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Phytosociological analysis and floristic composition of fabaceae species assessing human impact and edaphic variables

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The study of plant communities and their floristic composition provides a significant ecological insights, particularly into the extent and nuances of alterations in natural vegetation resulting from anthropogenic activities. This study aimed to verify the absence of anthropogenic influence on native flora by identifying the floristic composition and evaluating phytosociological characteristics in District Jhelum, Pakistan. Field surveys were conducted across various seasons during 2019–2020. A random vegetation sampling approach was used to establish ten sample plots (10 × 10 m²) at each of the 23 sites (73 stations). Three transects per site and three quadrats per transect were sampled, resulting in a total of 657 quadrats. A total of 32 species, belonging to the Fabaceae family were recorded, comprising 11 (34.4%) tree species, 16 (50%) herbaceous species, and 3 (11.5%) shrub species. The dominant species were *Dalbergia sissoo*, followed by *Neltuma juliflora* and *Acacia farnesiana*, while *Senna occidentalis* was identified as a rare species. Cluster analysis (CA) and two-way cluster analysis (TWCA) categorized the native vegetation into three distinct groups/associations. Vegetation group 1 included 26 stations and a total of 29 plant species. The dominant species of this group was *Neltuma juliflora* (344.1 ± 313.9), whereas the co-dominant was *Dalbergia sissoo* (319.7 ± 252.1). Group 2 contained 29 stations with 27 species, in which the leading species was *Acacia farnesiana* (676.4 ± 358.7), followed by *Neltuma juliflora* (673.3 ± 289.9). Group 3 comprised 19 stations with only six plant species. *Acacia nilotica* was dominant (749.9 ± 146.0) species of this group, followed by *Dalbergia sissoo* (669.0 ± 321.2), Canonical Correspondence Analysis (CCA) demonstrated that soil moisture (SM), soil phosphate (SP), phosphorus (P), and organic matter (OM) were key edaphic variables ($p > 0.05$), influencing species distribution and associations. This study provides a comprehensive sampling framework and emphasized the substantial relationship between edaphic factors and vegetation, highlighting the ecological importance of the family Fabaceae. These findings offer valuable insights for the restoration and conservation of native flora in the Jhelum region. However, to better understand regional biodiversity further in-depth studies covering a broader geographical area of the Jhelum region are required.

Keywords Fabaceae, Floristic composition, Edaphic variables, Multivariate analysis, Jhelum

Understanding plant community structure and its interaction with edaphic variables and anthropogenic influences is essential for assessing ecosystem resilience and adaptability. Phytosociology, a discipline that focuses on species composition, classification, and description, provides a framework for examining these dynamics[1–6]. By analyzing species composition and abundance, particularly the interactions between dominant and rare species, phytosociology offers valuable insights into biodiversity patterns and ecosystem stability. This

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approach integrates both biotic interactions and environmental factors to elucidate how plant communities organize and respond to their surroundings[1,7]. Phytosociological approaches are widely applied in vegetation mapping, biodiversity conservation, and the assessment of ecosystem services[8,9], making them essential tools in ecological research.

It is obvious that vegetation is not uniformly distributed around the globe, but rather follow various environmental and climatic gradients[10,11]. Environmental factors such as soil composition, species migration, habitat features, topography, hydrology, geology, plate tectonic activity, and many other biotic and abiotic factors have significant impact on plant species composition and distribution[12]. THe mosaics of species relationships in natural settings vary according to microenvironment and are shaped by a wide range of environmental parameters such as soil properties and canopy openness. Certain environmental factors allow for the coexistence of species with widely differing edaphic and light requirements, hence boosting the local biodiversity[13–15]. There are several biotic, abiotic, predictable and stochastic ecological variables that have significant influence on phytogeographical distribution of species in their natural environments[16]. One prominent theory demonstrating that how community assembly is environmental filtering, the process through which natural selection or environmental constraints exclude species that cannot survive in particular habitat condition.

Several ecological studies conducted across Pakistan have focused on the impact of environmental factors, particularly soil properties, topography, climate, and anthropogenic activities[12,17–19]. Soil properties, in particular, significantly influence species richness and diversity making them ecological indicators (EIs) of specific regions[12,20,21]. However, a variety of environmental variables such as precipitation, temperature, wind, and solar radiation significantly change with short distance and directly impact the species associations and distribution[22,23]. Owing to this, as plant species occur across in range of environmental conditions, they are often most abundant within their natural habitats, highlighting their distinctive ecological resilience[24]. As a result, distinct compositional units reflect the dynamic ecological conditions of specific regions. However, Jhelum remains underexplored in such ecological studies.

This study focuses on one of Pakistan's most significant plant families, Fabaceae, and examines the distribution of its in their native woodland habitats[1,3,5]. While prior studies have documented that the vegetation of the Jhelum region is strongly shaped by its unique local environment[25,26], a family-level phytosociological assessment particularly addressing species assemblages and their relationship with edaphic factors, lifeform, and leaf-size spectra has not yet been conducted in this region. Therefore, we hypothesized that species assemblages shift along the environmental gradient, influenced by a range of distinct climatic, physiographic, and edaphic variables. Keeping in view this hypothesis, this study aims to explore the diversity and species assemblages of the family Fabaceae along the environmental gradients of the study area. Consequently, this study addresses the following research questions: (i) How many Fabaceae dominated vegetation groups/associations, lifeforms, and diversity patterns exist in the study area? (ii) What are the key ecological indicator species of these groups? and (iii) How do edaphic factors influence the association and distribution of family Fabaceae species. We believe that the knowledge generated through this study will be fruitful for the sustainable management and conservation of family Fabaceae vegetation in the Jhelum region.

Methodology

Study area

Our study area (32°56′ N, and 73°44′ E) is located on the north bank of Jhelum River, on the Pothohar plateau of Punjab province of Pakistan (Fig. 1). The region reveals a wide altitudinal gradient ranging from 176 min the southeast to 965 m in the northwest[27], with an average altitude of approximately 250 m above sea level (a.s.l.). The climograph demonstrated that June, July and August are the hottest months, whereas January and December are the coldes(Fig. 1b). The highest precipitation was recorded in June (239 mm) and August (238 mm). Soils in the area may be classified into four major categories: loess, river alluvium, residual, and piedmont alluvium. The study area is a semi-arid to arid, desert and mild subtropical region[28]. It receives an average annual precipitation of 880 mm, with the majority of it falling in the region's north and northeast, and has average daily temperatures between 3 °C and 42 °C. A long history of human-caused deterioration and fragmentation of the region's forests from activities including deforestation, illicit logging, and overgrazing has left the region vulnerable to soil erosion and dwindling water supplies[28]. Vegetation covers the landscape in a patchwork pattern, and the amount of bare ground is growing. Several imported species, including *Broussonetia papyrifera* and *Eucalyptus camaldulensis*, coexist with native species, such as *Dalbergia sissoo*, *Morus alba*, and *Senegalia modesta*, as the most common trees.

Vegetation sampling and plant identification

A quantitative sampling of Fabaceae species was conducted across District Jhelum. The vegetation was sampled using the quadrat technique in combination with the line transect method[29,30]. The line transect method was utilized to present the spatial heterogeneity in species associationss and distributions and to systematically capture vegetation gradients across various topographic and edaphic variables[31,32]. Each transect provided a record of species occurrence and abundance along environmental gradients such as slope, altitude, and edaphic variables. This approach allowed for an accurate determination of species assemblage. A total of 73 stations were randomly selected. To represent all major habitat types, sampling was conducted at various altitudinal and climatic zones. In addition, to minimize spatial autocorrelation, we sampled each station at a distance of at least 5 km. At each sampling station, three transects were established, and data were obtained from three quadrats per transect, sustaining a uniform sampling intensity of 9 quadrats per sampling station, resulting in a total of 657 quadrats[33,34].Phytosociological attributes, including density, frequency, cover, relative values, and importance value index, were calculated[12,18]. Plant specimens were collected, labeled, air-dried at room temperature, and mounted on standard herbarium sheets[12]. Insecticides were applied to protect the plant specimens from pests.

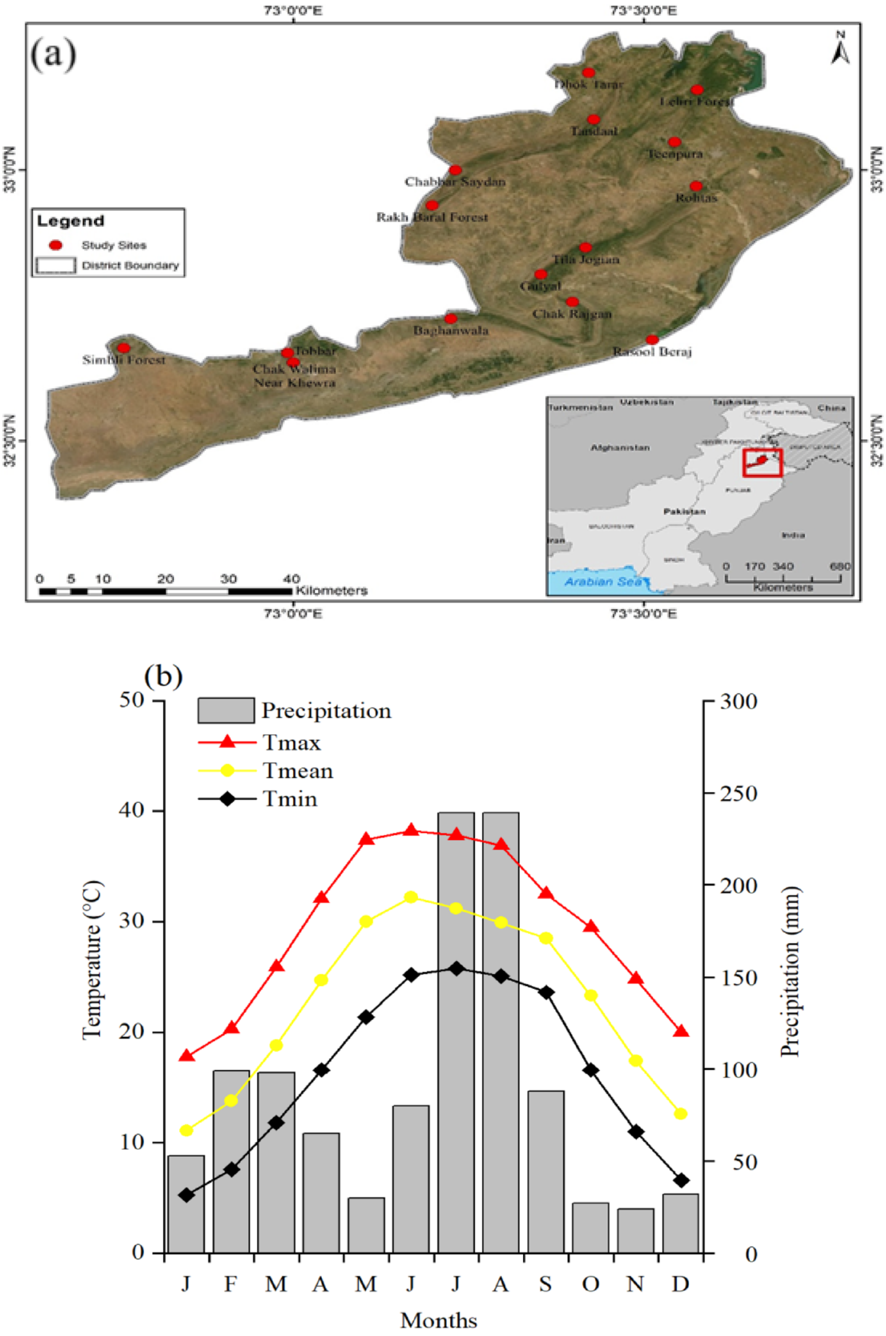

Fig. 1. (**a**) Map of study area showing the sampling stations from the Jhelum area of northern Punjab, Pakistan (This figure was generated using ArcMap ver. 10.8) (**b**) climograph of the study.

Geographic coordinates (longitude, latitude, and altitude) of each sampling station were recorded via Garmin eTrex-20X GPS device[12].

At each sampling station, 10 quadrats (1 m^2) were systematically applied to quantify the species composition, and phytosociological attributes such as frequency, density, and cover[35,36]. To ensure representative of all species confined in the sampling station the quadrats were taken at regular intervals. At each quadrate the covered area of each species was determined, following standard phytosociological approach[37,38]. Additionally, three soil samples were collected at a depth of 10–15 cm using a soil auger, combined into one composite sample, and stored in polyethylene bags[12]. Plant species were identified by Dr. Arshad Mahmood Khan, Assistant Professor, Department of Botany, Pir Mehr Ali Shah-Arid Agriculture University Murree Road, Rawalpindi through *Flora of Pakistan* (http://legacy.tropicos.org/Project/Pakistan)[39] (Ali and Nasir 1990), and verified using the *Plants of the World Online* database (https://powo.science.kew.org/). The voucher specimens were stored in the Herbarium of the Department of Botany, University of Gujrat, Pakistan, to serve as a reference for future plant identification.

Physico-chemical properties of soil

The physico-chemical properties of the collected soil samples, including soil moisture (SM), soil pH, saturation percentage (SP), electrical conductivity (EC), soil organic matter (OM), and calcium carbonate ($CaCO_3$), nitrogen (N), soil phosphorus (P), soil potassium (K) were analyzed in the laboratory of Botany, University of Gujrat. Soil organic matter (OM) was calculated with loss-on-ignition method at 550 °C via utilizing Furnace[40], whereas the percentage of carbon content was calculated with the protocol provided by Haq et al.., 2022[41].

$$\% \, of \, C \, \frac{S-T}{S} \times 4$$

Whereas S = blank reading, T = Volume of H_2SO_4 used.

Soil moisture (SM) and soil saturation following[42], and[43].

$$\% \, moisture = \frac{Wet \ soil - Dry \ soil}{Dry \ soil} \times 100$$

To determine soil pH, the obtained soil samples were mixed with an equal amount of distilled water (DW), after one-hour readings were recorded with Hanna Multiparameters (model HI9828). The electrical conductivity (EC) of the soil samples was measured after saturating the samples with DW, filtered, and the reading were recorded with electrical conductivity meter[44]. Calcium carbonate $CaCO_3$ was measured with the method of acid neutralization. The soil nitrogen was determined by using the Kjeldahl method, whereas the soil phosphorus (P), and Potassium (K) were quantified using Atomic Absorption Spectrophotometer (AAS) (model PG-990).

Data analysis

In order to determine the influence of edaphic variables on vegetation, the correlation between the analyzed variables — like soil moisture (SM), pH, soil potential (SP), electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K), organic matter (OM), and calcium carbonate ($CaCO_3$) and the vegetation cover of the collected species were analyzed. Based on presence-absence (0,1) data of 73 stations, and 32 species, the vegetation was classified into three distinct vegetation groups/zone[45]. For the determination of similarity index pattern of vegetation, we used Cluster analysis and two-way Cluster analysis (TWCA) by applying the Jaccard distance measure and Wards linkage method via PCORD V5[3,12]. The role of species in a group was determined by using Species richness (S), Species evenness (E), Shannon`s diversity index (H), and Simpson`s diversity index (D).

Results

A total of 32 plant species belong to Fabaceae family were obtained from the District Jhelum, Punjab. They vegetation comprised a total of 11 trees species (34.4% of the total flora), 16 herbs species (50%), and 3 shrub species (11.5%). Among all species, the dominant species was *Dalbergia sissoo*, (having mean cover of 492.7 ± 375.2), followed by *Neltuma juliflora* (401.1 ± 383.0), and *Acacia farnesiana*, (399.8 ± 302.5). The rare species was *Senna occidentalis* (2.2 ± 0.3). The species area curves (SAC) was extracted for determination of sample depth and the linked edaphic variables (Fig. 2). The SAC demonstrates the appearance of new species continuously from 8 to 35 in the sampling station.

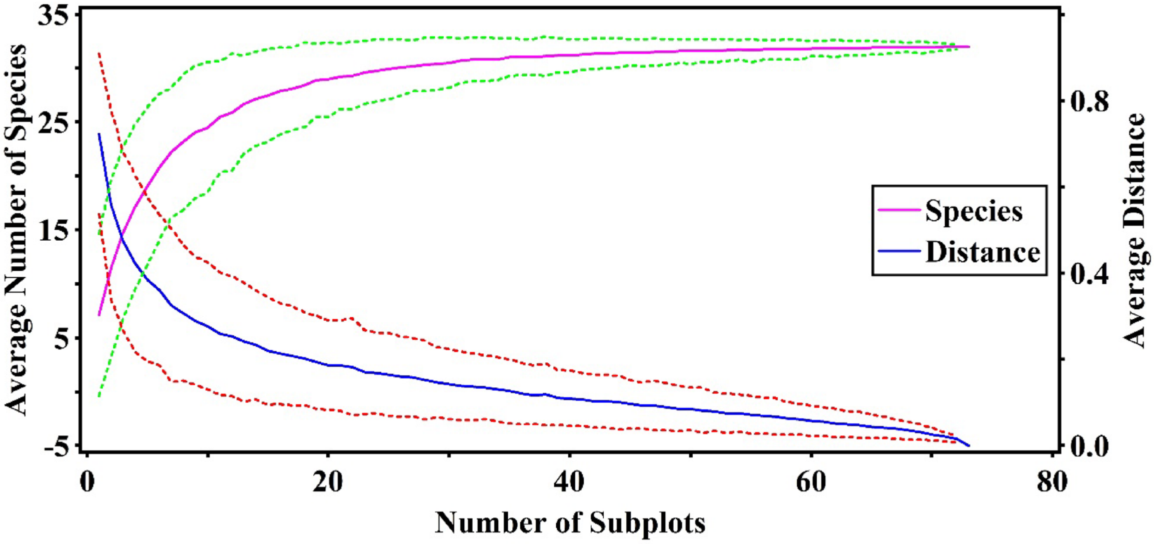

Fig. 2. Species area curve for the natural vegetation growing in the district Jhelum region of northern Punjab, Pakistan.

Cluster analysis (CA) and two-way cluster analysis (TWCA) of vegetation

Ward's CA and TWCA classified vegetation of sampling plots into three distinct ecological groups/zones, based on 75% information remaining via using Ward's linkage method and Jaccard Distance measure (Fig. 3). The TWCA further elaborate distribution of species at their specific sampling plot (Fig. 4). Details of each ecological group/zone are following.

Vegetation group 1

This vegetation group/zone comprised of 26 stations and hosted a total of 29 plant species (Figs. 3 and 4). The top three ecological indicator species (IS) of this group were *Parkinsonia aculeate*, *Ziziphus nummularia* and *Lathyrus aphaca.* The other characteristics individuals of this vegetation group were listed in Table 1. Among these species, the dominant species was *Neltuma juliflora* having mean cover area of (344.1 ± 313.9). However, indicator value of this species was low (17.4). The co-dominant species of this group were *Dalbergia sissoo* (319.7 ± 252.1) followed by *Senegalia catechu* (267.6 ± 246.3) (Table 1). The edaphic variables of this vegetation group reveal a mean soil moisture of 21.1 ± 10.0, slightly basic pH (7.9 ± 0.3), sandy loam (SP = 34.6 ± 6.7), moderate electrical conductivity, nitrogen, phosphorus, potassium, soil organic matter, and calcium carbonate (Table 2).

Vegetation group 2

The vegetation group 2 comprised of 29 stations with 27 plants species (Figs. 3 and 4). The top three IS of this vegetation group were *Acacia nilotica*, *Sesbania* concolor, and *Lathyrus pratensis* (Table 1). Though, the indicator value (IV) of *Sesbania concolor* is low (9.3), but it is still a representative of shrub (Table 1). Among 27 plants species, *Acacia farnesiana* was the leading species (676.4 ± 358.7) followed by *Neltuma juliflora* (673.3 ± 289.9), and *Senegalia modesta* (618.9 ± 438.9). The remaining plant species occupied less cover area (Table 1). The edaphic

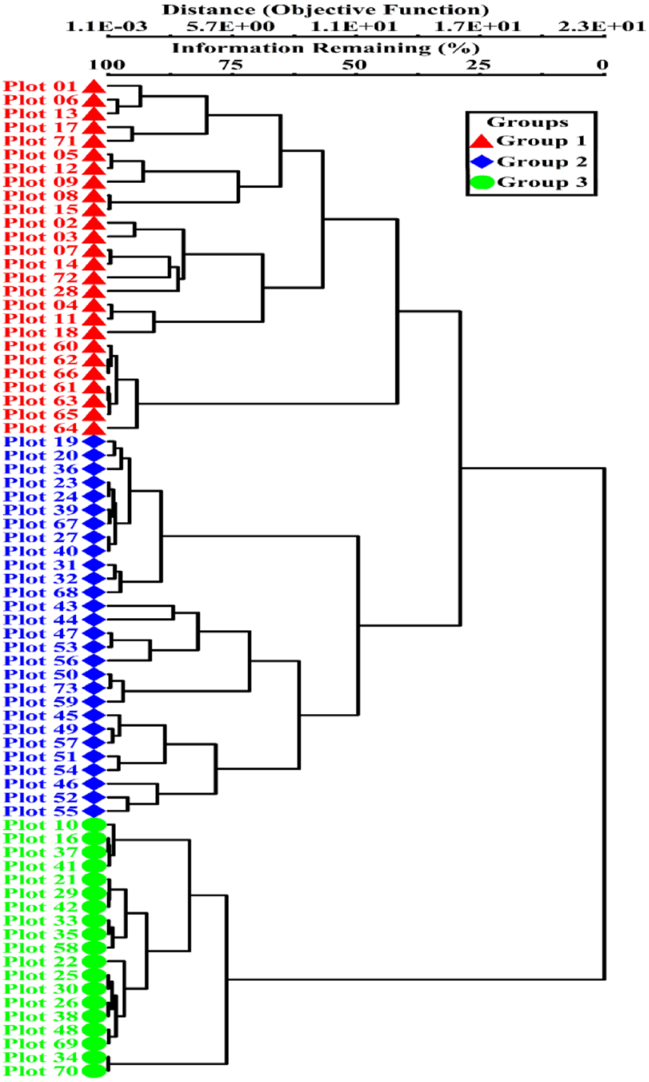

Fig. 3. Cluster analysis (CA) dendrogram via using Wards linkage method and Jaccard distance measurement, all the sampling plots were separated into three distinct vegetation groups/zones.

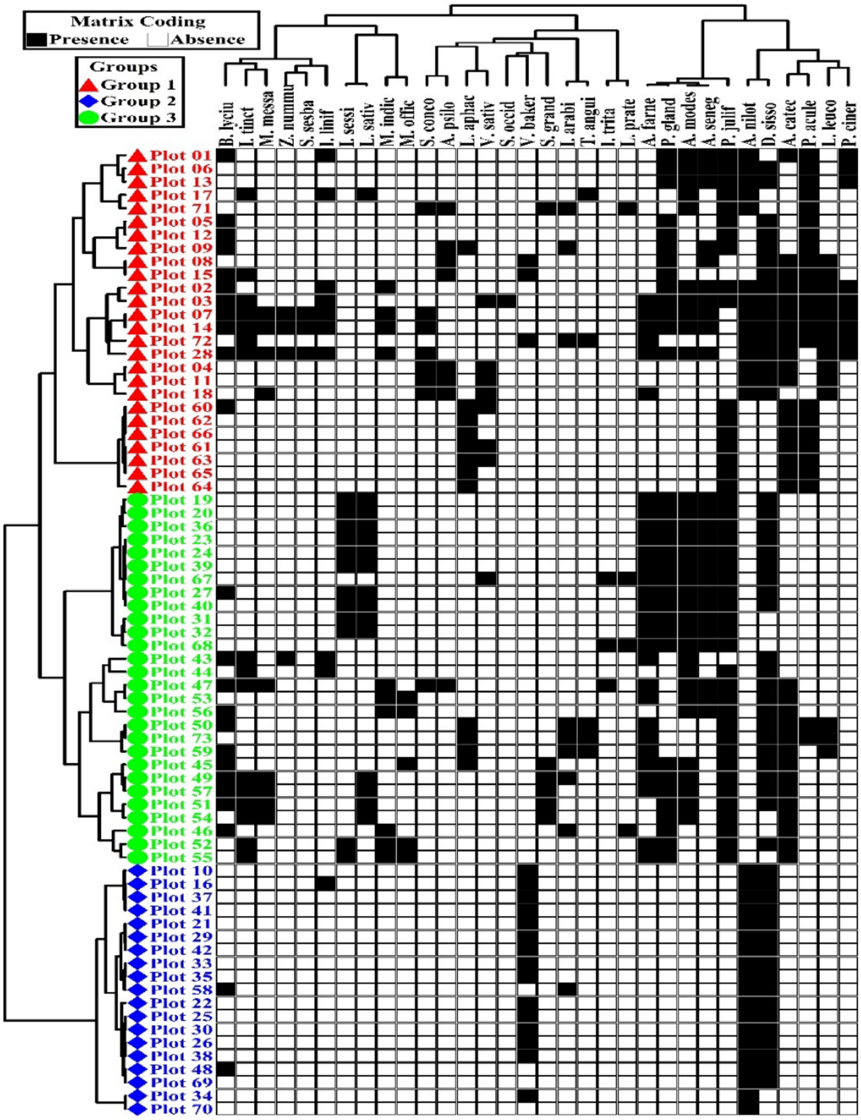

Fig. 4. Two-way cluster analysis (TWCA) demonstrates the distribution of natural vegetation in 73 sampling plots via using Ward's linkage methods and Jaccard Distance Measurements.

variables reveal lowest soil moisture (17.6 ± 5.7), basic pH (7.7 ± 1.5), and loam (31.9 ± 9.0). It possesses moderate electrical conductivity (2.3 ± 1.7), nitrogen (0.1 ± 0.0), phosphorus (4.0 ± 1.6), organic matter (0.6 ± 0.2), and calcium carbonate (2.3 ± 0.9). The potassium (148.3 ± 28.9) content of this group was higher than other groups (Table 2).

Vegetation group 3

This group possessed 19 stations, and only 6 plant species (Figs. 3 and 4). The top three ecological indicator species of this group were *Dalbergia sissoo*, *Berberis lycium*, and *Melilotus officinalis* (Table 1). Similar to group 2, the IV of *Berberis lycium* is low but still considered the indicator species because this was the only shrub restricted to this ecological zone. The dominant species of this group were *Acacia nilotica* (749.9 ± 146.0) followed by *Dalbergia sissoo* (669.0 ± 321.2), and *Vicia bakeri* (16.6 ± 9.5). The remaining plants species were *Berberis lycium*, *Indigofera linifolia*, and *Indigofera arabica*, which occupied the lowest cover area. The edaphic variables demonstrated comparatively good soil moisture (20.9 ± 8.7), basic pH (8.0 ± 0.2), and loam (34.9 ± 4.7), whereas moderate electrical conductivity (2.7 ± 3.3), nitrogen (0.1 ± 0.0), phosphorus (4.4 ± 1.2), potassium (148.4 ± 30.6), soil organic matter (0.6 ± 0.1), and calcium carbonate (2.3 ± 0.6) (Table 2).

Ordination of vegetation

The NMS ordination clearly separated the group obtained through CA and TWCA. Group 1 was spread over the right side of the ordination plane (Fig. 5). A few stations of this group intermix with group 2, which was restricted to the lower left site of the ordination plane. Most station of the group 3 were spread upper-right portion of the ordination plane, however, a few station were also extend to site of the ordination diagram.

Voucher ID	Name of species	Max groups	IV	F-values	*p*-values	Group 1 (Mean ± S.D)	Group 2 (Mean ± S.D)	Group 3 (Mean ± S.D)	Overall (Mean ± SD)
840/MM//2020	Berberis lycium (*Royle*)	42	7	6.2	0.996	32.9 ± 29.8	27.8 ± 14.6	6.5 ± 2.1	28.1 ± 15.3
849/MM//2020	*Indigofera tinctoria* L.	22	36.8	6.2	0.051	27.9 ± 22.8	36.2 ± 23.1	–	29.6 ± 14.4
620/MM//2020	Sesbania concolor J.B.Gillett	15	9.3	18.2	0.887	20.5 ± 15.3	8.2 ± 1.6	–	14.1 ± 4.3
612/MM//2020	Ziziphus nummularia (Burm. f.) Wight. & Arn.	22	20.2	17.5	0.445	10.0 ± 5.7	14.8 ± 2.9	–	13.4 ± 3.1
882/MM//2020	*Astragalus psilocentros* Fisch.	18	4.6	17.4	0.999	32.9 ± 8.9	2.6 ± 0.5	–	25.7 ± 8.2
714/MM//2020	*Indigofera linifolia* (L.f.) Retz.	22	57.6	13.2	0.014	9.7 ± 3.5	5.3 ± 1.3	1.6 ± 0.4	8.2 ± 2.9
646/MM//2020	*Indigofera arabica* Jaub. & Spach	14	9	3.0	0.892	10.2 ± 7.4	16.0 ± 6.5	1.6 ± 0.4	13.4 ± 4.1
759/MM//2020	*Indigofera sessiliflora DC.*	17	9.3	6.2	0.933	–	13.1 ± 10.9	–	9.7 ± 4.2
680/MM//2020	*Indigofera trita* L.f.	17	6.9	11.9	0.948	–	5.5 ± 1.9	–	3.5 ± 0.7
844/MM//2020	Lathyrus aphaca L.	42	43.2	38.6	0.047	19.8 ± 11.9	10.9 ± 4.2	–	15.9 ± 6.7
572/MM//2020	*Lathyrus sativus* L.	17	10.6	10.3	0.746	2.9 ± 1.8	14.6 ± 13.7	–	11.5 ± 5.6
818/MM//2020	Lathyrus pratensis L.	16	25.1	4.0	0.333	2.5 ± 1.5	6.4 ± 2.2	–	5.7 ± 1.3
754/MM//2020	*Melilotus indicus* (L.) All.	22	16.1	4.9	0.472	4.8 ± 2.7	9.6 ± 4.7	–	7.4 ± 2.8
600/MM//2020	*Melilotus officinalis* (L.) Pall.	14	23	13.1	0.361	–	10.5 ± 4.7	–	6.9 ± 1.8
790/MM//2020	*Melilotus messanensis* (L.) All.	12	14.1	21.5	0.608	6.2 ± 3.7	13.8 ± 6.1	–	10.3 ± 3.6
576/MM//2020	*Senna occidentalis* (L.) Link	13	20	36.0	0.421	3.7 ± 1.4	–	–	2.2 ± 0.3
568/MM//2020	*Trigonella anguina* Delile	14	11.9	8.3	0.686	7.7 ± 4.1	10.7 ± 3.6	–	8.2 ± 2.2
767/MM//2020	*Vicia sativa* L.	42	22	14.8	0.318	21.8 ± 16.7	5.8 ± 1.1	–	14.5 ± 4.5
549/MM//2020	*Vicia bakeri* Ali	12	14.3	2.4	0.410	2.6 ± 4.4	–	16.6 ± 9.5	9.0 ± 4.9
851/MM//2020	*Vachellia farnesiana* (L.) Willd	14	12.2	9.5	0.751	231.2 ± 185.7	676.4 ± 358.7		399.8 ± 302.5
783/MM//2020	Vachellia nilotica (L.) Delile	32	25.3	3.8	0.051	223.3 ± 161.9	–	749.9 ± 146.0	346.3 ± 278.5
514/MM//2020	*Senegalia catechu* (L.f.) Willd	42	18	26.8	0.394	267.6 ± 246.3	404.1 ± 393.8	–	339.9 ± 265.7
827/MM//2020	*Senegalia modesta* Wall.	16	15.4	17.7	0.575	263.4 ± 209.7	618.9 ± 438.9	–	412.4 ± 295.5
618/MM//2020	*Senegalia senegal* (L.) Willd	16	15.1	11.6	0.492	200.9 ± 162.0	489.9 ± 473.3	–	385.7 ± 226.6
695/MM//2020	Dalbergia sissoo DC	32	20.7	8.5	0.006	319.7 ± 252.1	571.0 ± 357.2	669.0 ± 321.2	492.7 ± 375.2
550/MM//2020	*Leucaena leucocephala* (Lam.) de Wit	18	10.2	20.6	0.867	185.5 ± 158.4	238.0 ± 79.9	–	192.5 ± 77.1
667/MM//2020	*Parkinsonia aculeata* L.	42	25.8	15.9	0.137	294.6 ± 227.4	169.2 ± 46.9	–	308.5 ± 197.0
745/MM//2020	*Prosopis cineraria* (L.) Druce	22	7.6	18.4	0.945	177.1 ± 139.7	–	–	118.0 ± 37.6
886/MM//20	*Neltuma glandulosa* Torr	16	12.6	9.1	0.748	154.8 ± 109.1	600.8 ± 405.8	–	379.6 ± 268.5
547/MM//2020	Neltuma juliflora (Sw.) DC.	42	17.4	21.2	0.309	344.1 ± 313.9	673.3 ± 289.9	–	401.1 ± 383.0
581/MM//2020	*Sesbania sesban* (L.) Merr.	12	17.3	37.7	0.418	68.1 ± 32.1	–	–	41.9 ± 6.5
607/MM//2020	Sesbania *grandiflora* (L.) Pers.	20	10.2	28.0	0.852	134.8 ± 51.9	297.1 ± 136.4	–	211.0 ± 61.9

Table 1. Variation of vegetation of the groups extracted by ward's cluster analysis, and their statistical feature from the district Jhelum region of Northern Punjab, Pakistan.

	Group 1 (Mean ± S.D)	Group 2 (Mean ± S.D)	Group 3 (Mean ± S.D)	Overall (Mean ± S.D)	F-values	*p*-values
SM	21.1 ± 10.0	17.6 ± 5.7	20.9 ± 8.7	18.4 ± 7.4	54.4841	0.997***
pH	7.9 ± 0.3	7.7 ± 1.5	8.0 ± 0.2	7.8 ± 1.1	47.3673	0.074
SP	34.6 ± 6.7	31.9 ± 9.0	34.9 ± 4.7	33.2 ± 7.7	53.4907	0.364**
EC	2.2 ± 1.3	2.3 ± 1.7	2.7 ± 3.3	2.4 ± 1.9	34.5183	0.101
N	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	51.1172	0.011
P	4.1 ± 1.4	4.0 ± 1.6	4.4 ± 1.2	4.1 ± 1.5	42.6716	0.264*
K	138.9 ± 34.3	149.3 ± 28.9	148.4 ± 30.6	141.7 ± 35.3	73.2244	-0.032
OM	0.6 ± 0.2	0.6 ± 0.2	0.5 ± 0.1	0.6 ± 0.2	51.2828	0.20*
Caco3	2.5 ± 0.9	2.3 ± 0.9	2.3 ± 0.6	2.4 ± 0.9	49.8425	0.021

Table 2. Variation in environmental variables of the vegetation groups/zone obtained by ward's cluster analysis, and their statistical features.

The relationship of vegetation with edaphic variables, we applied CCA ordination biplot (Fig. 6). The results revealed a total of 2.485% variance for CCA ordination axes ($F = 0.911$, $p > 0.05$) (Table 3). The first axis of CCA ordination define a significant positive correlation with the soil moisture ($r = 0.692$, $p > 0.05$), and soil organic matter ($r = 0.447$, $p > 0.05$) (Fig. 7). The CCA ordination axis 2 explained a significant negative correlation with

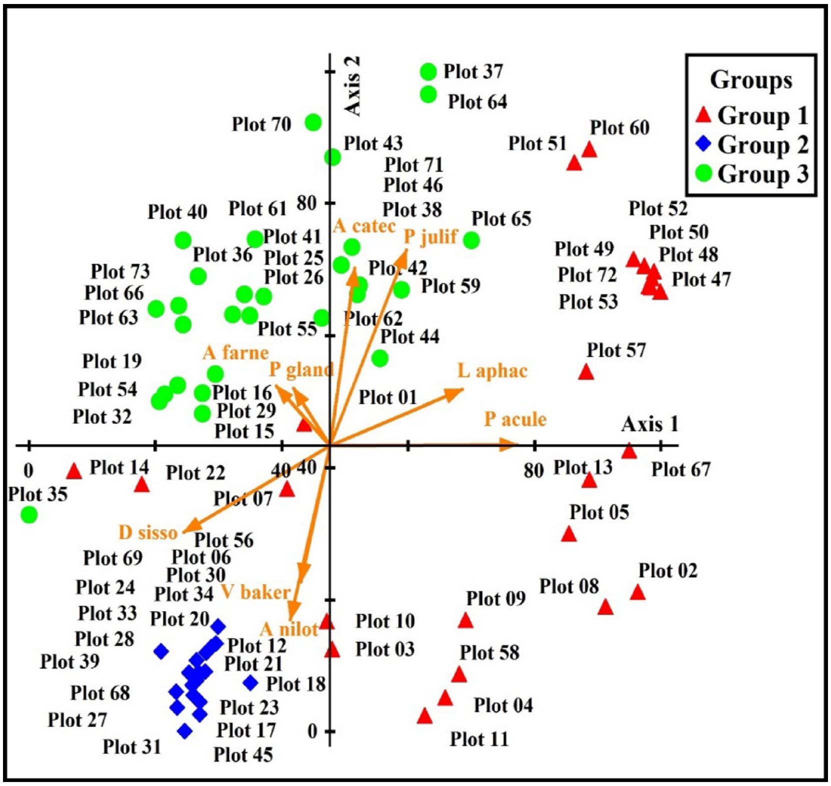

Fig. 5. NMS ordination biplot derived through distribution of natural vegetation with respect to their sampling stations and environmental variables. The groups obtained through Ward's CA were superimposed on NMS ordination biplot.

some of the edaphic variables such as SP (r = -0.344, $p > 0.05$), P (r = -0.594, $p > 0.05$), and K (r = -0.452, $p > 0.05$) (Fig. 7). Further, CCA ordination axis 3 shows significant positive ($r = 0.653$, $p > 0.05$), and negative correlation (r = -0.359, $p > 0.05$) with N and OM respectively. The CCA biplot demonstrated that edaphic variable significantly affects the vegetation zone/association (Fig. 7).

Habitat, life-form, leaf size spectra, biogeographical and conservation status and diversity characteristic of vegetation

The attributes of the collected plant species including Habitat, life cycle, season, phenology, lifeform, and leaf size spectra are shown in Table 4. Most of the species were trees, followed by herb and shrub. The abundant lifeform was Megaphanerophyte, whereas Nanophanerophyte and Liana were the rare lifeform in the study area. Leaf size spectra of plant species demonstrated that Nanophyll are the dominant species, followed by Leptophyll and Microphyll.

Most species were native or invasive, whereas some were introduced (Table 4). Species such as *Indigofera tinctoria* and *Melilotus officinalis* were neutralized, while *Lathyrus sativus* was Non-native. Out of 32 species, 15 species were classified as least concerned. Species such as *Berberis lycium*, *Indigofera trita*, *Lathyrus aphaca*, *Sesbania concolor*, and *Senegalia senegal* were threatened, whereas *Dalbergia sissoo*, *Lathyrus pratensis*, *Vachellia nilotica*, were near to threatened. Some of the species including *Astragalus psilocentros*, *Prosopis cineraria*, and *Senegalia catechu* were categorized as vulnerable, while *Indigofera tinctoria*, and *Senegalia modesta* were endangered. The rate of species richness was high for *Dalbergia sissoo (*55%) *and Neltuma juliflora* (44). Species evenness (E) of *Sesbania grandiflora* was high (0.99) compared to other species. Among the recorded species (Tables 1 and 4), some of the species like *Acacia nilotica*, *Albizia lebbeck*, *Dalbergia sissoo*, *Melilotus indicus*, and *Medicago sativa* widely used as an ethnomedicinal and pharmacological purposes in local traditional healthcare systems. However, additional research is required for more clarification.

Discussion

Vegetation refers to the collective community of plant species coexisting within a geographic region, characterized by distinct morphological, physiological, and ecological traits. These communities respond dynamically to environmental gradients, forming diverse biomes with unique structural and floral characteristics. In this study, a total of 32 plant species belonging to the family Fabaceae were documented from the Jhelum region. The ecological data revealed that herbs comprised 50% of the recorded species, followed by trees (34.4%) and shrubs (11.5%). Herbaceous species were the most abundant and exhibited the highest cover across the region, followed by trees and shrubs. Previous studies indicate that species distribution and community structure are significantly

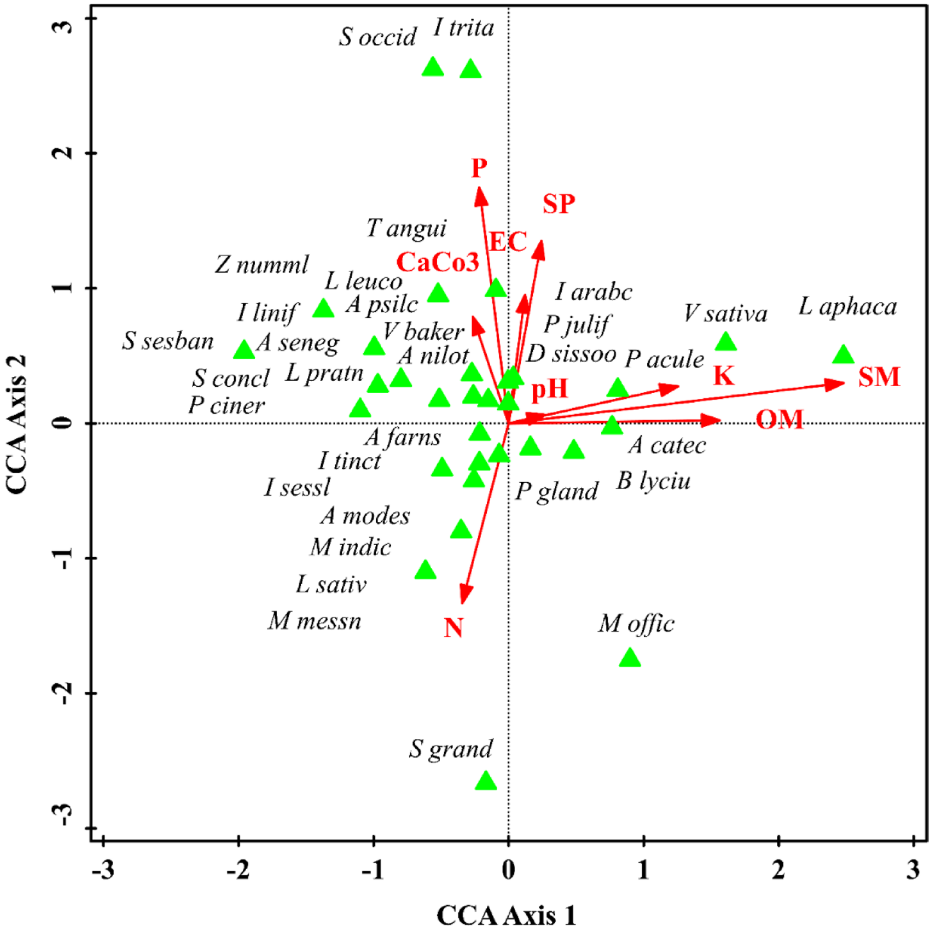

Fig. 6. CCA ordination biplot reveals the distribution of natural vegetation with respect to the environmental variables.

Axes	1	2	3	4
Eigenvalues	0.136	0.126	0.048	0.035
Species-environment correlations	0.699	0.588	0.460	0.462
Cumulative percentage variance of species data	5.5	8.3	10.3	11.7
Cumulative percentage variance of species-environment relation	38.5	58.5	72.1	81.8
Sum of all eigenvalues				2.485
Sum of all canonical eigenvalues				0.3542
Test of significance of first canonical axis			Test of significance of all canonical axes	
Eigenvalue	0.136		Trace	0.345
F-ratio	0.911		*F*-ratio	1.164
P-value	0.598		*P*-value	0.138

Table 3. Summary of vegetation-environmental variables association of CCA analysis.

influenced by edaphic characteristics, and altitudinal gradients[78,79]. The relationship between physicochemical variables and vegetation observed in this study aligns with the findings from previous research[45]. In addition, studies highlight physicochemical factors facilitating plant coexistence and species distribution[12,80]. Furthermore, physicochemical variables impacting plant growth contribute to a thinning of vegetation cover at higher elevations, which has not been explored in our study area.

Ward's agglomerative cluster analysis classified the vegetation of our study area into four distinct groups/associations. Vegetation Group 2 was the largest, comprising 29 stations, followed by Vegetation Group 1, which included 26 stations. The highest number of species was recorded in Group 3, while Group 2 had the lowest species count. Among the 32 species, *Neltuma juliflora* was the dominant species in Group 1, whereas

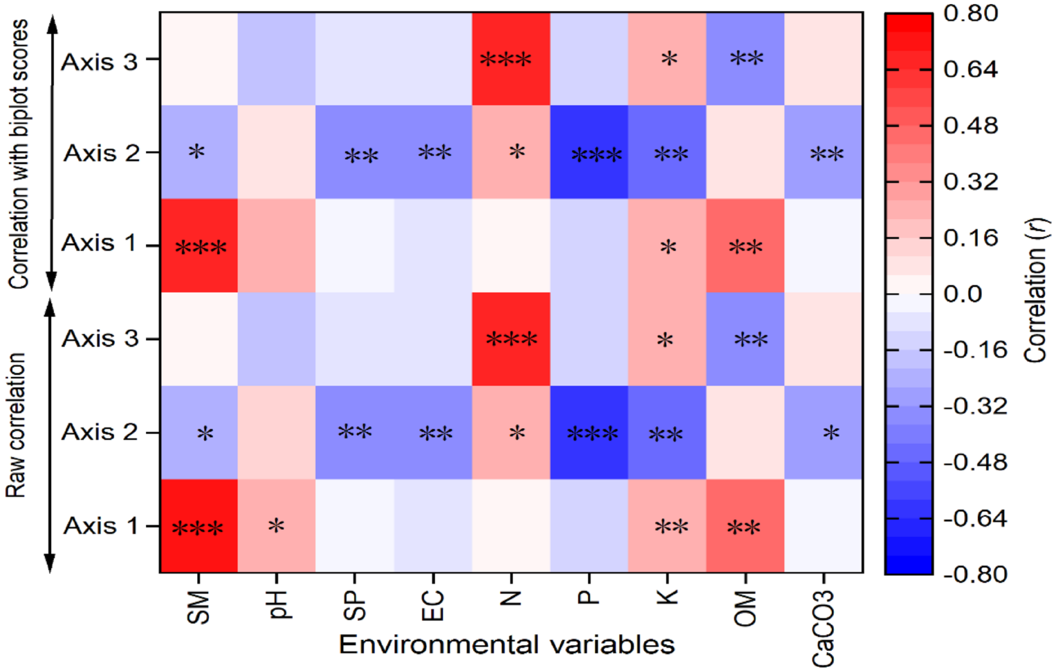

Fig. 7. Heat map showing raw correlations and correlations with biplot scores obtained through the environmental-vegetation relationship using CCA analysis. Symbols (*), (**), and (***) represent significance levels at 95% ($p < 0.05$), 99% ($p < 0.01$), and 99.9% ($p < 0.001$) confidence intervals, respectively.

Senna occidentalis was the rarest. In Group 2, *Acacia nilotica* dominated, while *Indigofera linifolia* and *Indigofera arabica* were rare. Similarly, *Dalbergia sissoo* was the dominant species in Group 3, and *Senna occidentalis* was again identified as a rare species. The Pearson's correlation analysis of plant cover revealed a significant positive correlation with soil moisture (SM), soil potential (SP), phosphorus (P), and organic matter (OM). A study conducted in district Jhelum, Pothohar Plateau ranges documented 291 species[28]. Their study demonstrated that soil manganese, available potassium, available phosphorus, zinc, lead, and solar aspect significantly influenced species distribution and associations. Compared to their findings, our sampling sites are located in a drier region, which may explain the lower species count in our study area. Additionally, an environment-vegetation study conducted in the Gorakh Hills reported even fewer species (74 in total) due to the study area's harsher environmental conditions[81]. The drier conditions of our sampling area likely contributed to the lower diversity of plant species.

It is evident that environmental variables have a significant influence on vegetation dynamics in arid and semi-arid regions of Pakistan[3,17,19]. Our analysis revealed distinct soil characteristics among the three groups. Group 1 showed the highest soil moisture (SM) content (21.1 ± 10.0) and $CaCO_3$ concentration (2.5 ± 0.9), while its electrical conductivity (EC) was comparatively lower (2.2 ± 1.3). In contrast, Group 2 demonstrated the highest potassium (K) content (149.3 ± 28.9) and the lowest pH (7.7 ± 1.5). Group 3 was characterized by higher pH (8.0 ± 0.2), EC (2.7 ± 3.3), and phosphorus (P) content (4.4 ± 1.2), but lower organic matter content (0.5 ± 0.1). The indicator species (IS) analysis revealed the influence of edaphic factors on plant communities. In Group 1, *Parkinsonia aculeata*, *Ziziphus nummularia*, and *Lathyrus aphaca* were associated with higher SM and $CaCO_3$ content. Group 2 species, including *Acacia nilotica*, *Sesbania concolor*, and *Lathyrus pratensis* showed interaction with elevated potassium levels. Meanwhile, *Dalbergia sissoo*, *Berberis lycium*, and *Melilotus officinalis* in Group 3 were associated with higher pH, EC, and phosphorus content. In our study area, anthropogenic and overgrazing pressures are higher compared to the higher elevation regions of Pothohar Plateau[28]. This observation aligns with the results of[82], who reported that vegetation growing at lower elevations tends to face higher grazing pressure due to proximity and accessibility to grazing livestock. In addition, our study also indicates the significance of soil disturbance on species associationss, distributions, cover, growth, and regeneration potential. Human-induced disturbances in the study area, such as land use changes, overgrazing, urbanization, and improper agricultural practices further degraded soil quality, resulting in diminished plant cover and regeneration capacity of vegetation[25,27,83]. These disturbances emphasize the need for sustainable land management practices to conserve vegetation and soil health in arid and semi-arid regions.

The Canonical Correspondence Analysis (CCA) ordination biplot further confirmed the influence of edaphic variables such as SM, SP, EC, N, P, K, OM, and $CaCO_3$ on species associationss and distributions of family Fabaceae vegetation. Nutrient availability (N, P, K) significantly influence growth and development of plants[12], whereas low OM reflect soil degradation from continuous socioeconomic disturbance. These findings align with previous studies highlighting the role of edaphic variables in shaping vegetation structure and dynamics in arid and semi-arid environments[3,12,18,19]. Soil moisture and potential enhance water availability, while EC promotes salt-tolerant species. Similarly, soil nutrients like N, P, and K are crucial for plant productivity and root

Species		Habitat	Life Cycle	Season	Phenology	Life form	L.S spectra	Biogeographical status	Conservation status	References	S	E	H	D
1. 1	*Berberis lycium*	T	Perennial	Spring	Mar-Apr	Megaphanerophyte	Microphyll	Native	Threatened	46	24	0.93	2.95	0.94
2. 2	*Indigofera tinctoria*	S	Annual	Summer	Nov-Dec	Nanophanerophyte	Microphyll	Neutralized	Endangered	47	16	0.97	2.70	0.93
3. 3	*Sesbania concolor*	S	Perennial	Monsoon	Aug-Sep	Nanophanerophyte	Nanophyll	Introduced	Threatened	48	8	0.94	1.96	0.84
4. 4	*Ziziphus nummularia*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Nanophyll	Native	Least Concern	49	4	0.98	1.36	0.74
5. 5	*Astragalus psilocentros*	H	Annual	Monsoon	Aug-Sep	Therophyte	Leptophyll	Native	Vulnerable	50	8	0.95	1.98	0.85
6. 6	*Indigofera linifolia*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Native	Least Concern	51	10	0.95	2.19	0.88
7. 7	*Indigofera arabica*	H	Annual	Spring	Mar-Apr	Therophyte	Leptophyll	Native	Data Deficient	52	9	0.89	1.94	0.84
8. 8	*Indigofera sessiliflora*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Native	Not Evaluated	53	12	0.99	2.46	0.91
9. 9	*Indigofera trita*	H	Annual	Spring	Feb-Mar	Therophyte	Leptophyll	Native	Threatened	54	3	0.98	1.07	0.65
10. 10	*Lathyrus aphaca*	H	Annual	Monsoon	Sep-Oct	Therophyte	Nanophyll	Native	Threatened	55	12	0.98	2.44	0.91
11. 11	*Lathyrus sativus*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Non-native	Least Concern	56	15	0.99	2.68	0.93
12. 12	*Lathyrus pratensis*	H	Annual	Spring	Mar-Apr	Liana	Nanophyll	Invassive	Near Threatened	57	4	0.97	1.35	0.73
13. 13	*Melilotus indicus*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Invassive	Least Concern	58	10	0.98	2.26	0.89
14. 14	*Melilotus officinalis*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Neutralized	Least Concern	59	5	0.98	1.57	0.78
15. 15	*Melilotus messanensis*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Introduced	Data Deficient	60	9	0.97	2.14	0.88
16. 16	*Senna occidentalis*	H	Annual	Spring	Mar-Apr	Therophyte	Leptophyll	Invassive	Least Concern	61	1	0.00	0.00	0.00
17. 17	*Trigonella anguina*	H	Annual	Spring	Mar-Apr	Therophyte	Microphyll	Native	Least Concern	62	5	0.99	1.59	0.79
18. 18	*Vicia sativa*	H	Annual	Spring	Mar-Apr	Therophyte	Nanophyll	Invassive	Least Concern	63	8	0.94	1.95	0.84
19. 19	*Vicia bakeri*	H	Annual	Monsoon	Aug-Sep	Therophyte	Nanophyll	Invassive	Data Deficient	64	18	0.99	2.85	0.94
20. 20	*Vachellia farnesiana*	T	Annual Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Leptophyll	Introduced	Least Concern	65	29	0.99	3.33	0.96
21. 21	*Vachellia nilotica*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Leptophyll	Invassive	Near Threatened	66	33	0.98	3.42	0.97
22. 22	*Senegalia catechu*	T	Perennial	Summer	July-Aug	Megaphanerophyt,	Microphyll	Native	Vulnerable	67	32	0.98	3.38	0.96
23. 23	*Senegalia modesta*	T	Perennial	Monsoon	Mar-Apr	Megaphanerophyt,	Nanophyll	Invassive	Endangered	68	32	0.96	3.32	0.96
24. 24	*Senegalia senegal*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Microphyll	Native	Threatened	69		0.95	3.04	0.95
25. 25	*Dalbergia sissoo*	T	Perennial	Spring	April-May	Megaphanerophyt,	Microphyll	Native	Near Threatened	70	55	0.97	3.90	0.98
26. 26	*Leucaena leucocephala*	T	Perennial	Spring	Mar-Apr	Megaphanerophyt,	Microphyll	Invassive	Least Concern	71	14	0.93	2.45	0.90
27. 27	*Parkinsonia aculeata*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Nanophyll	Invassive	Least Concern	72	24	0.98	3.11	0.95
28. 28	*Prosopis cineraria*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Nanophyll	Native	Vulnerable	73	9	0.93	2.04	0.85
29. 29	*Neltuma glandulosa*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Leptophyll	Invassive	Least Concern	74	33	0.94	3.29	0.96
30. 30	*Neltuma juliflora*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Nanophyll	Invassive	Least Concern	75	44	0.98	3.70	0.97
31. 31	*Sesbania sesban*	T	Perennial	Monsoon	Aug-Sep	Megaphanerophyt,	Leptophyll	Introduced	Least Concern	76	3	0.68	0.75	0.42
32. 32	Sesbania *grandiflora*	T	Perennial	Winter	Nov-Dec	Megaphanerophyt,	Nanophyll	Invassive	Least Concern	77	6	0.99	1.78	0.83

Table 4. Habitat, life cycle, phenology, life form, leaf size spectra, biological status, conservation status, and diversity characteristics of species characteristics from the district Jhelum region, Northern Punjab, Pakistan. S.D = Standard deviation, S = Species richness, E = Species evenness, H = Shannon`s diversity index, D = Simpson`s diversity index, - indicate absence of species, Bio status = Biogeographical Status, Conservation Status. For more detail table first are referred.

development, shaping species associations. Organic matter favors soil fertility and microbial activity; however, its reduced with anthropogenic disturbance, affecting regeneration. High $CaCO_3$ promotes the growth of plant species adapted to calcareous soils. These findings highlight the role of edaphic variables on species associations and distribution, as described by previous researchers[84–87], highlighting the significance of sustainable soil management for biodiversity and ecological integrity.

Studies have evidenced that environmental gradients and vegetation traits co-regulate species associations and distribution[23,88,89]. Research conducted in the Eastern Tianshan Mountains revealed that species spatial distribution and growth are substantially influenced by topographic variables such as elevation and slope[90]. Comparable studies from mountain ecosystems show that floristic composition, life-form structure, and species assemblages often change predictably along environmental gradients due to environmental filtering, with soil properties and disturbance regimes acting as strong drivers of community organization. Recent Himalayan vegetation studies further demonstrate that such gradients can shape not only overall diversity patterns but also the distribution of conservation-relevant and 'high-value' taxa (e.g., rare, threatened, or socio-economically important plant elements) under increasing anthropogenic pressure[91–94]. Likewise, environmental variables also have a significant impact on species associations and distribution[95]. Similarly, lifeform, leaf morphology and anatomical traits are critical adaptive features that regulate species distribution and association under varying climate and edaphic variables[96,97]. The differences in species distribution, association, and lifeform are therefore attributed to variation in edaphic variables.

The ecological attribute of flora, including habit, life-form, leaf size spectra provide valuable insights into the eco-physiological developments of plants communities to climatic conditions[24,98]. In this study, the collected plant species were categorized into four Raunkiaer life-form classes. The results showed that Megaphanerophytes were the dominant life-form followed by Therophytes, Nanophanerophytes, and Lianas. Similarly, the leaf size spectra classified vegetation into three categories, where the Nanophyll were dominant, followed by Leptophyll, and Microphyll. Comparable life-form have been observed in the vegetation of Kotli Hill, and Abbottabad[98,99]. These finding suggest that species diversity in district Jhelum is influenced not by a single factor but by the complex spatial interaction of multiple edaphic variables.

This study revealed an extensive evaluation of the floristic composition and relationship between vegetation and edaphic variables from the Jhelum region. The study focused on the Fabaceae family, which is an important ecological component in arid and semi-arid zones. The CA, ISA, and CCA ordinations demonstrate useful insight into the impact of topographic variables on species distributions and associations in this prior unexplored area of the Jhelum region. The generated knowledge about the impact of edaphic variables on vegetation patterns is crucial for sustainable rangeland, biodiversity conservation, and habitat rehabilitation in this understudied region. However, despite its contributions and significance, the current study focuses only on the Fabaceae family, while some important environmental variables such as temperature and precipitation were not included. Therefore, for a better understanding of the influence of environmental variables on vegetation, all vegetation types and inter-annual variations should be considered in future studies. In addition, socioeconomic impacts, such as overgrazing and land-use change were not measured quantitatively. To grasp the dynamics of vegetation disturbance patterns, these two variables should be investigated in future research.

Conclusions

In this study, we collected phytosociological data from 73 stations, 219 sites, and 675 quadrats documenting 32 plant species from the family Fabaceae. The vegetation comprises 50% herbs, 34.4% trees, and 11.5% shrub species. The dominant species was *Dalbergia sissoo*, followed by *Neltuma juliflora*, and *Acacia farnesiana*, while *Senna occidentalis* was identified as a rare species. Ward's Cluster analysis (CA) and Two-way Cluster Analysis (TWCA) classified the vegetation into three distinct vegetation groups. Vegetation group 1, comprising 26 stations, included 29 species; group 2 with 29 stations, had 27 species; and group 3 with 19 stations, and consisted of only six species. Key indicator species included *Parkinsonia aculeata*, *Ziziphus nummularia*, *Lathyrus aphaca*, *Acacia nilotica*, *Sesbania* concolor, *Lathyrus pratensis*, *Dalbergia sissoo*, *Berberis lycium*, and *Melilotus officinalis*. The Canonical Correspondence Analysis (CCA) ordination demonstrates that edaphic variables such as soil moisture (SM), soil potential (SP), electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K), organic matter (OM), and calcium carbonate ($CaCO_3$) significantly influenced species associations and distribution. Grazing and anthropogenic pressures also had a substantial impact on vegetation dynamics. Based on these findings, the sustainable utilization of vegetation resources in the Jhelum region can be achieved through (i) in-situ conservation of ecological indicator and rare species within their natural habitat (ii) strict control of overgrazing, and harvesting in the study area (iii) restoration of native vegetation in the disturbed sites through regeneration and plantation of socio-economically valuable plants such as *Acacia nilotica* and *Dalbergia sissoo* and (iv) awareness about over harvesting and their long-term challenges and consequences. These practices will help maintain vegetation resilience, support ecosystem stability, and promote biodiversity conservation in the region. This study thus provides a benchmark for future research on vegetation pattern and species distributions and contributes to the formulation of evidence-based land management and conservation strategies.

Data availability

The data analyzed during the current study are included within the manuscript. However, the raw data files are extensive and can be provided upon request from the corresponding authors.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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