Integrative Assessment of Floristic Diversity, Carbon Sequestration, and Phytochemical Potential in the Pinus roxburghii Forests of Lower Dir

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Abstract- Lower Dir's *Pinus roxburghii* forests are a vital socio-ecological system with great floristic and ethnobotanical diversity. Therophytes and microphylls indicate semi-arid climate and anthropogenic pressure adaption. This integrative study evaluates its floristic composition, vegetation structure, carbon sequestration capability, and phytochemical features to provide evidence-based conservation and sustainable management solutions for this rare temperate environment. The data was documented by systematic field visits, quantified vegetation structure using a quadrat system (10x10 m for trees, 5x5 m for shrubs, 1x1 m for herbs) and certified voucher specimens in a specific herbarium. Carbon sequestration capacity was assessed by calculating total carbon stock from aboveground biomass ($AGB = \rho \times A \times H$) and soil organic carbon ($SOC = BD \times D \times \%C$). Select medicinal species underwent elemental profiling using Energy-Dispersive X-Ray Spectroscopy (EDX) and phytochemical screening using sequential solvent extraction and standardized bioactive component tests. A high-resolution ecological profile revealed 10 plant communities with a therophyte-rich understory (45.07%), showing disturbance adaptation. Sandy to silty loams varied in texture across elevations, indicating diverse nutrient distribution. The forests show high carbon sequestration, with total stocks of 42.66 to 72.04 t C ha^{-1}, mostly from coniferous attitudes. The ethnobotanical value of the flora was empirically evaluated by phytochemical and elemental tests that confirmed bioactive chemicals and necessary elements in medicinal plants, supporting cultural uses. This study confirms the biological and cultural importance of study area. The study shows that adaptive plant community methodologies, edaphic variability, and indigenous behaviors maintain a dynamic and resourceful environment. Quantified sequestration capability and bioactive agent presence show that this landscape regulates global climate and improves community well-being. This area must be preserved by combining ecological stewardship with the economic value of its native species to ensure its future viability.

Keywords: Floristic diversity; ethnobotanical diversity; plant communities; carbon sequestration; biodiversity conservation; soil properties.

1.0 INTRODUCTION

This study was conducted in Lower Dir District, located in the Khyber Pakhtunkhwa province of Pakistan (34°37′–35°07′ N, 71°31′–72°14′ E). Established as an administrative unit in 1996, the district encompasses an area of 1,582 km², subdivided into seven tehsils: Timergara, Balambat, Khall, Samar Bagh, Munda, Lal Qilla, and Adenzai (W. Khan et al., 2023; Zeb et al., 2021). The region features a complex topography, with elevations ranging from 820 meters above sea level in the valleys to rugged mountainous terrain, supporting a mosaic of grasslands, shrublands, and forest ecosystems. Lower Dir is bounded by Chitral to the north, Malakand to the south, and Swat to the east. The climate is characterized by a significant annual temperature range, from a mean minimum of 5.2°C in December to a mean maximum of 35.8°C in July. A steep precipitation gradient exists across the region, with annual rainfall averaging 685 mm in Timergara (Lower Dir) compared to 1,431 mm in the upper elevations (Table 1). This diverse topography and climate foster a rich variety of vascular plants, making the region a significant area for biodiversity study (Ahmad et al., 2015; Hayat et al., 2020).

Months	**Mean Temperature (^{0}C)**		**Average temperature (^{0}C)**	**Precipitation/ Rainfall (mm)**
	Maximum	**Minimum**		
January	2.0	15.3	8.65	26
February	4.5	17.2	10.85	37
March	9.6	21.8	15.7	35
April	14.3	27.2	20.75	53
May	19.9	33.9	26.9	26
June	24.3	37.6	30.95	17
July	25.2	35.7	30.45	71
August	24.4	34.3	29.35	41
September	21.4	33.3	27.35	11
October	14.6	28.7	21.65	9
November	7.7	22.3	15.0	10
December	2.9	18.1	10.5	24
Annual average	**14.23**	**24.8**	**20.67**	**30.83**

Table 1: Climatic data of Lower Dir. **Source:** Pakistan Meteorological Department, Karachi, Pakistan

The region supports a diverse native flora, predominantly comprising xerophytic and resilient species such as Acacia modesta, Zizyphus jujuba, and Olea ferruginea in the tree stratum, with an understory of shrubs including Dodonaea viscosa and Justicia adhatoda (S. J. P. P. Ullah, 2025). These plant communities provide critical habitat structure for a variety of fauna, forming functional ecosystems that support avifauna such as the Grey Francolin (Francolinus pondicerianus) and Common Quail (Coturnix coturnix), as well as mammals like the Golden Jackal (Canis aureus) and Indian Crested Porcupine (Hystrix indica). Concurrently, the landscape is heavily influenced by traditional agro-pastoral practices (Shuaib et al., 2018). The agricultural matrix is characterized by terraced cultivation of staple cereals namely wheat (Triticum aestivum), maize (Zea mays), and rice (Oryza sativa) alongside extensive horticulture of temperate fruits such as apples (Malus domestica), plums (Prunus domestica), and cherries (Prunus avium) (JAVED et al.). This land-use complexity creates a mosaic of natural vegetation, croplands, and orchards, which defines the region's ecological character. A pivotal recent development is the implementation of the Billion Tree Afforestation Project (BTAP) across the district (N. Khan et al., 2019; S. Ullah et al., 2024).

The Billion Tree Afforestation Project (BTAP), initiated in 2015 by the Khyber Pakhtunkhwa Government, represents a critical large-scale intervention for sustainable forestry, climate change mitigation, and socio-economic development (Nazir, Farooq, Ahmad Jan, & Ahmad, 2019). This research provides a comprehensive evaluation of BTAP's multifaceted impact by analyzing the composition, structure, and dynamics of the newly established plant communities, which are fundamental to assessing the initiative's ecological health and success (M. D. Khan et al., 2021). Furthermore, the study quantifies the project's role in climate change mitigation through precise estimations of carbon sequestration potential, measuring biomass and soil carbon stocks to understand its contribution to global carbon cycles (Houghton, Hall, & Goetz, 2009). Concurrently, it examines the socio-economic dimensions of plant resource utilization by local communities, linking forest restoration to livelihood outcomes. By integrating these ecological, climatic, and socio-economic axes, this study delivers novel insights into sustainable forestry and is expected to provide critical information on the floristic composition and ecological features of the area's vegetation under BTAP management (Al-assaf, Nawash, Omari, & Ecology, 2014; Kokou, Syampungani, Chirwa, & Makhubele, 2024).

This study presents a comprehensive ecological and socio-economic assessment of the Pinus roxburghii (Chir Pine) forests within the Billion Tree Afforestation Project (BTAP) area in Lower Dir, Pakistan. To address the critical gap in baseline data as no such integrated research has been previously conducted in study area specifically this investigation is structured around four primary objectives: (1) to prepare a comprehensive floristic checklist and document the ecological characteristics of the area's vegetation; (2) to quantitatively analyze the vegetation structure; (3) to assess the above and below-ground carbon stock of Pinus roxburghii to quantify BTAP's role in carbon sequestration; and (4) to conduct a phytochemical analysis of selected medicinal plants to evaluate their bioactive potential. We hypothesize that the structure of these regenerating forests substantially influences their carbon sequestration potential and concurrently contributes to local socioeconomic development through the provision of medicinal, fodder, and timber resources. By integrating floristics, soil analysis, ethnobotany, and carbon stock assessment, this research provides a novel, holistic evaluation of BTAP's impact, offering critical insights for sustainable forest management, climate change mitigation, and community livelihood enhancement (Fig 1) (Chen, Shivakoti, Zhu, & Maddox, 2012; Kumar, Phukon, & Singh, 2021).

Figure 1: Some common flora recorded in study area district Dir Lower (a) Ficus carica, (b) Punica granatum, (c) Ajuga bracteosa, (d) Rhazya stricta, (e) Monotheca buxifolia, (f) Dodonaea viscose, (g) Cirsium arvense, (h) Convolvulus arvensis, (i) Fumaria indica, (j) Oxalis corniculata, (k) Malva neglecta, and (l) Mentha longifolia

2.0 MATERIALS AND METHODS

2.1 Data collection and vegetation sampling

Field surveys were conducted across the Billion Tree Afforestation Project (BTAP) area in Lower Dir, Khyber Pakhtunkhwa, Pakistan. Vascular plants were documented using stratified random sampling with quadrats of 10×10 m (trees), 5×5 m (shrubs), and 1×1 m (herbs) (Fig 2). Species identification followed Flora of Pakistan, with voucher specimens deposited at the Centre of Plant Biodiversity, University of Peshawar. Vegetation structure was quantified using standard ecological measures. Density, frequency, and cover were calculated and combined into Importance Value Index (IVI) to determine community dominance patterns. Plant communities were classified based on the three species with highest IVI values. Semi-structured questionnaires were administered to local inhabitants (herbalists, elders) to document traditional plant uses. Species were categorized by economic utility (medicinal, fodder, fuel, timber) following established ethnobotanical protocols (F. Ali et al., 2024; Q. Ali, Wazir, & Khan, 1987; Bayu, Soeprobowati, Adissu, & Warsito, 2023).

$$\text{Density}=\frac{\text{No. of individuals of a species}}{\text{Total number of quadrats}}$$

$$\text{Frequency}=\frac{\text{No. of quadrats in which a species was present}}{\text{Total number of quadrates applied}}$$

$$\text{Cover}=\frac{\text{\%Cover of a species}}{\text{Total cover of all species}}$$

$$\text{Relative Density RD}=\frac{\text{Density of a species}}{\text{Total densities of all species}}\times 100$$

$$\text{Relative Cover RC}=\frac{\text{Cover of a species}}{\text{Total cover of all species}}\times 100$$

$$\text{Relative frequency RF}=\frac{\text{Frequency of a species}}{\text{Total frequencies of all species}}\times 100$$

Based on RD, RF and RC the important value index (IVI) will be calculated by using the following formula

$$\text{IVI}=\frac{\text{RD+RC+RF}}{3}$$

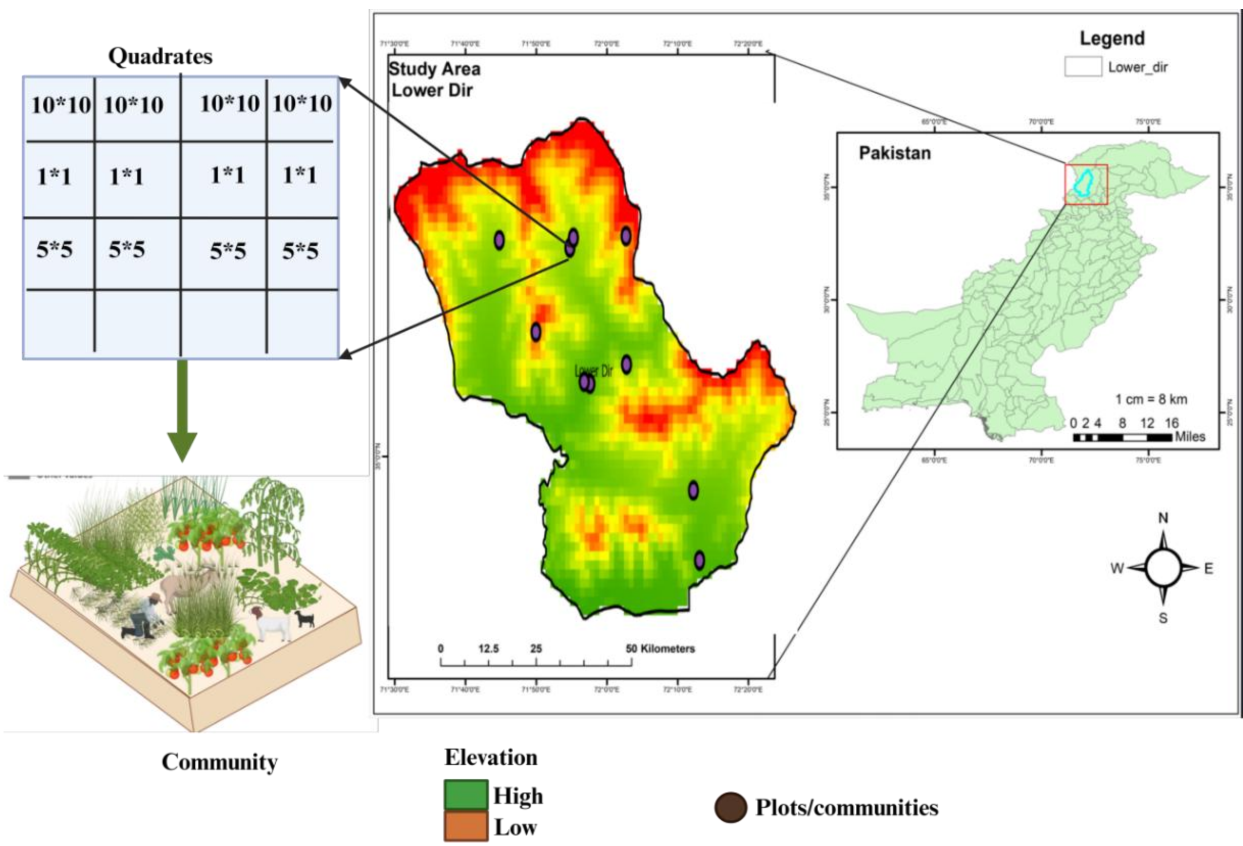

Figure 2: The figure shows spatial representation of study area District Dir Lower Pakistan, along with details of data sampling points their elevation and plots sizes for different vegetation.

2.2 Carbon Stock Assessment

Above-ground biomass carbon was calculated using species-specific wood density and structural measurements. Below-ground soil carbon was determined from bulk density and carbon content analyses. Total carbon stocks were derived as the sum of above- and below-ground components. The following formula was used to quantify the above ground carbon stock (Bārdulis et al., 2015; Cheng & Niklas, 2007).

$$AGB = \rho \times A \times H$$

AGB = Above-Ground Biomass (carbon stock)

ρ = Wood density (carbon content per unit volume)

A = Cross-sectional area of the tree or vegetation

H = Height of the tree or vegetation

The soil carbon extent was known by using the formula.

$$\text{Carbon Content} = BD \times D \times \%C,$$

BD = Bulk Density of the soil,

D = Depth of the soil layer

%C = Carbon content percentage in the soil

The total carbon stock was calculated by following this equation TCS = ACS + BCS (Machado *et al.,* 2015). Where, TCS is total Carbon stock, ACS is above carbon stock and BCS is below carbon stock

2.3 Statistical Analysis:

All statistical analyses and graphics were performed in R using the ggplot2 package (Wickham, 2011). Soil samples (0-15 cm depth) were analyzed for physicochemical properties (texture, pH, EC, organic matter, NPK). Twelve medicinal species were further analyzed for elemental composition (EDX spectroscopy) and phytochemical constituents (UV-Visible spectrophotometry of n-hexane, chloroform, ethyl acetate, and butanol extracts). Soil properties were characterized through standard laboratory protocols. Elemental composition of medicinal plants was determined via Energy Dispersive X-ray Spectroscopy (EDX), while phytochemical screening identified bioactive compounds using UV-Visible spectrophotometry (Peech, 1947). Carbon stocks were quantified from biomass measurements and soil core data. Ethnobotanical uses were documented through semi-structured questionnaires and descriptive analysis. Moreover spatial patterns of elevation, vegetation, and climate were mapped using ArcGIS pro 2024. Field-collected vegetation data were analyzed by calculating Importance Value Indices (IVI) to assess species dominance and define plant communities (Fig 2). Additionally vegetation classification was performed using hierarchical cluster analysis based on Bray-Curtis dissimilarities in PC-ORD version 5 and principal component analysis (PCA) was employed to identify the main structural gradients and carbon storage patterns among tree species (Maćkiewicz, Ratajczak, & Geosciences, 1993).

3.0 RESULTS

3.1 Floral composition and biological spectrum:

The study area district Lower Dir Chir Pine forests had 335 plant species from 262 taxa and 97 families (Supplementary table 1). Dicotyledons dominate the flora 217 species and 79 families, followed by monocots 32 species and 9 families. Four gymnosperms 3 families and two pteridophytes 6 families were present. Therophytes dominated Raunkiaer's system's life form spectrum (151 species, 45.1%), followed by nanophanerophytes (48 species, 14.3%) and mesophanerophytes (43 species, 12.8%). The species was 12.5% hemicryptophytes, 9.3% chamaephytes, and 6.0% geophytes. The most common leaf-size class was microphylls (135 species, 40.3%), followed by nanophylls (84 species, 25.1%). Morphologically, simple leaves (202 species, 60.3%) outnumbered dissected (89 species, 26.6%) and complex (42 species, 12.5%). More non-spiny species (250, 74.6%) than spiny species (85, 25.4%) were found. Most species (223, 66.6%) were reproductive, 21.8% pre-reproductive, and 6.0% post-reproductive at sampling (Supplementary table1).

3.2 Ethnobotanical utilization and its importance:

These plant species are used for ethnobotanical purposes. According to the consumption pattern, the most common category is fodder (247 species, 73.73%), which is followed by fuelwood sources (106 species, 31.64%), and medicinal uses (180 species, 53.73%). 28 species (8.35%) were timber species, whilst 27 species (8.05%) were vegetables and 19 species (5.67%) were fruits. Other applications included building material (12 species, 3.58%), condiments (15 species, 4.48%), applications connected to nicotine (8 species, 2.38%), and ornamental uses (54 species, 16.11%). *Cynodon dactylon, Cenchrus biflorus*, and *Bromus tectorum* were important fodder species. Among the medicinally important plants were *Caralluma tuberculata, Rhazya stricta*, and *Nerium oleander*. *Acacia modesta, Zizyphus mauritiana*, and *Acacia nilotica* were the main fuelwood species. *Eucalyptus camaldulensis, Dalbergia sissoo*, and *Pinus roxburghii* were found to have timber value. Among the edible species were fruits like *Morus alba* and *Vitis vinifera*, and vegetables like *Allium cepa* and *Chenopodium* spp. The main thatching materials were *Nannorrhops ritchiana* and *Saccharum munja*, while notable condiments were *Allium griffithianum* and *Coriandrum sativum* (Suplimentary table 2).

3.3 Ethnomedicinal diversity:

Local populations in study area use 114 species of medicinal plants from 53 families, according to the ethnobotanical survey. With 14 species (12.3%), the Asteraceae family was the most rich, followed by the Lamiaceae and Poaceae (7 species each, 6.1%). The documented species provided treatment for 28 different illnesses, mainly rheumatism, skin issues, respiratory conditions (cough, asthma, bronchitis), and gastrointestinal disorders. Among the notable multipurpose species were *Withania somnifera*, *Strobilanthes glutinosus*, and *Justicia adhatoda*. The most commonly used plant parts were leaves (38%) and entire plants

(22%). Decoctions (35%), powders (25%), and poultices (15%) were the main preparation techniques (Suplimentary table 3).

3.4 Socioeconomic utilization and ethnomedicinal applications:

Ethnobotanical analysis identified 113 plant species with socioeconomic connection. Medicinal applications were predominant, comprising 84 species (74%), followed by fuelwood with 22 species (19%), and food sources with 18 species (16%). Fodder plants comprised 16 species (14%), whereas timber species totaled 8 (7%). Fencing applications were limited to two species, representing 2%, and no species were recorded for thatching purposes. Moreover 114 medicinal species examined, 95 (83%) were found to address specific health conditions, including rheumatism, respiratory ailments (such as cough and asthma), dermatological issues, and gastrointestinal disorders. Leaves were the predominant plant component utilized, comprising 49 species, while whole plants accounted for 24 species. Predominant preparation methods encompassed extracts from 27 species, powders from 20 species, and fresh applications from 16 species. Diuresis-related treatments involved 12 species, whereas dermatological and respiratory conditions each utilized 9 species.

3.5 Soil Physicalchemical Properties:

Soil texture exhibited significant variation along the elevation gradient. High-elevation sites (Laj Book, Maidan, Lal Qilla, Samar Bagh) exhibited predominance of loamy sand and sandy loam textures, comprising 56-80% sand and 3-4% clay. Mid- and low-elevation sites (Kumber, Balambat) displayed silty loam textures, comprising 27-73% silt and 9% clay. Sandy loam soils, comprising 56-74% sand and 3-4% clay, were identified at sites named (Ouch, Munda, Timergara, Khal, and Chakdara). All soils exhibited a pH range of 7.1 to 8.0, indicating slight to moderate alkalinity. Electrical conductivity was measured at low levels (0.21-0.49 dS/m^{-1}), suggesting non-saline conditions. The carbonate content varied between 0.38% at Lajbook, Timergara, and 3.22% at Kumber, Balambat. Organic matter exhibited moderate variation (1.08-1.82%) among the sites. Total nitrogen concentration varied between 0.049 mg/kg^{-1} in Ouch and 0.089 mg/kg^{-1} in Maidan. Extractable phosphorus ranged from 10.7 mg/kg^{-1} at Khal to 20.5 mg/kg^{-1} at Kumber, whereas potassium levels varied between 18 and 42 mg/kg^{-1} across the sites. Elevated concentrations of phosphorus and potassium were correlated with silty loam textures at mid-elevation locations. (Figure 3 and table 2)

S. No	Sites	Altitude (ft)	Physio-chemical characteristics									Major Nutrients (mg/kg)		
			Soil Texture				pH	EC Dsm-1	TSS %	$CaCo_3$	O.M	N	P	K
			Clay %	Silt %	Sand %	Textural class								
1	Samar Bagh	4704.72	4.90	17.10	78.00	Loamy sand	7.2	0.25	0.079	1.71	1.81	0.085	13.9	20
2	Lal Qilla	4927.82	3.80	26.30	69.90	Sandy Loam	7.3	0.32	0.11	3.01	1.11	0.052	20.1	31
3	Laj Book	5104.35	3.10	22.20	56.70	Loamy sand	8	0.38	0.114	0.39	1.37	0.063	11.4	18
4	Kumber	3520.2	9.20	27.20	64.60	Silty loam	7.5	0.49	0.151	3.21	1.39	0.067	20.5	42
5	Maidan	5144.35	4.80	16.80	80.40	Loamy sand	7.2	0.21	0.081	1.73	1.82	0.089	11.9	21
6	Munda	2569.99	3.70	26.30	68.10	Sandy Loam	7.6	0.31	0.099	3.21	1.09	0.056	17.5	33
7	Timergara	2552.23	2.80	22.20	56.40	Loamy sand	8	0.35	0.101	0.38	1.38	0.059	12.3	20
8	Balambat	2470.34	8.90	72.60	59.40	Silty loam	7.9	0.43	0.147	3.22	1.41	0.071	19.3	39
9	Khal	3114.43	3.10	19.30	77.60	Loamy sand	7.1	0.22	0.069	1.69	1.75	0.083	10.7	19
10	Ouch	2357.21	4.30	21.70	74.00	Sandy Loam	7.7	0.33	0.071	3.11	1.08	0.049	15.1	27
11	Chakdara	2274.74	3.70	23.50	72.80	Sandy Loam	7.4	0.35	0.067	3.09	1.15	0.053	14.3	29

Table. 2: The soil analysis of the different research sites along with their altitudes
Keywords: EC = Electrical Conductivity, O.M = Organic matter, TSS = Total Soluble Salts, N = Nitrogen, K =Potassium, P = Phosphorus

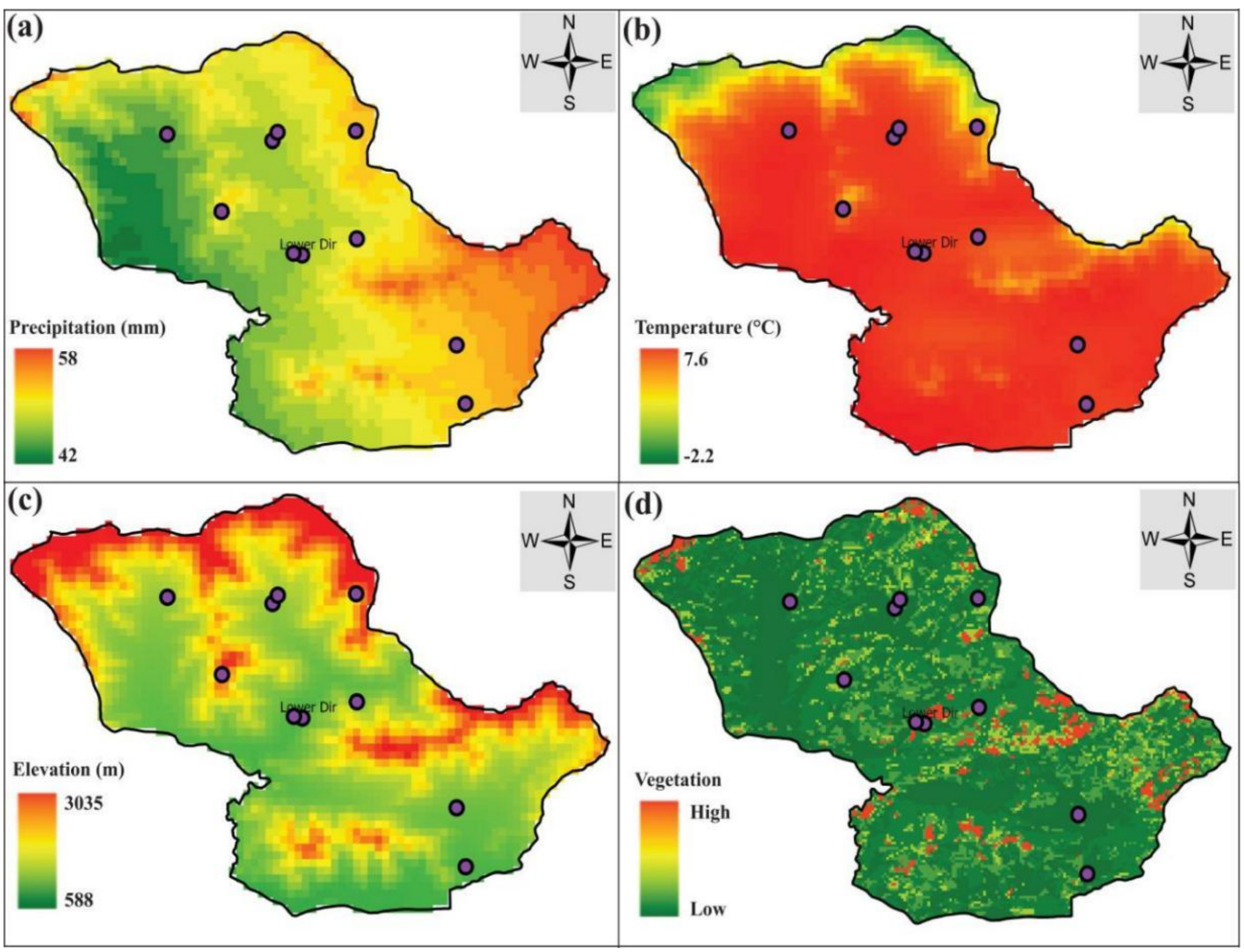

Figure 3. This figure shows detail spatial representation of (a) Precipitation (mm) (b) Temperature (°C), Elevation (m), and vegetation. The color gradient ranges from green (low) to red (high) in all maps. Source: (Arc GIS Pro)

3.6 Plant communities classification:

Cluster analysis of 145 plant species revealed three distinct vegetation associations along the elevation gradient. Coniferous forest communities (PDA, PSC, PMA) were primarily characterized by *Pinus roxburghii*, *Cedrus deodara*, and *Taxus baccata*. Subtropical dry forest communities (PDC, ACP, PDV) include xerophytic species such as *Acacia modesta* and *Ziziphus nummularia*. Shrub-grassland communities (MNH, MDC, FMH) were defined by the presence of *Cymbopogon jwarancusa* and *Desmostachya bipinnata*. Two-way cluster analysis identified diagnostic species assemblages associated with each community type. A coniferous assemblage delineated PDA, PSC, and PMA communities, whereas a xerophytic assemblage characterized PDC, PDV, and ACP communities. Shrub-grassland species such as *Cenchrus ciliaris* and *Nannorrhops ritchiana* characterized the MNH, MDC, and FMH communities.(Detail plant communities suplimentary file 1).

3.7 Phytochemical composition of medicinal plants:

A qualitative phytochemical analysis of 20 medicinal plants demonstrated unique secondary metabolite patterns. *Chenopodium album* demonstrated the greatest compositional diversity, characterized by notable saponins and triterpenoids, whereas *Mentha longifolia* and *Withania somnifera* displayed a wide array of phytochemicals. Alkaloids were identified in 13 species, with the greatest abundance observed in *Chenopodium murale* and *Mentha longifolia*. Flavonoids were prevalent in *Euphorbia helioscopia* and *Solanum nigrum*. Prominent profiles comprised: *Dodonaea viscosa* exhibiting predominant terpenoids and triterpenoids; *Ficus carica* including a broad spectrum of secondary metabolites, excluding alkaloids; *Justicia adhatoda* presenting a balanced array of moderate phytochemicals; and *Zanthoxylum armatum* demonstrating a widespread moderate composition. Multiple species, such as *Sonchus asper* and *Viola canescens*, exhibited restricted phytochemical diversity (table 4).

S. -	Plant Species	Part Used	Alkaloids	C.G	Saponins	Tannins	Steroids	Phe-ls	Flavo-ids	Terpe-ids	Triterpe-ids	Phlobatannins
1	*Che-podium album* L.	Whole Plant	+	+	+++	+	+	+	++	+	+++	+
2	*Conyza canadensis* (L.) Cron.	Whole Plant	-	+	+	++	+		++	++	+	+
3	*Che-podium murale* (L.) S.Fuentes, Uotila and Borsch	Leaves	+++	++	+	-	-	+	+	+	++	-
4	*Dodonaea viscosa* (L.) Jacq.	Leaves	-	-	+	++	++	-	-	++	+++	++
5	*Euphorbia helioscopia* L.	Whole Plant	+	-	-	++	++	+	+++	+	+	+
6	*Eriobotrya japanica* L.	Leaves	-	+	-	++	+	+	+	++	++	+
7	*Ficus carica* L.	Leaves	-	++	+++	+++	+++	-	++	+++	+++	++
8	*Fumaria indica* Hausskn.	Leaves	++	-	+	+++	-	-	+++	++	++	-
9	*Justicia adhatoda* L.	Leaves	++	-	++	++	-	+	++	+	+	-
10	*Mentha longifolia* L.	Whole Plant	++	-	-	++	-	+	+++	+	+	+
11	*Parthenium hysterophorus* L.	Whole Plant	++	+	++	++	+	+	++	+	-	-
12	*Ranunculus arvensis* L.	Whole Plant	++	+	-	+++	+	-	-	-	+	+
13	*Sonchus asper* (L.) Hill.	Whole Plant	+++	++	+	-	-	+	+	+	++	-
14	*Silybum marianum* (L.) Gaertn.	Flower	-	-	+	++	++	-	-	++	+++	++
15	*Solanum nigrum* L.	Whole Plant	+	-	-	++	++	+	+++	+	+	+
16	*Viola canescens* L.	Whole Plant	-	+	-	++	+	+	+	++	++	+
17	*Vitex negundo* L.	Leaves	-	++	+++	+++	+++	-	++	+++	+++	++
18	*Verbascum thapsus* L.	Whole Plant	++	-	+	+++	-	-	+++	++	++	-
19	*Withania somnifera* (L.) Dunal	Leaves	++	-	++	++	-	+	++	+	+	-
20	*Zanthoxylum armatum* DC.	Leaves	++	+	++	++	+	+	++	+	-	-

Table 4: The phytochemical analysis of the selected plant from different localities.

3.8 Elemental composition of medicinal plants:

SEM-EDX investigation of 20 medicinal plant species demonstrated unique elemental compositions. Carbon (34.62-61.36%) and oxygen (29.54-41.63%) were the predominant elements in all organisms. Nitrogen content exhibited significant variation (3.87-8.33%), with peak values observed in *Viola canescens* and *Withania somnifera*. Essential minerals such as potassium (2.32-5.44%), calcium (5.99-8.2%), and sulfur (1.91-2.96%) were consistently identified. Prominent elemental patterns featured increased zinc in *Dodonaea viscosa* (3.4%) and *Mentha longifolia* (3.27%), raised copper in *Conyza canadensis* (3.65%) and *Euphorbia helioscopia* (3.78%), and significant silicon in *Eriobotrya japonica* (4.88%). *Chenopodium album* demonstrated a balanced macroelement composition, but *Justicia adhatoda* displayed notable quantities of iron (1.3%) and chlorine (5.36%) (table 3 and supplementary figure S3,S4).

S. -	Plant Species	Major elements								Mi-r elements						
		C	N	O	Mg	Cl	Ca	K	P	Fe	Na	S	Al	Zn	Cu	Si
1	*Che-podium album* L.	43.6	4.63	39.6	0.49	2.18	5.34	1.28	-	0.3	4.94	2.36	-	4.11	2.89	4.43
2	*Conyza canadensis* (L.) Cron.	54.96	7.56	35.86	0.82	3.61	5.18	2.85	0.14	0.34	0.25	-	0.54	2.64	3.65	1.65
3	*Che-podium murale* (L.) S.Fuentes, Uotila and Borsch	56.99	3.44	33.02	0.29	6.08	5.99	2.32	0.19	0.6	1.69	2.24	0.99	-	1.99	0.89
4	*Dodonaea viscosa* (L.) Jacq.	59.44	6.32	30.9	0.97	5.42	6.41	1.09	0.73	0.44	-	2.96	-	3.4	1.53	1.14
5	*Euphorbia helioscopia* L.	61.36	4.91	29.54	-	3.16	7.54	5.23	0.11	-	2.15	-	-	1.82	3.78	-
6	*Eriobotrya japanica* L.	44.36	-	31.2	0.26	2.24	2.29	-	1.23	-	4.37	-	-	-	2.25	4.88
7	*Ficus carica* L.	48.16	-	33.09	0.98	6.75	3.01	-	0.52	-	0.28	1.91	-	0.45	-	-
8	*Fumaria indica* Hausskn.	38.38	3.87	34.85	0.99	1.92	6.38	4.69	0.43	1.15	1.9	1.97	-	0.63	3.37	-
9	*Justicia adhatoda* L.	36.53	3.24	40.41	0.92	5.36	-	3.68	-	1.3	3.77	2.74	-	0.9	-	-
10	*Mentha longifolia* L.	55.83	-	37.82	-	1.63	6.2	2.04	0.91	0.81	3.63	1.87	-	3.27	1.63	-
11	*Parthenium hysterophorus* L.	45.92	-	32.72	0.95	4.4	4.59	3.4	0.84	0.67	1.31	2.06	1.05	1.08	2.98	-
12	*Ranunculus arvensis* L.	60.62	5.03	34.6	0.62	2.97	6.99	5.44	-	-	-	2.14	1.06	0.71	0.92	1.57
13	*Sonchus asper* (L.) Hill.	59.44	6.32	30.9	-	5.42	6.41	-	0.73	0.44	1.82	2.96	0.64	-	1.53	-
14	*Silybum marianum* (L.) Gaertn.	50.17	5.99	30.03	0.73	4.1	-	0.98	0.21	1.37	2.91	1.33	0.32	1.95	0.63	0.5
15	*Solanum nigrum* L.	34.62	-	36.11	0.5	5.2	3.89	4.56	-	-	1.54	-	1.31	2.31	0.71	1.37
16	*Viola canescens* L.	41.22	8.33	38.99	0.84	3.04	8.2	4.11	0.62	0.77	4.02	0.96	0.57	-	-	-
17	*Vitex negundo* L.	39.79	3.52	41.63	0.93	0.94	-	0.68	0.4	0.39	3.1	1.14	-	1.26	3.1	3.9
18	*Verbascum thapsus* L.	34.62	7.47	36.11	0.5	5.2	3.89	4.56	0.36	-	1.54	2.27	1.31	2.31	0.71	1.37
19	*Withania somnifera* (L.) Dunal	41.22	8.33	38.99	-	3.04	8.2	4.11	0.62	-	4.02	0.96	-	2.88	1.89	1.98
20	*Zanthoxylum armatum* DC.	39.79	3.52	41.63	-	0.94	3.24	0.68	-	0.39	3.1	1.14	-	1.26	3.1	-

Table 3: The elemental composition of selected plant species from different localities of research areas.

3.9 Carbon storage capacity:

The study of above-ground carbon stocking (ACS) demonstrated significant variability across 14 tree species. *Pinus wallichiana* demonstrated the greatest per-tree carbon sequestration (610.1 kg C tree^{-1}), succeeded by *Broussonetia papyrifera* (822.3 kilogram C tree^{-1}) and *Ficus carica* (493.5 kg C tree^{-1}). Coniferous species exhibited considerable carbon sequestration capacity, with *Pinus roxburghii* sequestering 235.2 kg C per tree and *Cupressus sempervirens* sequestering between 195.1 and 345.6 kg C per tree. Total carbon stocks in 11 plant communities varied from 42.66 t C ha^{-1} (FSC Ouch) to 72.04 t C ha^{-1} (PDC Samar Bagh). Tree biomass represented the principal carbon reservoir (10.33-21.25 t C ha^{-1}), but shrub (3.38-3.94 t C ha^{-1}) and herbaceous (0.73-0.94 t C ha^{-1}) strata contributed marginally. Subterranean carbon sequestration exhibited significant variability (26.46-47.7 t C ha^{-1}), with PJC Kumber demonstrating the highest soil carbon concentration. PDC Samar Bagh and PJC Kumber have developed into carbon-dense communities, with total stocks above 70 t C ha^{-1}. Coniferous-dominated stands and rapidly proliferating broadleaf species *Ailanthus altissima*, *Populus alba*, *Morus nigra* significantly enhanced carbon sequestration, whereas riparian species *Salix* spp. and smaller trees *Zanthoxylum armatum*, *Acacia modesta* exhibited restricted storage potential (<13 t C ha^{-1}) (Figure 4,5 and table 5,6).

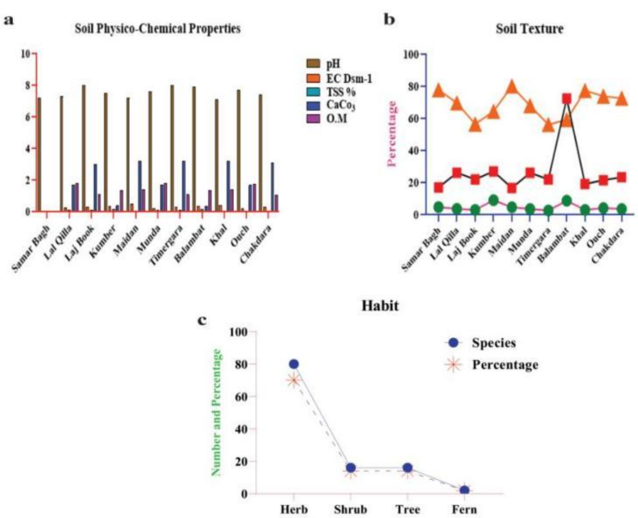

Figure. 4: This figure shows the soil analysis (Physio-chemical properties, soil texture and habitat of the communities) of the different plant communities in study area.

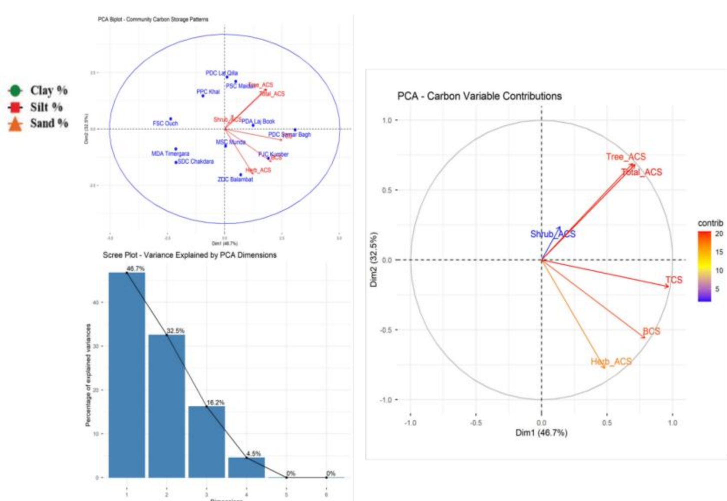

Figure. 5: PCA analysis of plant community carbon storage patterns. Biplot shows communities and their carbon variables closeness show similar carbon deposit, Variable contributions arrows represents value, community agreement spatial grouping pretending ecological assemblage.

Plant Species	D	BA	DBH (cm)	H (m)	ρ (g/cm³)	Biomass (kg/tree)	ACS (kg C/tree)	Density (trees/ha)	ACS (t C/ha)
Ailanthus altissima (Mill.) Swingle	0.8	1.1	41.8	15	0.6	800.6	376.3	80	30.1
Broussonetia papyrifera (L.) L'Hér. ex Vent.	0.6	0.7	38.6	15	0.6	683.2	321.1	60	19.3
Cupressus sempervirens L.	1	1.01	35.9	25	0.45	735.4	345.6	100	34.6
Ficus carica L.	0.6	1.09	47.9	15	0.6	1050	493.5	60	29.6
Melia azedarach L.	1.4	1.07	31.1	15	0.6	443.1	208.3	140	29.2
Morus nigra L.	2.6	1.12	23.4	15	0.6	250.7	117.8	260	30.6
Ficus palmata Forssk.	1	0.98	35.4	15	0.6	573.2	269.4	100	26.9
Populus alba L.	2.2	1.12	25.4	20	0.4	262.5	123.4	220	27.1
Punica granatum L.	1.4	1.51	37	7	0.6	281.6	132.4	140	18.5
Acacia modesta Wall.	0.6	0.5	32.6	7	0.6	223.8	105.2	60	6.3
Ailanthus altissima (Mill.) Swingle	1.6	1.71	36.8	15	0.6	619.5	291.2	160	46.6
Broussonetia papyrifera (L.) L'Hér. ex Vent.	0.4	1.2	61.8	15	0.6	1749.6	822.3	40	32.9
Cupressus sempervirens L.	1.4	0.8	26.9	25	0.45	415.2	195.1	140	27.3
Ficus carica L.	1	1.1	37.5	15	0.6	643.5	302.4	100	30.2
Ficus palmata Forssk.	1	0.9	33.9	15	0.6	526.1	247.3	100	24.7
Melia azedarach L.	1	0.7	29.9	15	0.6	408.5	192	100	19.2
Morus nigra L.	0.8	1.1	41.8	15	0.6	800.6	376.3	80	30.1
Pinus wallichiana A.B. Jacks.	0.6	1.2	50.4	30	0.45	1298	610.1	60	36.6
Pinus roxburghii Sarg.	1.6	1.1	29.6	25	0.45	500.4	235.2	160	37.6
Populus alba L.	1.8	1.7	34.8	20	0.4	494.8	232.6	180	41.9
Punica granatum L.	0.4	0.5	39.9	7	0.6	327.2	153.8	40	6.2
Salix tetrasperma Roxb.	1.6	0.7	23.6	15	0.4	169.2	79.5	160	12.7
Salix tomentosa L.	1	0.8	31.9	4	0.6	155.7	73.2	100	7.3
Zanthoxylum armatum DC.	1	0.9	33.9	4	0.6	175.4	82.4	100	8.2

Table. 5: Above-Ground Carbon Stocking (ACS) of the tree vegetation among 11 communities of the Lower Dir research sites.

Community	Tree ACS (t C/ha)	Shrub ACS (t C/ha)	Herb ACS (t C/ha)	Total ACS (t C/ha)	BCS (t C/ha)	TCS (t C/ha)
PDC Samar Bagh	19.91	3.94	0.94	24.79	47.25	72.04
PDC Lal Qilla	21.25	3.38	0.74	25.37	26.88	52.25
PDA Laj Book	19.32	3.38	0.94	23.64	35.55	59.19
PSC Maidan	19.71	3.94	0.73	24.38	31.59	55.97
PJC Kumber	16.45	3.38	0.94	20.77	47.7	68.47
PPC Khal	17.61	3.38	0.74	21.73	26.46	48.19
MSC Munda	13.79	3.94	0.94	18.67	36	54.67
MDA Timergara	10.33	3.38	0.79	14.5	32.01	46.51
ZDC Balambat	12.85	3.38	0.94	17.17	45.9	63.07
FSC Ouch	11.52	3.94	0.74	16.2	26.46	42.66
SDC Chakdara	10.33	3.38	0.94	14.65	28.14	42.79

Table. 6: The comparative above, below and total carbon stocking of all vegetation communities of the Lower Dir research sites

4.0 DISCUSSION

4.1 Floral composition and biological spectrum:

The floristic composition of the Chir Pine forest in Lower Dir, comprising 335 species from 97 families, signifies substantial biodiversity and environmental variety. This abundance aligns with other regional studies and indicates the existence of varied ecological niches that sustain a broad spectrum of plant lineages. The pronounced prevalence of therophytes (annuals) in the life-form spectrum serves as a robust signal of a seasonal environment and considerable disturbance pressure. Therophytes conclude their life cycle during a single season, representing an effective strategy in habitats characterized by significant aridity or persistent human-induced disturbances such as grazing (Araujo, Canassa, Machado, & Tabarelli, 2023). The significant percentage of phanerophytes (trees and shrubs; around 27%) affirms the integrity of the forest canopy, with *Pinus roxburghii* as the predominant framework species. The occurrence of microphyllous and nanophyllous leaves (totaling 65.4%) is a recognized adaptation to minimize water loss in temperate areas experiencing seasonal water scarcity. The local climate's selective pressure is immediately reflected in this leaf-size range. Additionally, the large percentage of spiky species (25.4%) is probably a defensive adaptation against herbivory, which is frequently severe in managed forest environments, whereas the high frequency of simple leaves may be related to nutrient-use efficiency. A dependable picture of the community's functional status was provided by the observed phenological pattern, which shows that the majority of the species were in a reproductive stage during the data collection period, which also coincided with the peak growing season. In summary, this forest's biological spectrum shows an ecosystem influenced by both biotic and climatic stress. A robust ecosystem that sustains high floristic diversity through a range of adaptive methods in spite of the obvious environmental constraints is suggested by the co-dominance of stress-adapted therophytes and a stable tree layer (Lavorel et al., 2015; Mori, Furukawa, & Sasaki, 2013).

4.2 Ethnobotanical utilization and its importance:

The extensive ethnobotanical use of all documented species (335) highlights the significant interdependence between local communities and forest resources in Lower Dir. The significant prevalence of fodder species (73.73%) indicates the agro-pastoral basis of the local economy, wherein livestock rearing constitutes a principal livelihood strategy. This pattern corresponds with socioeconomic structures in comparable Himalayan communities, where forest resources directly underpin agricultural economies. The high proportion of medicinal species (53.73%) indicates a persistent dependence on traditional healthcare systems, especially in remote mountainous areas with restricted access to contemporary medical facilities. The documentation of species such as *Rhazya stricta* and *Caralluma tuberculata* substantiates the preservation of indigenous pharmacological knowledge. The significant use of plants for fuelwood (31.64%) and timber (8.35%) underscores the reliance on forest resources for energy and construction. Multipurpose species like *Acacia modesta* and *Pinus roxburghii* predominate for these reasons, indicating their ecological and economic significance. Edible plant diversity (vegetables: 8.05%, fruits: 5.67%) promotes food security and nutritional diversity, while decorative species (16.11%) reflect cultural aesthetics and environmental management. Nicotine-related species (2.38%) suggest traditional applications beyond essential needs. This ethnobotanical profile shows how biological diversity boosts regional socioeconomic resilience. Long-term human-environment interactions created multifunctional species that optimize resource consumption. These utilitarian principles must be recognized to create community-supported conservation management plans that address ecological sustainability and human well-being. Using all recorded species makes a strong argument for integrating ethnobotanical knowledge into biodiversity conservation frameworks to recognize plants' functional functions in local cultural and economic systems (Dean, 2024).

4.3 Ethnomedicinal diversity:

The documentation of 114 medicinal species from 53 families demonstrates extensive ethnobotanical knowledge across study area district Dir lower populations and notable floristic variety that underpins traditional treatment. The prevalence of Asteraceae corresponds with global ethnomedicinal trends, perhaps attributable to the family's abundant secondary metabolites and extensive distribution. The frequent utilization of leaves indicates sustainable harvesting methods, as leaf collection maintains plant vitality more effectively than root or bark extraction. The variety of preparation techniques ranging from intricate Water extract to basic raw consumption exemplifies an advanced pharmacological comprehension designed for the extraction of specific bioactive compounds. The extensive range of addressed illnesses, especially the focus on gastrointestinal and respiratory disorders, is closely linked to common health issues in rural mountainous areas.

This functional alignment indicates that conventional knowledge has developed through repeated validation against local illness burdens (Sinthumule, 2023).

Species such as *Withania somnifera*, noted for many applications, exemplify the intersection of traditional usage and scientific validation, underscoring potential subjects for phytopharmacological investigation. The dependency on medicinal species that are sourced from the wild highlights the need to protect these species, especially those that rely on roots for their survival (Radha, Kosuri, & Kumar, 2023). Both the primary healthcare it offers in areas without access to contemporary treatments and the intangible cultural legacy it represents are preserved in this ethnomedicinal repository. To guarantee the survival of cultural artifacts and public health, conservation efforts of the future should combine traditional wisdom with sustainable farming practices. Our results highlight the importance of ethnobotanical studies in biodiverse areas with long histories of cultural plant usage in connecting traditional knowledge with modern conservation and healthcare planning (Pandey, 2002).

4.4 Socioeconomic utilization and ethnomedicinal applications:

The significant dependence on medicinal plants (74-83% of documented species) highlights their essential function in primary healthcare in rural communities of district Lower Dir. This predominance likely indicates restricted access to contemporary medical facilities and the maintenance of traditional knowledge systems. The significant use of leaves indicates sustainable harvesting methods that preserve plant viability; however, the utilization of whole plants (21%) raises conservation issues for at-risk species. The variety of preparation methods, ranging from crude extracts to powdered forms, reflects advanced traditional pharmacological knowledge aimed at optimizing the extraction and bioavailability of bioactive compounds. The emphasis on addressing diuresis, dermatological, and respiratory conditions corresponds with the common health issues in the region, illustrating the adaptability of traditional healthcare to local disease trends. The secondary significance of fuelwood species (19%) underscores ongoing energy reliance on forest resources, whereas food plants (16%) play a role in nutritional security and dietary diversity. The lower documentation of fodder species (14%) may indicate underreporting rather than actual usage, considering the region's agro-pastoral economy. The lack of thatching species and sparse fencing applications point to either possible documentation gaps or cultural changes in building practices. The significant proportion of species (17%) that have no known medical application suggests either neglected resources or a lack of anthropological documentation. Particularly for overused medicinal species, our findings highlight the necessity of integrated conservation methods that address socioeconomic dependencies and biodiversity preservation. In order to preserve ecological integrity and community healthcare supplies, sustainable harvesting practices and cultivation activities are crucial for medicinal plants that are in high demand (Johns, Powell, Maundu, Eyzaguirre, & Agriculture, 2013; Maity & Development, 2023).

4.5 Soil physiochemical properties:

The elevation gradient's distinct textural gradient represents the region's primary pedogenetic processes. Higher elevations have coarse-grained textures due to erosion and weathering, while valley bottoms have finer textures from alluvial and colluvial deposition. This pattern matches mountain toposequence. Alkalinity across locations supports Himalayan calcareous parent material. Mid-elevation sites (Kumber, Balambat) had high carbonate concentration, suggesting less leaching and slope carbonate redistribution. Low electrical conductivity values indicate good drainage throughout the studied region. Texture controls spatial nutrient distribution. Higher phosphorus and potassium in silty loam soils indicate better nutrient retention due to surface area and cation exchange. Sandy high-elevation soils have poor nutritional status, which increases leaching and decreases nutrient retention. The observed moderate levels of organic matter, in light of the forested environment, indicate accelerated mineralization rates due to the existing climatic conditions. Nitrogen availability varies according to organic matter distribution, highlighting the essential function of soil organic carbon in nutrient cycling. The collective soil characteristics form a mosaic of edaphic conditions that likely affect vegetation patterns along the elevation gradient. The well-drained and typically fertile soils sustain the recorded floristic diversity, whereas variations in texture and nutrients enhance habitat heterogeneity at local scales. Soil parameters are essential for comprehending the distribution of plant communities and the productivity of ecosystems within the Chir Pine forest landscape (Rezaei & Gilkes, 2005).

4.6 Plant communities classification:

The distinct separation of three principal vegetation groups indicates robust environmental filtering across altitudinal and edaphic gradients. The coniferous forest communities at higher elevations are similar to the usual montane forests in the Himalayas, where cooler temperatures and more rainfall support *Pinus roxburghii* and other species. The subtropical dry forest communities at middle elevations show how they adapt to dry conditions, with xerophytic features seen in dominating species like *Acacia modesta* and *Dodonaea viscosa*. These groups are in between montane forests and lowland vegetation. The shrub-grassland communities show that they have been disturbed a lot, perhaps because of grazing and human activity. The presence of disturbance-tolerant species like *Cynodon dactylon* and *Cenchrus ciliaris* indicates that these communities are in the second stage of succession in regions that have been damaged. The diagnostic species assemblages found through two-way clustering serve as ecological indicators for habitat types and environmental conditions. The usefulness of floristic composition in vegetation classification and ecological process inference is highlighted by the robust species-community correlations. A synthetic picture of vegetation organization in the Chir Pine forest landscape is provided by these community patterns, which incorporate the combined impacts of altitude, soil characteristics, and disturbance regimes reported in earlier research. The establishment of focused conservation strategies for every species of vegetation is supported by the distinct community differentiation. (supplementary table 4).

4.7 Elemental composition of medicinal plants:

Elemental composition varies greatly between species due to physiological and environmental absorption mechanisms. Carbon and oxygen dominance matches fundamental organic structures, but nitrogen variability reflects species-specific protein composition and metabolic activity. Certain elemental profiles are therapeutic, Zinc and copper, important cofactors in enzymatic defense systems, are found in high concentrations in *Mentha longifolia* and *Euphorbia helioscopia*, which have antioxidant and antibacterial effects. Calcium-rich *Withania somnifera* and *Viola canescens* may explain their traditional usage in bone health and neuromuscular problems. *Eriobotrya japonica* and *Vitex negundo* contain silicon, which may strengthen tissue and reduce inflammation, whereas sulfur-rich species like *Parthenium hysterophorus* may have antibacterial properties from sulfur-containing chemicals. The traditional usage of *Fragaria indica* and *Justicia adhatoda* as hematinic agents is supported by their iron content. A physicochemical foundation for comprehending the ethnopharmacological uses of these plants is provided by these elemental profiles. The unique elemental signatures are useful biomarkers for standardizing and ensuring the quality of herbal remedies (Noviana, Indrayanto, & Rohman, 2022). Additionally, by connecting traditional knowledge with biochemical confirmation, the association between particular elemental patterns and traditional medicinal usage provides insights into the molecular basis of herbal medicine efficacy (Messaoudi, Benchikha, Zahnit, & Rebiai, 2025). The results highlight the value of elemental analysis in phytomedicine research, especially in establishing evidence-based quality standards for medicinal plant materials and comprehending mineral-mediated therapeutic effects.

4.8 Phytochemical composition of medicinal plants:

The phytochemical variety of the 20 medicinal plants underpins their ethnopharmacological uses. Saponins and triterpenoids, which membrane-permeabilize and immunomodulate, make *Chenopodium album* useful for anti-inflammatory and antibacterial applications. The phytochemical profile of *Mentha longifolia* and *Withania somnifera* supports their traditional medicinal usage. These species' various bioactive chemical classes suggest synergistic interactions that may boost their therapeutic potency. Terpenoids, which block cyclooxygenase and relieve pain, are the main components of *Dodonaea viscosa*, which is anti-inflammatory and analgesic. The high flavonoid content of *Euphorbia helioscopia* and *Solanum nigrum* matches their traditional use as antioxidants and hepatoprotectants. *Sonchus asper* and *Viola canescens* may benefit from specific compounds or synergistic combinations rather than broad-spectrum phytochemicals because to their limited phytochemical variety. Alternatively, qualitative screening may miss specialized metabolites in these species. Cardiac glycosides and phlobatannins are absent in many species, which may be due to biochemical or detection threshold issues. The identified phytochemical gaps contribute to the understanding of species-specific metabolic specializations. The relationship between traditional medicinal practices and identified phytochemical profiles supports indigenous knowledge and offers a scientific basis for ongoing therapeutic use. Additionally, these phytochemical signatures provide direction for the targeted isolation of bioactive compounds and the standardization of herbal preparations. The variation in secondary metabolite composition among different species emphasizes the chemical diversity present in medicinal plants and identifies species with significant potential for pharmacological advancement. Species exhibiting rich and diverse phytochemical profiles, such as *Chenopodium album* and *Mentha longifolia*, are prime candidates for further phytopharmacological investigation.

4.9 Carbon storage capacity:

The significant interspecific variation in carbon storage capacity highlights the essential role of species selection in forest management aimed at climate change mitigation. The enhanced performance of *Pinus wallichiana* and other conifers is attributed to their high wood density, considerable size, and longevity, rendering them suitable for long-term carbon sequestration. This is consistent with global trends indicating that coniferous forests typically demonstrate greater biomass accumulation compared to deciduous stands. The substantial carbon sequestration by fast-growing broadleaved species like *Broussonetia papyrifera* and *Ficus carica* illustrates the capacity of these rapidly developing species for short- to medium-term carbon capture. The integration of long-lived conifers with fast-growing broadleaves may enhance carbon sequestration efficiency across various temporal scales in reforestation initiatives. Variation in carbon stocks at the community level underscores the direct impact of vegetation composition on the capacity for ecosystem carbon storage. The significant carbon accumulation in PDC Samar Bagh and PJC Kumber indicates that these communities may represent mature successional stages or environmentally favorable sites with optimal growth conditions. The reduced carbon stocks in FSC Ouch may suggest the presence of younger stands, less advantageous edaphic conditions, or increased disturbance regimes. The significant below-ground carbon contribution, especially in PJC Kumber, highlights the essential role of soil organic matter in overall ecosystem carbon budgeting. The below-ground pool frequently serves as a more stable long-term carbon reservoir compared to above-ground biomass, which is vulnerable to disturbance events. The limited contributions of shrub and herbaceous layers, though anticipated in forest ecosystems, remain significant components of overall carbon cycling, especially during early successional phases or after disturbances. The findings hold considerable implications for forest management and strategies for climate change adaptation in the region. Focusing on high-carbon-accumulating species in reforestation, safeguarding carbon-rich mature stands, and adopting sustainable harvesting practices that preserve carbon stocks may improve the climate regulation services of Lower Dir forests, while also promoting biodiversity conservation and supporting local livelihoods.

4.0 CONCLUSION

In conclusion, this comprehensive investigation of the Chir Pine forests in Lower Dir synthesizes a powerful narrative of ecological resilience and profound human-forest interdependence. The floristic composition, shaped by climatic and edaphic filters, reveals a biodiverse ecosystem strategically adapted to seasonal stress and disturbance through a dominance of therophytes and xeromorphic traits. Crucially, this botanical richness is not merely ecological but forms the very foundation of local socio-economic and cultural systems, with every documented species serving a utilitarian purpose predominantly in ethnomedicine, livestock fodder, and fuel. The elemental and phytochemical profiles of key medicinal plants provide a scientific validation of indigenous knowledge, revealing a sophisticated, chemically driven pharmacopoeia. Furthermore, the significant carbon sequestration potential, particularly in coniferous stands, positions these forests as vital regional assets for climate change mitigation. Ultimately, this study underscores that the conservation of this landscape is an imperative triad: protecting a reservoir of biodiversity, safeguarding a living library of ethnobotanical wisdom, and maintaining a critical carbon sink. Future management must adopt an integrative framework that equally values ecological integrity, cultural heritage, and ecosystem services to ensure the resilience of both the forest and the communities that depend on it.

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Conflict of interest

The authors declare that there is no conflict of interest

Author Contributions:

Zia Ul Islam designed the study, performed the statistical analysis, and led the drafting of the manuscript. Dr. Syed Mukaram Shah supervised the research, provided critical guidance, and contributed to manuscript writing. Taqweem Ul Haq assisted with data collection and analysis procedures. Wajid Khan, as the corresponding author, conceived the project, supervised all stages, secured funding, and was responsible for the final review, editing, and correspondence. All authors reviewed and approved the final manuscript.

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Supplementary file (Separate document)
Please see Supplementary files for better understanding and clarity (Details plant communities, supplementary tables and supplementary figures)