RESEARCH PAPER

ASSESSMENT OF SOIL PHYSICOCHEMICAL PROPERTIES AND BRYOPHYTE DIVERSITY AS INDICATORS OF ENVIRONMENTAL STRESS IN RAJOURI DISTRICT

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ABSTRACT

The present study investigated the relationship between soil physicochemical properties and bryophyte diversity in Rajouri District, Jammu & Kashmir, India. Soil parameters including pH, electrical conductivity (EC), organic carbon (OC), macronutrients (N, P, K), and selected micronutrients (Zn, Fe, Mn, Cu) were analyzed from multiple bryophytes dominated sites. A total of diverse bryophyte taxa was recorded, with plagiochasma appendiculatum, Marchantia paleacea, and several Fissidens species beung frequently encountered. Soil pH ranged from slightly acidic to neutral (5.2-7.5), while EC values indicated predominantly non-saline conditions. Organic carbon and nitrogen levels showed considerable spatial variation and were positively associated with bryophyte richness. Micronutrient concentrations varied across sites but remained within ecologically tolerable ranges. The findings demonstrate that soil pH, nutrient availability, and salinity significantly influence bryophyte composition and distribution. The study highlights the ecological sensitivity of bryophytes and supports their potential role as indicators of soil health and environmental quality in montane ecosystems.

Keywords: Bryophyte diversity, Soil properties, Nutrient status, Micronutrients, Bioindicators

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INTRODUCTION

Bryophytes are integral components of terrestrial ecosystems and contribute significantly to nutrient cycling, moisture retention, and soil stabilization. Owing to the absence of a well-developed vascular system and true roots, bryophytes absorb water and nutrients directly through their surfaces, making them highly responsive to substrate chemistry and environmental variation (Shaw et al., 2011; Pakeman et al., 2019). Consequently, soil physicochemical properties play a critical role in regulating bryophyte establishment, distribution, and community composition.

Soil pH influences nutrient solubility and metal mobility, thereby affecting plant growth and microbial activity (Tyler & Olsson, 2016). Organic carbon enhances soil structure, improves moisture retention,

and supports microhabitat stability, which is particularly important for bryophyte persistence (Li et al., 2022). Macronutrients such as nitrogen and phosphorus regulate metabolic activity and vegetative growth, whereas micronutrients including zinc, iron, manganese, and copper are involved in enzymatic and physiological processes (Zhang et al., 2021; Fasani et al., 2022). Recent ecological studies have demonstrated that variation in these edaphic factors significantly shapes bryophyte community patterns in forested and montane ecosystems (Kutnar et al., 2023; Singh et al., 2020).

The northwestern Himalayan region, including Rajouri District of Jammu & Kashmir, exhibits considerable topographic and land-use heterogeneity that may generate spatial variability in soil properties. However, systematic investigations linking soil physicochemical parameters with bryophyte diversity in this region remain limited. Understanding these interactions is essential for evaluating ecosystem functioning and assessing the ecological sensitivity of bryophyte communities under varying edaphic conditions.

The present study therefore aims to (i) examine spatial variation in soil physicochemical characteristics across selected sites of Rajouri District, (ii) document bryophyte species distribution, and (iii) evaluate the influence of edaphic factors on bryophyte diversity patterns.

Methodology

2.1 Study Area

The present study was conducted in Rajouri District, Jammu & Kashmir, India. The district is characterized by varied topography, altitudinal gradients, and diverse land-use patterns including forested regions, roadside habitats, semi-urban settlements, agricultural lands, and institutional campuses. Such heterogeneity provides varied microhabitats suitable for bryophyte colonization. Sampling was conducted during the active growing season to ensure optimal bryophyte development and accurate ecological assessment.

2.2 Sampling Design and Soil Collection

A total of 23 sampling sites were selected across different ecological zones of Rajouri District. Site selection was based on visible bryophyte presence and variation in habitat conditions. At each site, soil samples were collected from beneath well-established bryophyte mats.

From each site, three replicate soil samples were collected at a depth of 0–10 cm after removing surface litter. Approximately 50 g of soil was collected per replicate using sterilized stainless-steel tools to avoid contamination. Thus, a total of 62 soil samples were obtained for analysis.

Samples were placed in labeled polyethylene bags and transported to the laboratory. In the laboratory, soil samples were air-dried at room temperature, gently crushed, and sieved through a 2 mm mesh prior to analysis following standard soil analytical procedures (Jackson, 1973).

2.3 Collection and Identification of Bryophytes

Bryophyte specimens occurring directly above the soil sampling points were carefully collected along with ecological notes including moisture condition, shading intensity, and substrate type. Specimens were cleaned of adhering soil particles and preserved in paper packets.

Identification was carried out using standard bryological floras and taxonomic keys. Morphological features such as thallus structure, leaf arrangement, costa characteristics, and cell anatomy were examined under stereo and compound microscopes. Nomenclature was verified following Shaw et al. (2011) and Proctor et al. (2007). Voucher specimens were preserved for reference.

2.4 Analysis of Soil Physicochemical Properties

2.5 Soil pH

Soil pH was measured in a 1:2.5 soil–water suspension using a calibrated digital pH meter following Jackson (1973). The instrument was standardized using buffer solutions (pH 4.0, 7.0, and 9.2) before measurement.

2.5.1 Electrical Conductivity (EC)

Electrical conductivity was determined in the soil extract using a digital conductivity meter and expressed in dS/m as described by Jackson (1973).

2.5.2 Organic Carbon (OC)

Soil organic carbon was estimated using the Walkley and Black wet oxidation method (Walkley and Black, 1934). The percentage organic carbon was calculated based on titration values.

2.5.3 Available Nitrogen (N)

Available nitrogen was determined using the Kjeldahl digestion and distillation method as described by Allen (1974). Results were expressed in mg/kg of soil.

2.5.4 Available Phosphorus (P)

Available phosphorus was analyzed using the Olsen extraction method (Olsen et al., 1954), and concentration was determined colorimetrically.

2.5.5 Exchangeable Potassium (K)

Exchangeable potassium was determined using ammonium acetate extraction followed by flame photometric estimation.

2.6 Determination of Micronutrients (Zn, Fe, Mn, Cu)

Soil samples were digested using a mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) in a 3:1

ratio following the method of Mathiyazhagan and Natarajan (2011). The digested samples were filtered and diluted to a known volume with distilled water.

Micronutrient concentrations (Zn, Fe, Mn, Cu) were determined using Atomic Absorption Spectrophotometry (AAS). Calibration curves were prepared using certified standard solutions prior to analysis.

2.7 Quality Assurance and Control (QA/QC)

All analyses were performed in triplicate. Instrument calibration was carried out using standard reference solutions. Reagent blanks were included to minimize analytical error. Detection limits and standard deviations were monitored to ensure accuracy and reproducibility of measurements.

RESULTS

3.1 Soil Physicochemical Characteristics Across Study Sites

Considerable spatial variation in soil physicochemical properties was observed across the sampling sites in Rajouri District (Tables 1). Soil pH ranged from 5.2 (Darhal S4) to 7.5 (Narian S2), indicating that most sites exhibited slightly acidic to neutral conditions. Slightly acidic soils (pH 5.5–6.5) were predominant across locations such as GDC Nowshera, Lam Phata, Manjakote, Budhal, and Sunderbani, whereas neutral to slightly alkaline conditions were recorded at selected sites including Narian S2 (pH 7.5) and Palwal S1 (pH 7.2).

Electrical conductivity (EC) varied between 0.12 dS/m (Manglamata S3) and 0.99 dS/m (BGSBU S1). Most sites recorded EC values below 0.7 dS/m, indicating non-saline conditions. However, relatively higher EC values were observed at BGSBU S1 (0.99 dS/m), Kalakote S2 (0.96 dS/m), Palwal S3 (0.98 dS/m), and Kungra S4 (0.77 dS/m), suggesting localized variation in soluble salt concentration.

Organic carbon content ranged from 0.5% (Manglamata S3) to 2.0% (BGSBU S7). Sites such as Lam Phata S1 (1.65%), Kakora S2 (1.59%), Manjakote S2 (1.59%), and BGSBU S7 (2.0%) exhibited comparatively higher organic carbon, whereas Manglamata S3 (0.55%) and Manglamata S2 (0.77%) showed lower values.

Available nitrogen concentrations showed substantial variability across sites, ranging from 104 mg/kg (BGSBU S1) to 1105 mg/kg (Manglamata S3 and Budhal S3). Several sites including Narian S3, Budhal S1–S3, Manjakote S2, and Palwal S3 exhibited relatively higher nitrogen levels (>1000 mg/kg). Available phosphorus ranged from 12.4 mg/kg (Dhoka S1) to 25 mg/kg (Manjakote S1), while exchangeable potassium varied from 155 mg/kg (BGSBU S6, Jhulla Water Point S1) to 215 mg/kg (Manglamata S1).

Table 1. Soil physicochemical properties of all sampling sites in Rajouri District.

Site	pH	EC (dS/m)	OC (%)	N (mg/kg)	P (mg/kg)	K (mg/kg)
GDC Nowshera	5.5	0.18	1.59	1105	18.0	212
Manglamata S1	5.7	0.13	0.77	535	18.0	215
Manglamata S2	7.0	0.15	0.55	634	15.1	212
Manglamata S3	6.3	0.12	0.50	632	17.1	209
Lam Phata S1	6.5	0.18	1.65	1147	14.0	213
Lam Phata S2	7.3	0.20	1.61	1119	19.0	207
Lam Phata S3	5.8	0.19	1.40	973	20.0	204
Narian S2	7.5	0.20	1.61	1119	18.0	204
Narian S3	6.5	0.18	1.62	1115*	13.2	206
Dhoka S1	6.5	0.18	1.35	972	12.4	205
Dhoka S2	6.2	0.19	1.40	973	19.0	206
Darhal S1	6.5	0.30	1.35	955	22.0	207
Darhal S2	7.0	0.32	1.37	952	20.0	205
Darhal S3	6.8	0.22	1.30	755	16.0	194
Darhal S4	5.2	0.20	1.52	1102	18.1	204

Dabbar S1	5.5	0.17	1.23	855	20.0	202
Dabbar S2	6.5	0.13	1.43	905	16.2	204
Kakora S1	5.8	0.35	1.55	1103	15.0	205
Kakora S2	5.9	0.38	1.59	1105	17.0	203
Kakora S3	7.0	0.15	1.62	1023	15.7	196
Manjakote S1	6.2	0.15	1.40	978	25.0	195
Manjakote S2	5.9	0.37	1.59	1103	17.0	203
Manjakote S3	6.4	0.18	1.41	980	17.2	194
Manjakote S4	5.5	0.42	1.52	1104	16.1	201
Chingus	6.8	0.41	1.43	804	18.3	204
Channi	5.5	0.32	1.22	908	16.4	195
BGSBU S1	5.6	0.99	1.76	104	12.5	175
BGSBU S2	5.3	0.35	1.29	666	1.6	166
BGSBU S3	5.7	0.48	1.59	975	14.5	170
BGSBU S4	5.6	0.52	1.43	755	14.0	200
BGSBU S5	5.5	0.55	1.45	1103	16.0	199
BGSBU S6	6.5	0.48	1.80	667	17.8	155
BGSBU S7	6.2	0.33	2.00	980	18.0	179
Kungra S1	5.8	0.62	1.90	788	17.5	184
Kungra S2	6.5	0.42	1.22	655	17.0	166
Kungra S3	5.7	0.46	1.40	540	15.8	170
Kungra S4	5.8	0.77	1.40	660	15.6	172
Kungra S5	7.0	0.15	1.62	1023	15.7	196
Peli S1	5.7	0.46	1.50	870	18.0	199
Peli S2	5.5	0.55	1.33	560	24.0	201
Peli S3	5.9	0.63	1.32	820	16.3	205
Peli S4	6.5	0.66	1.30	994	15.0	207
Jhulla S1	6.3	0.44	1.50	108	18.3	155
Jhulla S2	5.7	0.34	1.90	1102	17.2	177
Budhal S1	6.5	0.49	1.44	1104	19.4	176
Budhal S2	6.7	0.42	1.22	1104	21.3	178
Budhal S3	6.2	0.42	1.34	1105	22.5	199
Budhal S4	6.5	0.46	1.34	907	20.4	202
Sodapani Ziarat	6.5	0.53	1.33	807	21.4	184
Minka	7.0	0.54	1.40	974	18.9	194

Breri Nowshera	5.7	0.63	1.30	874	14.2	159
Mangalnar S1	5.5	0.67	1.50	990	15.3	155
Mangalnar S2	7.0	0.47	1.22	698	14.2	187
Palwal S1	7.2	0.87	1.53	797	18.9	176
Palwal S2	5.9	0.87	1.24	997	18.6	178
Palwal S3	5.9	0.98	1.30	1071	17.0	194
Sunderbani S1	5.6	0.65	1.22	1034	18.0	175
Sunderbani S2	5.5	0.70	1.45	857	17.9	201
Kalakote S1	5.7	0.92	1.34	844	17.4	202
Kalakote S2	5.9	0.96	1.80	925	18.0	176
Kalakote S3	6.5	0.73	1.60	956	18.9	167
Brebi Kalakote	6.5	0.83	1.50	766	18.6	180

3.2 Micronutrient Distribution in Soil

Micronutrient analysis revealed site-specific variability in zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) concentrations (Table 2).

Zinc concentrations ranged from 0.2 mg/kg (Dabbar S1) to 0.9 mg/kg (Palwal S3). Elevated Zn values were observed at Palwal S2 (0.84 mg/kg) and S3 (0.9 mg/kg), as well as at Sunderbani S2 (0.8 mg/kg).

Iron concentrations varied between 0.33 mg/kg (Darhal S3 and Channi) and 0.88 mg/kg (Manjakote S3). Higher Fe levels were recorded at BGSBU S7 (0.86 mg/kg), Manjakote S3 (0.88 mg/kg), and Mangalnar S1 (0.83 mg/kg).

Manganese ranged from 2.8 mg/kg (Manjakote S2 and Kakora S1) to 6.3 mg/kg (BGSBU S3). Elevated Mn concentrations were observed at BGSBU S3 (6.3 mg/kg), Chingus (5.1 mg/kg), and Darhal S4 (4.6 mg/kg).

Copper concentrations ranged from 0.19 mg/kg (Manjakote S1) to 4.4 mg/kg (Darhal S4). Apart from Darhal S4, most sites exhibited copper concentrations below 1.0 mg/kg. Elevated Cu values were also recorded at Kungra S4 (0.9 mg/kg), Palwal S2 (0.9 mg/kg), and Budhal S1 (0.87 mg/kg).

Table 2. Micronutrient concentrations (mg/kg) in soils of all sampling sites, Rajouri District.

Site	Zn	Fe	Mn	Cu
GDC Nowshera	0.60	0.90	4.0	0.24
Manglamata S1	0.66	0.66	3.6	0.40
Manglamata S2	0.64	0.60	3.2	0.25
Manglamata S3	0.62	0.50	3.8	0.30
Lam Phata S1	0.64	0.90	4.0	0.24
Lam Phata S2	0.60	0.84	3.6	0.48
Lam Phata S3	0.50	0.83	3.5	0.47
Narian S2	0.60	0.84	3.6	0.48
Narian S3	0.50	0.80	3.5	0.40
Dhoka S1	0.40	0.80	3.4	0.42
Dhoka S2	0.42	0.72	4.0	0.50
Darhal S1	0.44	0.70	3.5	0.55

Darhal S2	0.50	0.66	3.8	0.51
Darhal S3	0.30	0.33	3.6	0.20
Darhal S4	0.22	0.43	4.2	4.40*
Dabbar S1	0.20	0.64	4.0	0.52
Dabbar S2	0.30	0.55	4.0	0.43
Kakora S1	0.65	0.72	2.8	0.32
Kakora S2	0.70	0.76	2.8	0.34
Kakora S3	0.44	0.52	4.2	0.43
Manjakote S1	0.62	0.85	4.1	0.19
Manjakote S2	0.66	0.81	2.8	0.34
Manjakote S3	0.66	0.88	4.2	0.20
Manjakote S4	0.34	0.55	4.6	0.70
Chingus	0.71	0.60	5.1	0.30
Channi	0.60	0.33	3.7	0.36
BGSBU S1	0.42	0.38	5.1	0.60
BGSBU S2	0.41	0.63	4.5	0.40
BGSBU S3	0.30	0.71	6.3	0.64
BGSBU S4	0.22	0.65	4.6	0.32
BGSBU S5	0.20	0.54	3.8	0.44
BGSBU S6	0.39	0.74	4.1	0.47
BGSBU S7	0.40	0.86	3.8	0.74
Kungra S1	0.35	0.54	4.4	0.50
Kungra S2	0.29	0.48	3.6	0.48
Kungra S3	0.34	0.47	2.9	0.78
Kungra S4	0.55	0.67	3.6	0.90
Kungra S5	0.44	0.52	4.2	0.43
Peli S1	0.44	0.72	4.2	0.85
Peli S2	0.38	0.49	4.0	0.80
Peli S3	0.60	0.74	3.7	0.70
Peli S4	0.51	0.52	4.2	0.74
Jhulla S1	0.34	0.75	3.6	0.70
Jhulla S2	0.43	0.79	4.1	0.57
Budhal S1	0.44	0.48	3.0	0.87
Budhal S2	0.29	0.64	4.4	0.66
Budhal S3	0.47	0.58	4.9	0.48

Budhal S4	0.47	0.47	3.8	0.67
Sodapani Ziarat	0.65	0.55	3.0	0.80
Minka	0.55	0.63	4.7	0.57
Breri Nowshera	0.48	0.52	3.8	0.78
Mangalnar S1	0.63	0.83	4.2	0.70
Mangalnar S2	0.49	0.51	4.7	0.68
Palwal S1	0.70	0.60	4.9	0.70
Palwal S2	0.84	0.71	3.8	0.90
Palwal S3	0.90	0.50	3.0	0.72
Sunderbani S1	0.70	0.50	3.6	0.60
Sunderbani S2	0.80	0.58	4.2	0.75
Kalakote S1	0.77	0.66	4.4	0.55
Kalakote S2	0.66	0.67	3.8	0.52
Kalakote S3	0.55	0.83	4.2	0.70
Brebi Kalakote	0.65	0.48	4.8	0.66

3.3 Bryophyte Diversity Patterns

A diverse assemblage of bryophytes was recorded across the study sites (Table 3). *Plagiochasma appendiculatum* was the most frequently occurring species and was observed in multiple localities including GDC Nowshera, Manglamata, Lam Phata, Kakora, BGSBU, Kungra, Peli, Breri Nowshera, Sunderbani, and Kalakote.

Mixed species assemblages were recorded at sites exhibiting relatively higher organic carbon and balanced nutrient levels. For example, Lam Phata S2 supported *Marchantia paleacea* and *Fossombronia cristula* under pH 7.3 and OC 1.61%. Similarly, Narian S2 exhibited a diverse combination of *Asterella khasyana*, *Hymenostylium recurvirostre*, and *Fissidens bryoides* at pH 7.5 and OC 1.61%.

Budhal S1–S3 displayed multiple co-dominant taxa including *Brachythecium salebrosum*, *Marchantia nepalensis*, and *Philonotis angusta*, corresponding with moderate to high nitrogen levels (1104–1105 mg/kg) and phosphorus (19.4–22.5 mg/kg).

Sites such as Manglamata S3, which exhibited lower organic carbon (0.55%), showed comparatively reduced species diversity, primarily dominated by *Plagiochasma appendiculatum*.

Table 3. Distribution of dominant bryophyte species across sampling sites in Rajouri District.

Site	Dominant Bryophyte Species
GDC Nowshera	*Plagiochasma appendiculatum*, *Hyophila rosea*
Manglamata S1–S3	*Plagiochasma appendiculatum*
Lam Phata S1 & S3	*Plagiochasma appendiculatum*
Lam Phata S2	*Marchantia paleacea*, *Fossombronia cristula*
Narian S2	*Asterella khasyana*, *Hymenostylium recurvirostre*, *Fissidens bryoides*
Narian S3	*Plagiochasma appendiculatum*
Dhoka S1	*Targionia indica*, *Bryoerythrophyllum recurvirostrum*
Dhoka S2	*Marchantia paleacea*
Darhal S1–S3	*Marchantia paleacea*, *Eurhynchium swartzii*

Darhal S4	*Marchantia paleacea*, *Eurhynchium swartzii*
Dabbar S1	*Semibarbula orientalis*, *Plagiochasma appendiculatum*
Dabbar S2	*Fissidens mittenii*, *Reboulia hemisphaerica*
Kakora S1	*Plagiochasma appendiculatum*
Kakora S2	*Pellia endiviifolia*, *Hageniella isopterygioides*
Kakora S3	*Asterella waryana*, *Bryum capillare*
Manjakote S1	*Eurhynchium muelleri*, *Pellia endiviifolia*
Manjakote S2	*Marchantia paleacea*
Manjakote S3	*Pellia endiviifolia*, *Fissidens grandifrons*
Manjakote S4	*Eurhynchium muelleri*
Chingus	*Asterella khasyana*, *Fissidens grandifrons*, *Plagiochasma appendiculatum*
Channi	*Dumortiera hirsuta*, *Asterella wallichiana*
BGSBU S1	*Plagiochasma appendiculatum*
BGSBU S2	*Ceratodon stenocarpus*
BGSBU S3	*Hymenostylium recurvirostrum*, *Athalamia pinguis*
BGSBU S4	*Ectropothecium ramuligerum*
BGSBU S5	*Isopterygium distichaceum*, *Plagiochasma appendiculatum*
BGSBU S6	*Plagiochasma appendiculatum*
BGSBU S7	*Bryum argenteum*
Kungra S1	*Targionia hypophylla*
Kungra S2	*Ceratodon purpureus*, *Athalamia pusilla*
Kungra S3	*Anisothecium molliculum*, *Barbula vinealis*
Kungra S4	*Plagiobryum zierii*, *Targionia hypophylla*, *Plagiochasma appendiculatum*
Kungra S5	*Targionia hypophylla*, *Barbula vinealis*
Peli S1	*Plagiochasma appendiculatum*
Peli S2	*Hymenostomum edentulum*
Peli S3	*Eurhynchium swartzii*, *Targionia hypophylla*
Peli S4	*Solenostoma fusiforme*
Jhulla S1	*Athalamia pusilla*, *Hageniella isopterygioides*, *Plagiochasma appendiculatum*
Jhulla S2	*Leucobryum* spp., *Fissidens lexitextus*
Budhal S1	*Brachythecium salebrosum*, *Marchantia nepalensis*
Budhal S2	*Haplodontium angustifolium*, *Marchantia nepalensis*
Budhal S3	*Philonotis angusta*, *Leptodontium handelii*
Budhal S4	*Brachythecium salebrosum*, *Haplodontium angustifolium*
Sodapani Ziarat	*Weissia controversa*, *Hymenostylium recurvirostre*, *Plagiochasma appendiculatum*

Minka	*Asterella blumiana*, *Ditrichum tortuloides*
Breri Nowshera	*Plagiochasma appendiculatum*
Mangalnar S1	*Eurhynchium swartzii*
Mangalnar S2	*Fissidens subpulchellus*
Palwal S1	*Fissidens griffithii*, *Plagiochasma appendiculatum*
Palwal S2	*Asterella blumiana*
Palwal S3	*Fissidens taxifolius*
Sunderbani S1–S2	*Plagiochasma appendiculatum*
Kalakote S1	*Hyophila rosea*, *Trichosteleum luxurians*, *Plagiochasma appendiculatum*
Kalakote S2	*Jungermannia vulcanicola*
Kalakote S3	*Asterella khasyana*, *Oxystegus cylindricus*
Brebi Kalakote	*Marchantia paleacea*, *Hydrogonium gracilentum*

3.4 Relationship Between Soil Parameters and Species Distribution

Sites characterized by slightly acidic pH (5.5–6.5), moderate organic carbon (>1.3%), and balanced nitrogen content generally supported higher bryophyte richness and mixed assemblages. In contrast, sites with relatively extreme values of EC or nutrient imbalance tended to show dominance of a limited number of tolerant species, particularly *Plagiochasma appendiculatum*.

Elevated EC values at BGSBU S1 and Palwal S3 did not eliminate bryophytes but were associated with reduced heterogeneity. Similarly, localized elevated copper at Darhal S4 (4.4 mg/kg) corresponded with fewer dominant taxa.

Overall, variation in soil pH, organic carbon, nitrogen, and micronutrient concentrations appeared to influence bryophyte distribution patterns across Rajouri District.

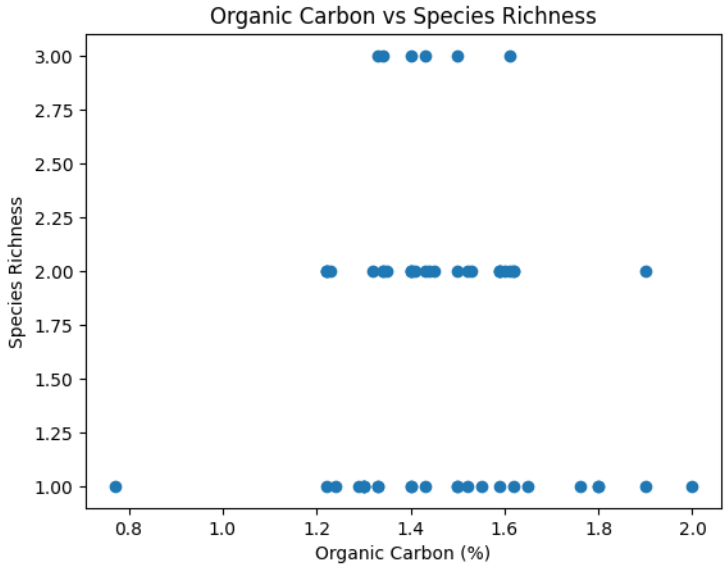

Figure 1. Relationship between soil organic carbon (%) and bryophyte species richness across sampling sites in Rajouri District, Jammu & Kashmir.

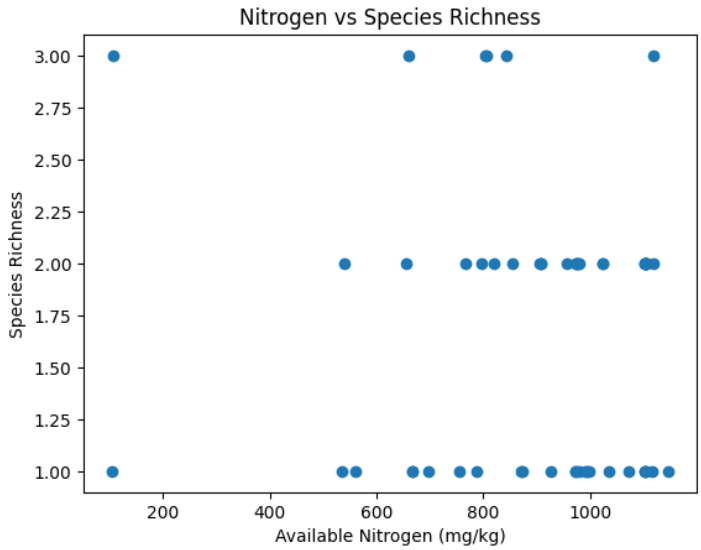

Figure 2. Scatter plot showing the relationship between available nitrogen (mg/kg) and bryophyte species richness across studied sites in Rajouri District.

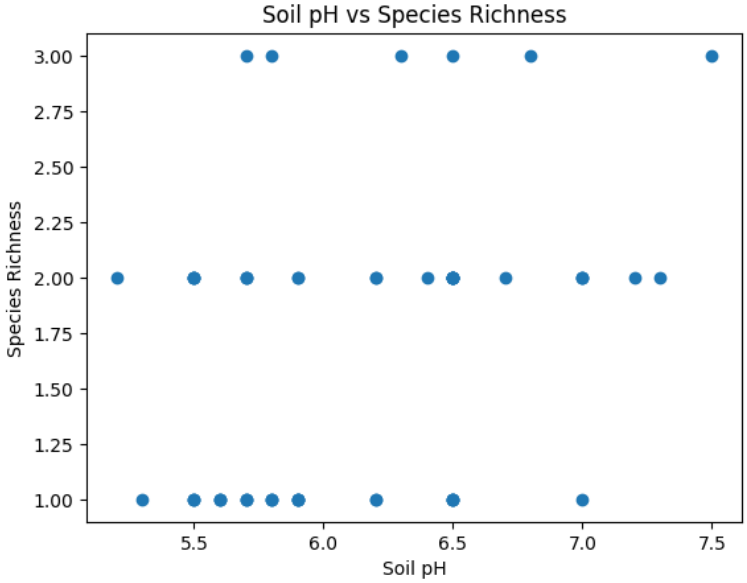

Figure 3. Relationship between soil pH and bryophyte species richness across different ecological sites in Rajouri District, Jammu & Kashmir.

Scatter plot analysis revealed a moderate positive association between organic carbon content and species richness, with sites exhibiting OC between 1.3–1.7% generally supporting higher bryophyte diversity (Figure 1). Available nitrogen showed a weak to moderate relationship with richness, where sites with nitrogen concentrations above 800 mg/kg often recorded two to three species per site, although no strictly linear trend was observed (Figure 2). Soil pH demonstrated that slightly acidic to near-neutral conditions (5.8–6.8) supported relatively higher richness, whereas more extreme values tended to correspond with lower species counts (Figure 3). Overall, the graphical analysis suggests that organic carbon and nitrogen exert a stronger influence on bryophyte distribution compared to pH within the studied range.

DISCUSSION

The present study revealed significant spatial heterogeneity in soil physicochemical properties across Rajouri District, which corresponded with variations in bryophyte richness and species composition. Slightly acidic to near-neutral soils (pH 5.5–6.8) supported comparatively higher species richness, as observed in

the scatter plot analysis. Similar findings have been reported by Pharo and Vitt (2018) and Singh et al. (2020), who demonstrated that mildly acidic soils enhance nutrient bioavailability and favor bryophyte colonization in temperate and montane ecosystems.

Organic carbon emerged as a key determinant of bryophyte diversity in the present study. Sites with organic carbon ranging between 1.3% and 1.7% generally exhibited higher species richness. Organic matter enhances soil structure, moisture retention, and microbial activity, thereby creating stable microhabitats suitable for bryophyte establishment. Recent studies by Wang et al. (2019) and Li et al. (2022) similarly reported positive associations between soil organic carbon and bryophyte abundance in forest ecosystems.

Available nitrogen showed considerable variation and displayed a moderate positive association with species richness. While sites with higher nitrogen levels often supported multiple species, the absence of a strong linear relationship suggests that nitrogen enrichment alone may not determine diversity patterns. According to Stevens et al. (2018) and Zhang et al. (2021), excessive nitrogen inputs may alter community composition rather than increase richness, indicating the importance of balanced nutrient availability.

Electrical conductivity values indicated predominantly non-saline conditions; however, sites with relatively elevated EC showed reduced heterogeneity. Moderate salinity tolerance observed in certain species such as *Plagiochasma appendiculatum* aligns with recent reports by González-Mancebo et al. (2019), who documented adaptive tolerance mechanisms in bryophytes under mild osmotic stress conditions.

Micronutrient concentrations (Zn, Fe, Mn, Cu) varied across sites but generally remained within ecologically acceptable limits. The persistence of bryophytes at sites with relatively higher copper concentrations suggests species-specific tolerance mechanisms. Recent research by Varela et al. (2020) and Di Palma et al. (2021) indicates that bryophytes possess metal-binding capabilities and cellular detoxification pathways that allow survival under moderate trace metal exposure.

The repeated dominance of *Plagiochasma appendiculatum* across diverse edaphic conditions highlights its ecological plasticity and adaptive capacity. Similar ecological amplitude in liverwort communities has been documented in Himalayan landscapes by Kumar and Rai (2019) and Joshi et al. (2022), where certain taxa demonstrated broad tolerance to soil variability.

Overall, the findings suggest that organic carbon and nitrogen availability exert stronger influence on bryophyte richness compared to pH variations within the observed range. Balanced nutrient status and moderate soil reaction appear to create optimal microhabitats for bryophyte establishment in montane environments. These observations reinforce the role of bryophytes as sensitive indicators of soil ecological status under varying edaphic conditions.

CONCLUSION

The present study revealed significant spatial variation in soil physicochemical properties across different sites of Rajouri District, which was reflected in bryophyte distribution patterns. Slightly acidic to near-neutral soils supported comparatively higher species richness. Organic carbon and nitrogen emerged as important factors influencing bryophyte occurrence, whereas electrical conductivity showed limited but noticeable effects at higher values. Micronutrient concentrations remained within ecologically tolerable limits and did not appear to severely restrict species presence. The widespread occurrence of *Plagiochasma appendiculatum* indicates broad ecological tolerance under varying edaphic conditions. Overall, the findings highlight the role of soil characteristics in shaping bryophyte community structure in montane ecosystems. These results support the ecological significance of bryophytes as indicators of soil environmental conditions.

Conflict of interest – None

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