community at higher elevations.

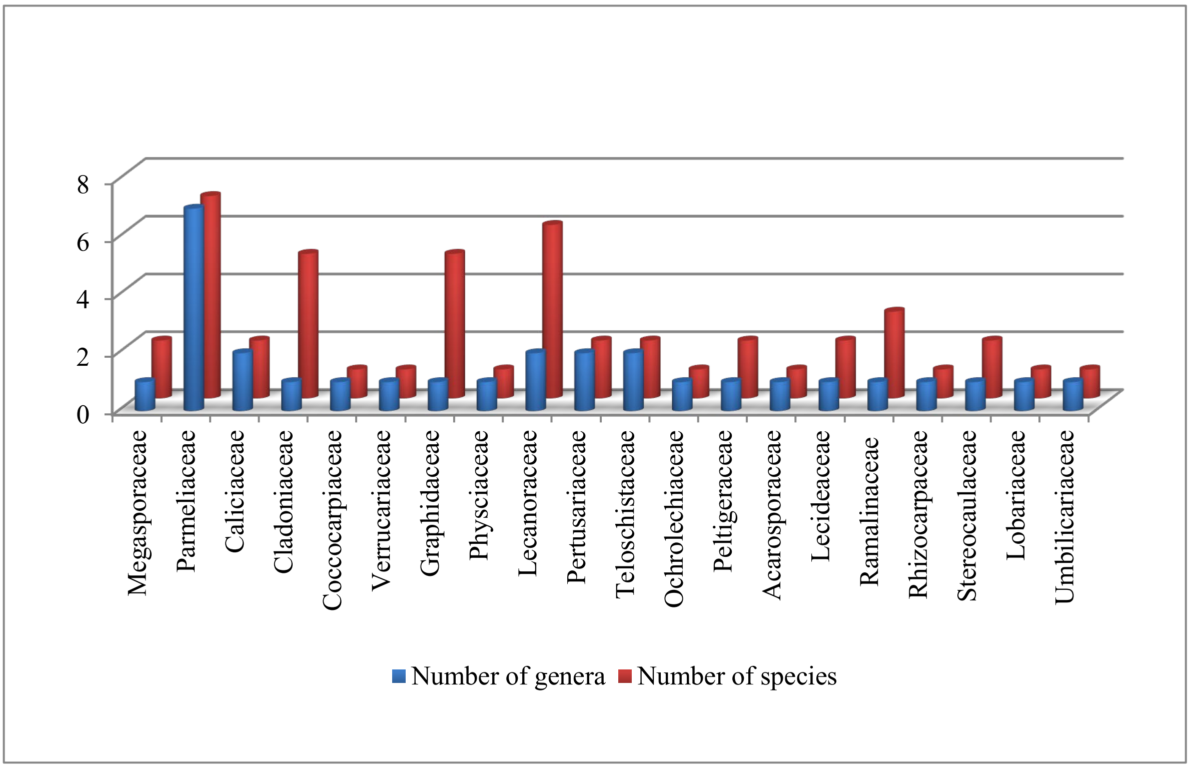

Fig. 6: Distribution of lichen families with respect to abundance of their species in higher elevation (3200 - 3600 m a.s.l.)

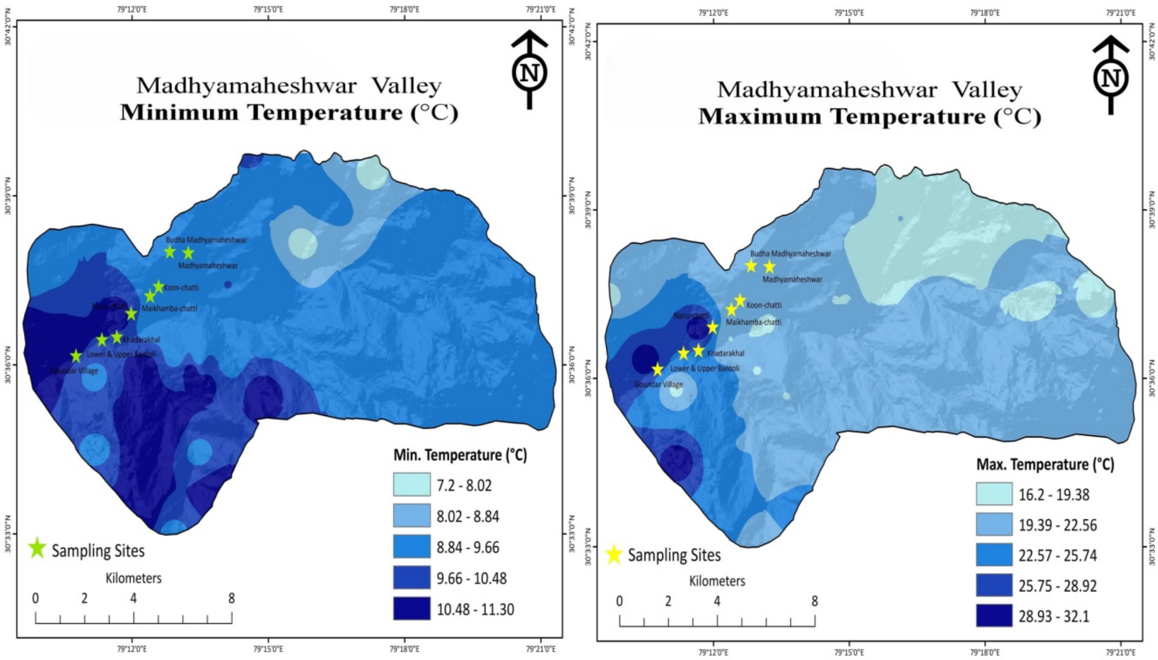

Fig. 7: Map showing spatial variation in maximum and minimum temperature across the study area.

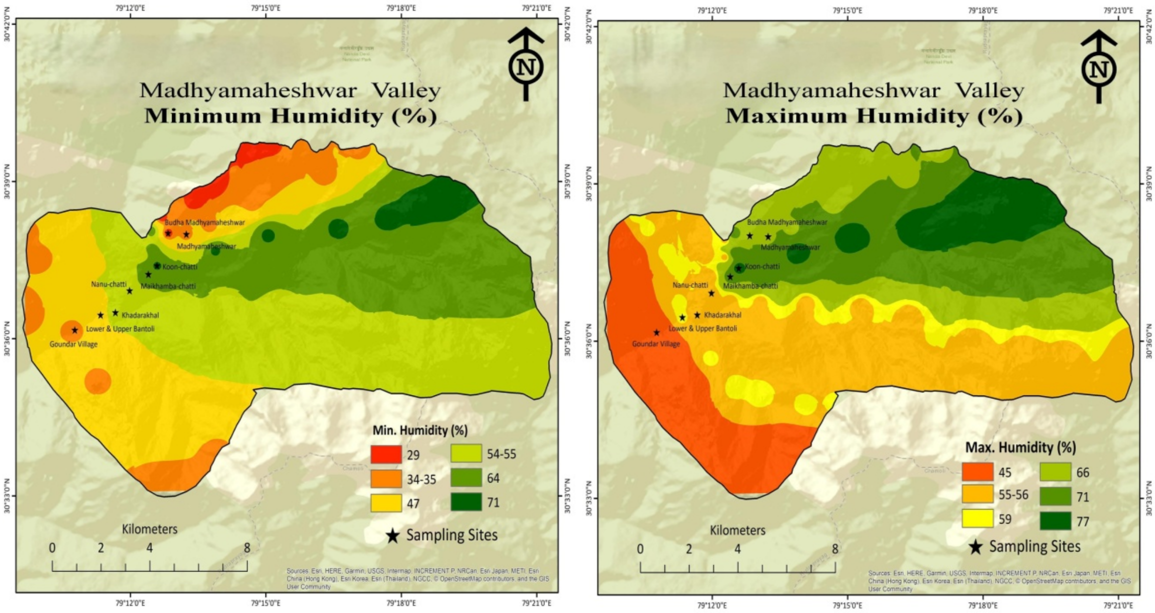

Fig. 8: Map showing spatial variation in maximum and minimum relative humidity across the study area.

3.2. Diversity of lichens across slope gradients

Lichen distribution varied with slope angle (Table 1, Fig. 9 and 10).Gentle slopes (10.5°-30.2°) supported the highest diversity (34 species), likely due to better moisture retention.Moderate slopes (32.9°-48.6°) had 28 species, possibly affected by microclimatic variation.Steep slopes (50.6°-72.0°) supported 15 species, indicating the presence of stress-tolerant, specialized lichens.Overall, these findings highlight that lichen diversity is influenced by slope angle, with gentler slopes supporting higher diversity, while steeper slopes host a more specialized, lower diversity of species.

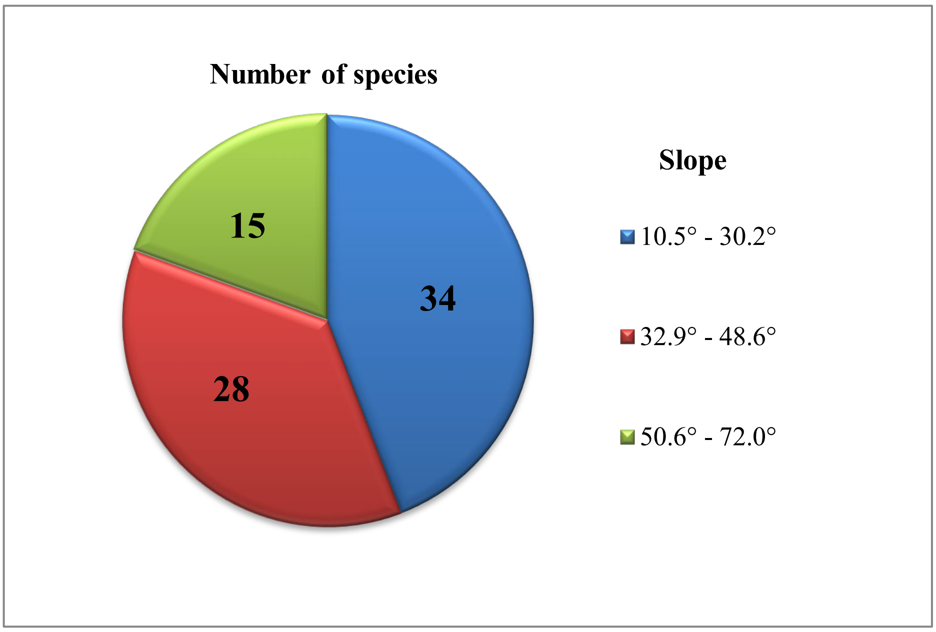

Fig. 9: Distribution of lichen species based on slope.

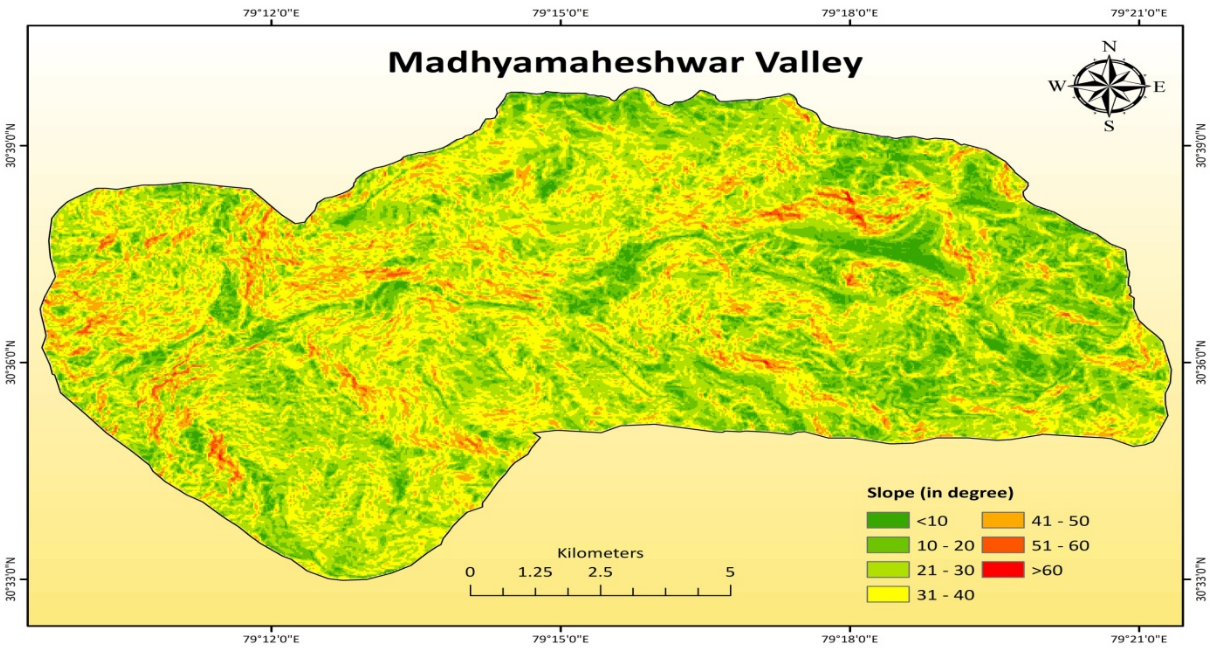

Fig. 10: Slope map (in degrees) of the study area, depicting terrain steepness.

3.3. Diversity of lichens in different directional aspects

In the present study, the term 'aspect' refers to the direction a surface of a hill, mountain slope, or terrain faces relative to the sun, and it is used to describe how different orientations significantly affect lichen distribution (Table 1, Fig. 11 and 12).

The southern aspect supported the highest diversity (21 species) due to greater sunlight and warmth.The northern aspect had 12 species, influenced by cooler, shaded conditions.

Eastern and western aspects supported 10 and 8 species respectively, while intercardinal directions showed varying diversity based on differential sunlight exposure.

The study found that southern aspects had the highest lichen diversity, likely due to greater sunlight and warmth. In contrast, northern, eastern, and western aspects showed lower species richness, influenced by temperature, light, and moisture. These results highlight the role of directional exposure in shaping lichen distribution in the valley.

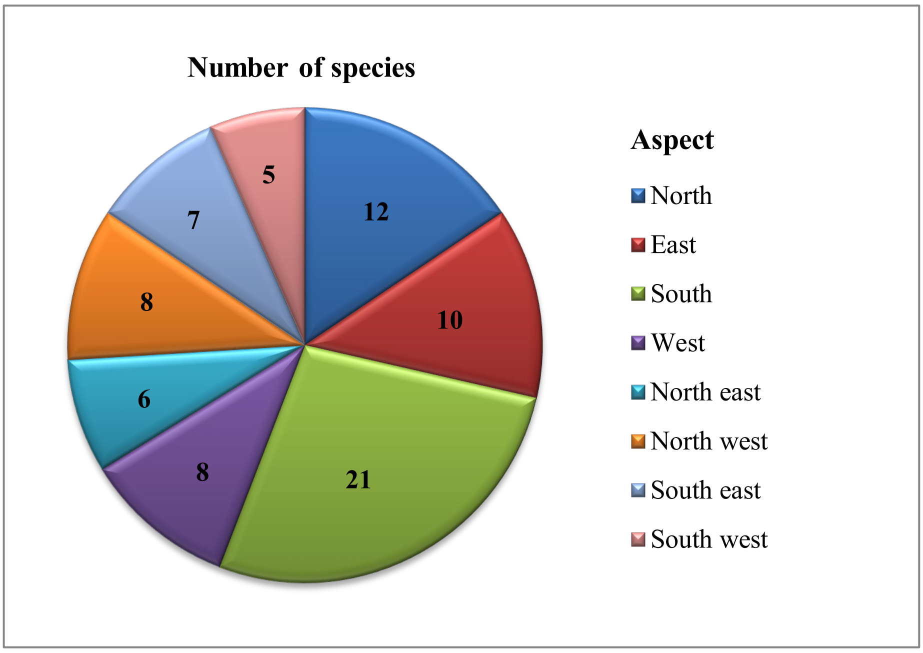

Fig. 11: Distribution of lichen species based on aspect.

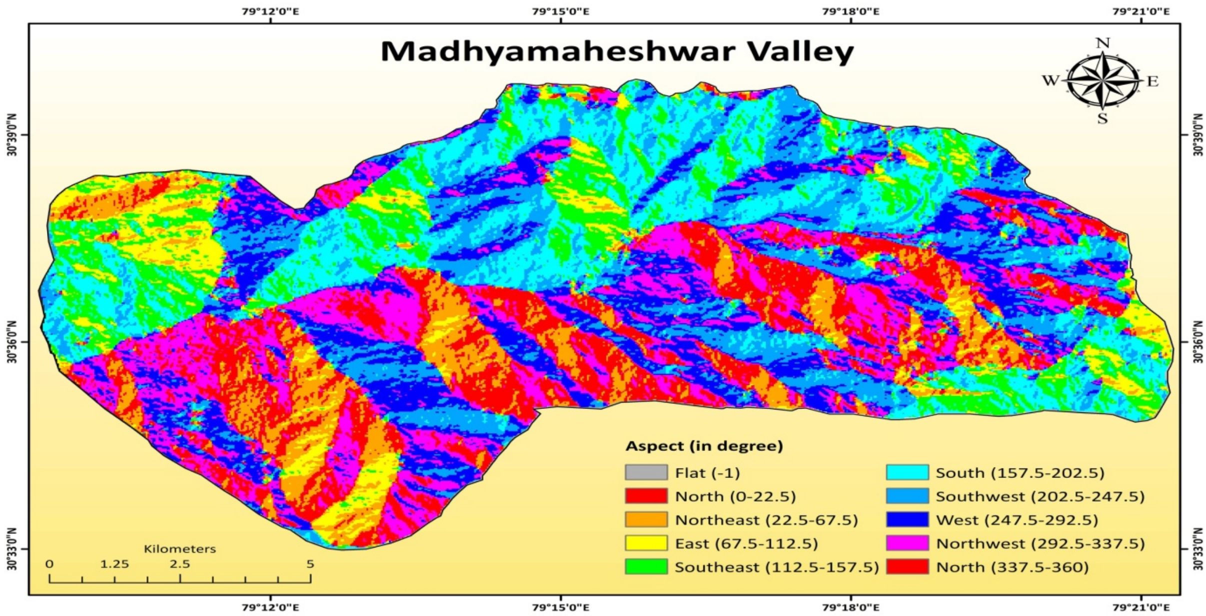

Fig. 12: Aspect map of the study area, showing terrain orientation (cardinal directions).

3.4. Altitudinal variation in lichen species and substrate preference

Substrate preference shifted across elevations.At lower elevations, foliose lichens dominated on bark, rock, and soil.At mid elevations, foliose and fruticose forms increased, occupying bark, mosses, and twigs.At higher elevations, crustose lichens were more prevalent, particularly on rocks and tree trunks, reflecting adaptation to colder, wind-exposed environments.This indicates that increasing altitude correlates with a shift in both species composition and substrate preference, favoring more specialized, resilient species at higher elevations.

3.5. Distribution patterns of lichens across elevation zones in Madhyamaheshwar Valley

The distribution of lichen species in the Madhyamaheshwar Valley reveals distinct patterns across three elevation zones (1600-2300 m, 2600-3100 m, and 3200-3600 m a.s.l.). Based on these zones, lichens were categorized by their presence in one, two, or all three zones (Table 2), providing insights into their habitat specificity.

Table 2: Lichen species and their distribution across elevation zones and substrates in the Madhyamaheshwar Valley.

S.n.	Name of lichens	Elevation zones (m a.s.l.)			Substrates
		1600 – 2300 m.	2600 – 3100 m.	3200 – 3600 m.	
1	*Aspicilia cinerea*	×	×	✓	Rock
2	*Aspicilia dwaliensis*	×	×	✓	Rock
3	*Bryoria himalayana*	×	×	✓	Bark
4	*Buellia himalayensis*	×	×	✓	Bark
5	*Calicium adspersum* subsp. *himalayense*	×	×	✓	Bark
6	*Caloplaca flavorubescens*	✓	×	×	Bark
7	*Chrysothrix candelaris*	✓	×	×	Bark
8	*Cladonia coccifera*	×	✓	×	Soil
9	*Cladonia corniculata*	×	✓	✓	Deadwood, mosses
10	*Cladonia fimbriata*	×	×	✓	Bark
11	*Cladonia fruticulosa*	✓	×	×	Soil
12	*Cladonia laii*	×	×	✓	Mosses
13	*Cladonia pocillum*	×	×	✓	Rock
14	*Cladonia pyxidata*	×	×	✓	Mosses
15	*Cladonia ramulosa*	×	✓	×	Soil
16	*Cladonia squamosa*	×	×	✓	Rock
17	*Cladonia subulata*	✓	×	×	Soil
18	*Coccocarpia erythroxyli*	×	×	✓	Rock
19	*Dermatocarpon miniatum*	✓	✓	✓	Rock
20	*Dermatocarpon vellereum*	×	×	✓	Rock
21	*Dolichousnea longissima*	×	✓	✓	Twigs
22	*Flavoparmelia caperata*	✓	✓	✓	Bark, rock
23	*Graphis cfr. duplicata*	×	×	✓	Bark
24	*Graphis furcata*	×	×	✓	Bark
25	*Graphis scripta*	×	×	✓	Bark
26	*Graphis* sp.1	×	×	✓	Bark
27	*Graphis* sp.2	×	✓	×	Bark
28	*Graphis* sp.3	×	×	✓	Bark
29	*Heterodermia diademata*	✓	✓	✓	Bark, rock
30	*Heterodermia japonica*	×	×	✓	Bark
31	*Hypotrachyna cirrhata*	×	✓	×	Bark
32	*Hypotrachyna nepalensis*	×	×	✓	Bark
33	*Lecanora caesiorubella*	×	×	✓	Bark
34	*Lecanora fimbriatula*	×	✓	✓	Bark
35	*Lecanora interjecta*	×	×	✓	Bark
36	*Lecidella carpathica*	×	×	✓	Rock

37	*Lecidella elaeochroma*	×	×	✓	Bark
38	*Lecidella euphorea*	×	×	✓	Bark
39	*Lepra leucosorodes*	×	×	✓	Bark
40	*Leptogium askotense*	×	✓	✓	Bark, mosses
41	*Leptogium burnetiae*	×	✓	✓	Bark, mosses
42	*Leptogium delavayi*	✓	✓	✓	Bark, mosses
43	*Leptogium trichophorum*	×	✓	✓	Bark, mosses
44	*Lobaria kurokawae*	×	✓	×	Mosses
45	*Lobaria retigera*	✓	✓	✓	Bark, mosses
46	*Loplaca pindarensis*	×	×	✓	Rock
47	*Nephromopsis laii*	×	✓	✓	Bark
48	*Ochrolechia subpallescens*	×	×	✓	Bark
49	*Parmelia masonii*	×	×	✓	Rock
50	*Parmelinella wallichiana*	×	✓	✓	Bark, rock
51	*Parmotrema nilgherrensis*	×	✓	✓	Bark, rock
52	*Parmotrema reticulatum*	✓	✓	✓	Bark, rock
53	*Parmotrema thomsonii*	×	✓	✓	Bark, Twigs rock
54	*Parmotrema tinctorum*	✓	✓	✓	Bark, rock
55	*Peltigera canina*	×	×	✓	Mosses
56	*Peltigera membranaceae*	×	×	✓	Mosses
57	*Peltigera polydactylon*	×	✓	✓	Mosses
58	*Pertusaria composita*	×	×	✓	Bark
59	*Pertusaria velata*	✓	×	×	Bark
60	*Pleopsidium flavum*	×	×	✓	Rock
61	*Polyblastidium microphyllum*	×	✓	✓	Mosses
62	*Porpidia crustulata*	×	×	✓	Rock
63	*Porpidia macrocarpa*	×	×	✓	Rock
64	*Ramalina conduplicans*	×	✓	✓	Bark, twigs
65	*Ramalina himalayensis*	×	×	✓	Rock
66	*Ramalina intermedia*	×	✓	✓	Twigs
67	*Ramalina sinensis*	×	✓	✓	Twigs
68	*Rhizocarpon geographicum*	×	×	✓	Rock
69	*Stereocaulon foliolosum*	×	×	✓	Rock
70	*Stereocaulon myriocarpum*	×	×	✓	Mosses
71	*Sticta henryana*	×	×	✓	Bark
72	*Sulcaria sulcata*	×	✓	✓	Twigs
73	*Umbilicaria indica*	×	×	✓	Rock
74	*Umbilicaria vellea*	×	✓	✓	Rock

75	*Usnea orientalis*	×	✓	✓	Twigs
76	*Usnea subfloridana*	×	✓	✓	Twigs
77	*Xanthoria elegans*	×	×	✓	Rock

3.6. Lichens present in all three elevational zones

Several species occur across all elevation zones (1600-2300 m, 2600-3100 m, and 3200-3600 m a.s.l.), exhibiting varied substrate preferences. Species such as *Dermatocarpon miniatum*, *Flavoparmelia caperata*, *Heterodermia diademata*, *Leptogium delavayi*, *Lobaria retigera*, *Parmotrema reticulatum*, and *Parmotrema tinctorum* were observed across all zones. These lichens occupy substrates including rock, bark, and mosses; for example, *Flavoparmelia caperata* and *Parmotrema reticulatum* were found on both bark and rock. Their widespread presence suggests broad ecological tolerance.

3.7. Lichens present in two different elevational zones

Lichen distribution indicates an absence of species exclusive to the lower elevation zone (1600–2300 m a.s.l.). In contrast, species such as *Cladonia corniculata*, *Dolichousnea longissima*, and *Leptogium askotense* were found in both mid (2600-3100 m a.s.l.) and high (3200-3600 m a.s.l.) elevations, primarily on bark, mosses, twigs, and rock. Their distribution reflects a preference for cooler, stable environments typical of higher altitudes. The use of multiple substrates also indicates ecological flexibility.

3.8. Lichens present in only one specific elevational zone

Certain lichen species exhibit strong elevation-specific patterns. At lower elevations (1600-2300 m a.s.l.), species such as *Caloplaca flavorubescens*, *Chrysothrix candelaris*, *Cladonia fruticulosa*, *Cladonia subulata*, and *Pertusaria velata* occur exclusively. Mid-elevation species include *Cladonia coccifera*, *Cladonia ramulosa*, *Graphis sp2*, *Hypotrachyna cirrhata*, and *Lobaria kurokawae*. At higher elevations (3200-3600 m a.s.l.), 41 species were documented, many of which are restricted to this zone, indicating adaptation to harsher conditions. These patterns reflect the niche specialization of lichen species along the altitudinal gradient.

4. DISCUSSION

The study revealed that 48 lichen species were most abundant at higher elevations in the Madhyamaheshwar Valley (Table 1). This observation aligns with findings from several researchers who have noted greater diversity of lichens in the higher mountain ranges of Europe and Asia (Baniya et al. 2010; Vittoz et al. 2010). Variations in diversity along an elevation gradient are influenced by a combination of evolutionary adaptations and ecological factors (Rahbek 2005). Our study found that lichen abundance was greater at higher elevations, where temperatures ranged from 7.2°C to 20.6°C and relative humidity fluctuated between 29% and 66%. Similarly, an earlier study by Cobanoglu and Sevgi (2009) found that elevation significantly influences both the quantity and composition of epiphytic lichen communities. Climatic factors such as temperature, rainfall, and evaporation are closely linked to altitude. As a result, the highest elevation zone displays the greatest number of species.

According to the study, we found that gentler slopes support a higher diversity of lichen species. Findings highlight that lichen diversity is influenced by slope angle, with gentler slopes supporting higher diversity, while steeper slopes host a more specialized, lower diversity of species. As suggested by Lepp (2011), slopes with gentler angles foster higher lichen abundance and diversity due to the influence of water runoff.

Based on cardinal direction aspect, a total of 21 lichen species were found on the southern aspect, while 12 lichen species were found on the northern aspect, clearly indicating higher species richness on the southern aspect. Similarly, Armstrong and Welch (2007) reported that the conditions on south-facing surfaces are more favorable for the survival of competitive species, whereas only those species that are resistant to unfavorable conditions are found on north-facing aspects.

We observed that the distribution pattern was different according to elevation and substratum, with lichen species dominating on tree branches and bark, and less frequently in the soil. Similarly, several authors have emphasized that most lichen species prefer tree bark as their substrate, while others demonstrate higher host specificity, favoring specific host trees (Sequeira & Kumar 2008; Shravanakumara et al. 2010).

In our study, we found that some lichen species were present at all three elevations. The main reason for this could be that these species are less responsive to the environmental conditions of their surroundings. This ability may enable them to survive under various environmental conditions by maintaining their thallus structure. Similarly, Zulkifly et al. (2011) observed that certain species were prevalent in montane forests across all elevations.

5. CONCLUSION

Based on the findings of the current study in the Madhyamaheshwar Valley assessed that lichen diversity increases with elevation, with the highest abundance at higher elevations. This pattern is linked to favourable climatic conditions, such as cooler temperatures and stable humidity. Additionally, gentle slopes supported greater lichen diversity, likely due to better water retention, while steeper slopes hosted more specialized species. The southern aspects showed higher species richness compared to the northern aspects, highlighting the importance of sunlight and temperature. We also observed that lichen species predominantly favored tree bark as a substrate, with fewer species found on soil. Some species were found across all elevation zones, suggesting their adaptability to varying environmental conditions. Overall, the study emphasizes how elevation, slope, aspect, and substrate type shape lichen diversity in the region.Lichens, due to their high sensitivity to environmental perturbations, have emerged as reliable bioindicators of climate change. Our results indicate that spatial variations in lichen diversity across different slopes and altitudes may offer valuable insights into the impacts of climate variables such as temperature and humidity on ecosystem dynamics. Given that lichens are among the first organisms to exhibit responses to environmental stress, their presence or absence can serve as an early warning system for climate-induced changes. Systematic monitoring of lichen communities, particularly in ecologically sensitive regions such as the Kedarnath Wildlife Sanctuary, could be instrumental in detecting climate-driven shifts and guiding targeted conservation strategies. Additionally, long-term monitoring efforts, combined with citizen science initiatives, could significantly strengthen our capacity to detect and mitigate the effects of climate change on biodiversity.

Future studies should emphasize the establishment of consistent, long-term monitoring protocols for lichen populations to accurately track changes over time and their reactions to climate variability. Additionally, conservation priorities must include the protection and restoration of habitats within crucial elevation ranges, taking into account the specific microhabitat requirements of vulnerable lichen species. Incorporating lichen-based bioindicators into local climate resilience and adaptation strategies can play a vital role in safeguarding biodiversity and strengthening ecosystem stability in the Garhwal Himalaya region.

AUTHORS' CONTRIBUTIONS

N.K.P. collected lichen samples, gathered ecological data, and wrote the manuscript. J.P.M. conducted the data analysis. M.A. conducted the data analysis. R.S.A. assisted with lichen identification. S.N. performed additional data analysis and made essential corrections to the manuscript. A.P. provided guidance in the manuscript preparation. All authors read and approved the final manuscript.

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