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Plant species richness and conservation status of protected and unprotected areas of Kohat District, Northern Pakistan

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Abstract Kohat, located in northern Pakistan, holds ecological importance due to its distinct climate, diverse vegetation, and conservation concerns. This study hypothesizes that protected areas exhibit higher plant diversity and biomass than unprotected areas, primarily due to the impact of protection measures on domestic and wild animal activities. We assessed the abundance and diversity of native vegetation across 25 plots in protected and unprotected areas. Our findings revealed 67 native plant species, including 39 herbs, 18 shrubs, and 10 trees. Key tree species such as *Grewia opptiva*, *Vachellia nilotica*, and *Senegalia modesta* demonstrated higher basal areas in protected areas. In contrast, shrub species like *Rhazya stricta*, *Withania coagulans*, and *Gymnosporia royleana* exhibited higher densities in these areas. Species of conservation concern, such as critically endangered *W. coagulans* and nearly threatened *G. royleana*, were more prevalent in protected areas, suggesting the effectiveness of conservation measures. Additionally, locally important and consumable medicinal plant species, including *Ajuga bracteosa*, *Amaranthus viridis*, *Peganum harmala*, *Sonchus arvensis*, and *Zygophyllum indicum* revealed substantial abundance, richness, and distribution within protected areas. In conclusion, the study indicates that conservation measures, particularly protected areas, play a crucial role in safeguarding and preserving native plant communities and enhancing species richness.

Keywords: plant diversity, medicinal plants, forest restoration, vegetation assessment, threatened species, semiarid climates.

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Introduction

Native vegetation supports the ecological balance and biodiversity of a particular ecosystem. In northern Pakistan, Kohat has a distinctive climate, diverse ecosystems, and a biogeographically momentous location. It is characterized by a mix of humid temperate and semi-arid subtropical climates, with an average annual rainfall of approximately 638 mm. It supports various soil types and terrain, including mountains, semi-deserts, grasslands, and small forests (Haq et al. 2023). The diverse climate and ecological conditions in Kohat harbor various medicinal plant species adapted to different environmental niches (Zamin et al. 2024).

The natural vegetation in the study area predominantly comprises subtropical dry scrub rather than sclerophyllous oak forests. This vegetation type is well-adapted to the semi-arid and rocky terrain, supporting thorny shrubs, grasses, and drought-resistant species rather than dense oak forests. Regarding oak species, (*Quercus baloot* Griff.) is typically found in some semi-arid and dry regions of northern Pakistan, including specific areas adjacent to Kohat. However, Kohat's climate and vegetation may not support extensive oak stands; scattered trees or shrubs are part of the broader dry scrub vegetation. Kohat district has a distinctive biogeography and diverse flora within the Irano-Turanian zone.

An essential characteristic of this area is the combination of Mediterranean and Central Asian elements, which has resulted in a rich diversity of indigenous plant species. These species have long been used in local traditional medicines in the study area but are unsustainably harvested, which may lead to their complete disappearance from the ecosystem.

Kohat has a diverse soil composition due to its topography and underlying geology. However, these soils lack organic matter and nutrients, making plant growth difficult. Despite this, native plants are adapted to thrive in these conditions. A notable relationship exists between soil parameters and human-induced factors, influencing medicinal plant communities and their distribution (Arshad et al. 2024).

Anthropogenic activities substantively affect plant distributions, making conservation efforts essential for preserving native vegetation. Despite the substantial deforestation and habitat loss that have resulted in decreased forest cover and the extinction of economically valuable plant species, conservation measures can help mitigate these effects. For instance, protected areas can enhance the abundance and diversity of native vegetation by reducing human impact and providing refuge for these plant species.

The decline in forest cover in Pakistan, which spans 4.6 million hectares, is deeply concerning, particularly across temperate zones. The alarming rate of deforestation, estimated at 3.1% per year, is primarily attributed to the chaotic disappearance of environmentally friendly and valuable plant species. This deforestation will have severe effects on our natural environment. (Najeeb et al. 2023). If left unchecked, this distressing trend could result in the loss of two-thirds of forests by 2035 (Tanvir et al. 2006) and the complete disappearance of large semi-arid subtropical regions by 2050 (Vancutsem et al. 2021).

An evaluation by the Worldwide Conservation Planning of Biodiversity highlights a grave concern: over 15,000 medicinal and aromatic plants are endangered (Li 2010). Considering this alarming statistic, conservation measures are urgently needed to protect these valuable plant species.

In addition to supporting ecological diversity, these plants also play an essential role in traditional medicine. In addition to meeting primary healthcare needs, forest clearing has led to a substantial increase in the export of medicinal plants to neighboring countries for easy cash (Sher et al. 2014). However, agricultural, forestry, herding, and ethnobotanical practices pose alarming threats to abundance and plant diversity.

Studies indicate that once rare species become extinct, they require more extended periods to regenerate than more common species (Volkov et al. 2003, Bralower & Millet 2021). Furthermore, it has also been concluded that anthropogenic disturbances initiate a negative feedback loop, adversely impacting plant diversity, including saplings and seedlings (Mangan et al. 2010).

Noted for its productive soil and unique geographical features, Kohat district is ideal for ecological research and conservation efforts. However, native plant species are threatened, facing declines from land use changes and human activities. Indigenous people and migrants (IDPs) of the vicinity encounter genuine challenges, including limited healthcare services, inadequate educational opportunities, and dwindling income sources (Shah et al. 2023). In these rural areas, plant species serve as a critical and accessible alternative to address financial and health-related needs. It has been reported that *Ajuga bracteosa* Wall. (Lamiaceae), *Amaranthus viridis* L. (Amaranthaceae), *Peganum harmala* L. (Nitrariaceae), *Sonchus arvensis* L. (Asteraceae), and *Zygophyllum indicum* (Burm.f.) Christenh. & Byng (Zygophyllaceae) are among the most valuable and widely used medicinal plants for local people in the study area.

A comprehensive survey conducted within local communities surrounding the study area documented various uses and the cultural significance of these plants. Similarly, identifying the distribution of plant species in an unexplored area is essential for designing effective conservation strategies for native vegetation (Ullah et al. 2024). Consequently, conducting an extensive biodiversity survey in the entire zone is crucial for understanding ecosystem dynamics and planning conservation measures (Zamin et al. 2024).

A geological survey revealed that the soil in Kohat contains clay, silt, gypsum, and limestone, creating a favorable environment for plant growth (Yaseen et al. 2007). Historically, soil fertility has been one of the key factors in shaping the region's unique ecosystem. Despite the region's prolific soil and varied topography, recent urbanization and the resettlement of internally displaced persons (IDPs) have led to a decline in native plant diversity and a surge in invasive species. As urban areas expand, native flora is increasingly replaced by invasive, weedy species (Lobovikov et al. 2007) posing a serious threat to local biodiversity. Anthropogenic activities strongly modify ecological functions, which could be restored if a regenerative area is protected (Adnan & Hölscher 2010).

Forest loss is widely recognized as a leading cause of species extinction, a process that can be mitigated through reforestation and regeneration efforts (Kemppinen et al. 2020). In response, we conducted this study on conservation measures in the protected and unprotected areas within and around Kohat University of Science and Technology (Figure 1C) to assess ecological features and vegetation structures. Since 2005, the Administrative Department of

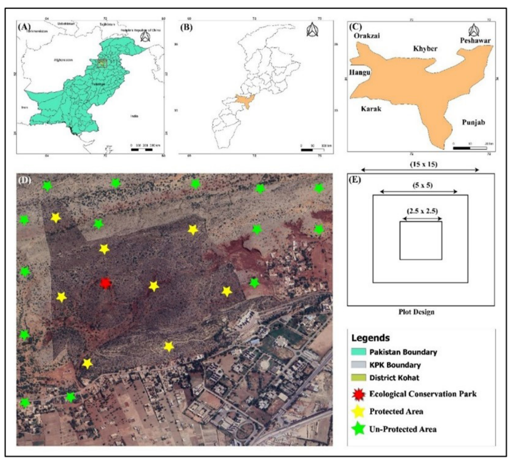

Figure 1 The map of the study area and plot design: (A) Pakistan and location of the study area **(B)** Khyber Pakhtunkhwa **(C)** District Kohat showing the protected and unprotected areas" **(D)** Protected area with a perimeter of KUST, the adjoining degraded area outside the fence and randomly selected plots from both types of land use. **(E)** The plot design includes: an inventory plot for trees (225 m^2), a plot for shrub density (25 m^2), and a plot for herbs density and coverage (6.25 m^2).

KUST has conserved the wild area (so-called protected area) by restricting human access to recreation, fodder, medicinal plant collection, and livestock grazing. Durable barbed-wire fencing has been installed, helping to preserve plant diversity and natural resources.

The protected area has been fenced off community access for over two decades and is monitored continuously by a dedicated security team assigned by the institution's administration department. These protection measures, which support wood production and environmental preservation, align well with sustainable forest management practices (Shinwari & Qaiser 2011). In protected area seedlings and saplings of species of *Senegalia modesta, Dalbergia sissoo, Olea ferruginea*, and *Eucalyptus camaldulensis* (Table 1) have been cultivated. Despite over two decades of fencing and reforestation efforts, the area has shown considerable spatial improvement. Findings from the plantation experiment suggest that degraded areas can be effectively restored by planting native plant species (Shinwari 2010).

Human-managed plantations can serve multiple purposes, including controlling soil erosion, preventing desertification, and stabilizing slopes. The study area's regeneration efforts also function as an in-situ conservation program for specific species of *S. modesta, D. sissoo, O. ferruginea,* and *E. camaldulensis* (Table 3). In contrast, the unprotected area faces substantial use and degradation due to a lack of safety measures. The vicinity reveals a high prospective for anthropogenic pressures, including agriculture, grazing, and the collection of plants for various purposes.

This study seeks to assess how these protection measures impact the abundance and diversity of native vegetation by comparing these attributes in both habitats. Specifically, we test hypotheses such as: (i) protected areas exhibit higher species abundance and diversity due to reduced anthropogenic activities; (ii) plant species that otherwise struggle in unprotected areas are successfully regenerating in protected areas; and (iii) lack of protective measures critically endangered certain plant species, increasing their risk of extinction. By addressing these hypotheses, the research aims to stipulate valuable perceptions about the effectiveness of conservation measures. Our findings offer an in-depth narrative of the native plant communities in the northern part of district Kohat, a region previously unexplored.

Materials and Methods

Study site

The Kohat district in northern Pakistan lies between 32° 47' and 33° 53' north latitude and 70° 34' east longitude at 558 m ASL It is bordered by Peshawar to the south, Hangu to the east, Orakzai to the west, Khyber to the southwest, and Karak to the north (Figure 1C). Geologically, the region is rocky and arid, with varied rock formations that create a rugged and craggy appearance. According to Bhatti and Ullah (2011) the soil ranges from clay to sandy loam with an alkaline pH. A healthy ecosystem relies on the dynamic interaction between climate, soil, and plants, forming an ecological circuit. Climate factors, such as temperature and precipitation, influence soil formation, while soil quality directly affects plant growth. In turn, plant roots and organic matter contribute to changes in soil properties, creating a continuous feedback loop (Lauer et al. 1996).

Kohat district has a diverse topography, including mountains such as the Kohat and Miranzai hills and semi-desert landscapes with thorny shrubs, grasslands, and small forests. The study area belongs to the semi-arid subtropics, depicted by lowlands and a long lasting thermic vegetation period. Additionally, Kohat covers an area of 983 square miles (Shinwari et al. 2011). The climate of the study area is described by a combination of humid, temperate, and semi-arid conditions, with distinct seasonal variations ranging from prolonged and hot summers to brief and cold winters. For instance, in the summer, the average rainfall is approximately 638 mm with maximum humidity, and the minimum rainfall (2 mm) is recorded in the dry month of December (Khan et al. 2022). These climatic factors are crucial in shaping the native flora and ecosystems. Long-term climatic data, including temperature, precipitation, wind patterns, and humidity, has been compiled by the Pakistan Meteorological Department (Figure 3).

The Kohat region blends traditional and modern elements from a socioeconomic perspective. Agriculture and livestock are the primary economic drivers, while traditional customs remain firmly ingrained in daily life. However, limited access to healthcare, poor infrastructure, and financial constraints pose significant challenges. As a result, the local populations heavily depend on natural vegetation to meet their daily needs.

A study on fuel wood usage, fodder consumption, and the collection of medicinal plants in the northern region highlights the intricate relationship between human activities and the local ecosystem (Shinwari & Qaiser 2011). The area is known for its distinct vegetation dominated by arid-adapted native plants. The natural vegetation comprises subtropical dry scrub, featuring a perspective of native plant species, including trees, bushes, herbs, and wildflowers, all well-suited to the semi-arid climate. A few rare and endemic species have been identified in the region, particularly *V. nilotica, S. modesta, Z. nummularia, S. mascatense, O. ferruginea,* and other xerophytes (Table 3).

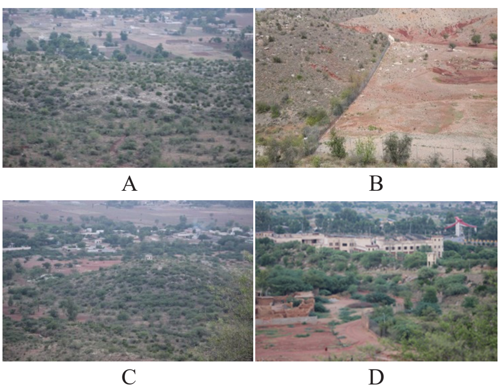

Figure 2 The regeneration in protected areas (A & C), The fence installed between protected (left) and unprotected (right) areas (B), the community adjacent to the unprotected area (Left), and plant abundance and diversity in the protected area (right) (D).

Over the past two decades, 81.23 ha of wild land at Kohat University of Science and Technology has been prioritized for conservation efforts. These initiatives include habitat restoration, regeneration of native flora, the removal of invasive species, and active participation by the administration department in conservation activities. In contrast, unprotected areas face significant ecological threats, such as habitat degradation, overgrazing, deforestation, and land-use changes (Fig. 2B). These human-induced factors drastically impact biodiversity and vegetation, with overgrazing being a key driver.

Overgrazing is the prolonged and unsustainable grazing of plants without sufficient recovery time, leading to land degradation and biodiversity loss. The primary contributors to this issue are goats, sheep, and cattle, including breeds such as Beetal and Kamori goats, Bibrik and Kajli sheep, and local cattle breeds like Sahiwal and Red Sindhi. These animals, well-adapted to dry conditions, often graze selectively on young plants and seedlings, hindering vegetation regeneration and reducing plant diversity. Our findings indicate that stocking rates exceed the sustainable carrying capacity, typically 2-3 ha per livestock unit, though this varies

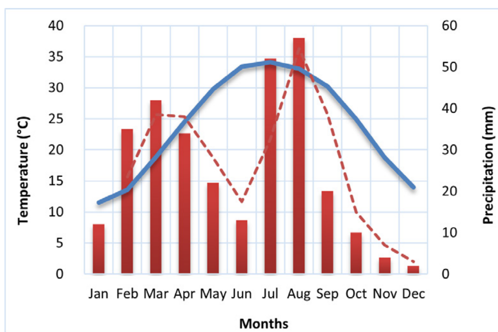

Figure 3 Temperature & precipitation trends in District Kohat.

with vegetation cover and soil conditions. Population pressures exacerbate overstocking, amplifying its detrimental effects on vegetation and soil. Additionally, overgrazing facilitates the spread of non-native and invasive plants, further altering the ecosystem.

Vegetation inventory and assessment of abundance and diversity

The study area was categorized into protected and unprotected zones using a systematic grid pattern as part of the research methodology. Protected zones refer to areas actively managed for conservation through measures like controlled access, habitat restoration, and the cultivation of native species. In contrast, unprotected zones are subject to unplanned activities such as grazing, deforestation, and land-use changes.

Sampling points were selected using stratified random sampling to account for variations in plant species distribution and environmental conditions within these zones. Twenty-five square quadrat plots were randomly designed as sampling tools for each land-use type within an altitudinal variation ranging from 504 m to 558 m. These plots covered sample areas of 81.23 ha and > 81.23 ha, respectively, and were oriented toward the north-south slope, with 45% and 38% of their northern aspects. The abundance and diversity of native flora were assessed using transects and quadrats (Figure 1D).

Furthermore, these sampling tools were subdivided into three square subplots to evaluate plant community dynamics and life-form compositions (Khan & Hussain 2013). Accordingly, 225 m^2 (15 × 15 m) square quadrats were selected to assess the abundance and diversity of tree species, including 25 m^2 (5 × 5 m) used for shrubs and bushes density and 6.25 m^2 (2.5 × 2.5 m) used for herbs and grasses density and coverage (Figure 1E). These quadrats were demarcated following the distance sampling technique (DST) for assessing various life forms of native vegetation across both land use types by measuring the distances of individual plants from a sampling line or point (Aubin et al. 2021).

Data were collected over three years, from March 2017 to February 2020, allowing us to observe seasonal variations in plant abundance and diversity and assess the effectiveness of protection measures. The three-year timeframe accounted for inter-annual variation, providing a comprehensive understanding of ecological dynamics.

Monthly sampling sessions included replicates of quadrats at various locations within both land-use types to address spatial variability. Soil analysis revealed significant differences between the protected and unprotected areas, influenced by geological properties. Protected areas had higher water-holding capacity, greater soil fertility, and lower salinity compared to unprotected areas. Additionally, protected areas had fewer clay particles, enhancing soil quality and structure.

Plant specimens from the study area were identified by a team of plant taxonomists from Kohat University and Peshawar University. The botanical names were verified using open-access databases, including the Plant List, the World Flora Online, and the Flora of Pakistan. To ensure accurate identification, taxonomic keys, botanical literature, and reference collections were also consulted. The specimens were pressed, dried, and mounted on herbarium cards to retain their original characteristics. These cards were stored under environmentally controlled conditions in the Herbarium Room of the Department of Botany at KUST.

Tree species dominance and basal area calculation

The basal area (BA) was calculated by measuring individual trees' diameter at breast height (DBH) to identify the dominant tree species in each plot.

A square quadrat plot was surveyed for both sites to record plant species' average number and thickness. The average values from all quadrats in the protected area revealed a high plant density, indicating a significant correlation of plants relative to the quadrat area. Population size (N) was estimated using the following formula:

$$N = \left(\frac{A}{a}\right) \times n$$

where N = Estimated total population size, A = Total area surveyed, a = Area of the quadrat, and n = Number of species found per quadrat.

To evaluate plant community composition and diversity, various diversity indices, including "species richness" and metrics, were developed by (Shannon 1948, Simpson 1949). Species richness (S) was determined by counting the number of species in each quadrat, providing insights into changes in diversity.

Simpson's diversity index (D) was calculated to measure biological diversity, which represents the probability that two individuals randomly selected from a community belong to different species of plants. It was calculated using the formula:

$$D = 1-\sum \frac{n\,(n-1)}{N\,(N-1)}$$

where: D = Simpson's diversity index, n = Number of individuals of a particular plant species, N = Total number of individuals of all plant species.

The Shannon-Wiener Index (H') was also employed to assess the community's richness and evenness of plant species (Clarke et al. 2001). This assessment is based on the following formula, considering the abundance of plant species:

$$H' = \sum_{i=1}^{S} pi \text{ In } pi$$

where, H′ = Shannon Diversity Index, *pi* = proportion of individuals of species *i* in the quadrat (relative abundance), ln *pi* = natural logarithm of the proportion of species i, ∑= is the sum of all species (species richness) in the community.

Rapid vulnerability assessment

This study adopted a rapid vulnerability approach (Cunningham 2001) to evaluate the conservation status of native plant species in Kohat district. A systematic three-year field survey was conducted to document the presence, abundance, and distribution of native plant species in protected and unprotected areas. The conservation status of individual species was assessed using the Red List vulnerability criteria alongside the rapid vulnerability approach.

For each criterion, the reported species were assigned a score ranging from 1 to 6. A lower score signified high vulnerability, while a higher score represented low vulnerability (Table 6). Data were collected through various sources, including expert consultations, interviews with residents, secondary data (literature), survey results, and studies of regional flora.

To assess vulnerability, a final threat score was assigned by summing the scores of all parameters and integrating them into a single composite score. Based on these scores, the species were categorized into three groups: highly threatened (1-19), moderately threatened (20-30), and less threatened (31-50).

Soil physicochemical characteristics and native vegetation

In semiarid to humid subtropical ecosystems, species diversity plays a key role in determining the types and structures of plant communities. There is a strong correlation between the abundance and diversity of plant species and the soil properties of a particular ecosystem (Dölarslan et al. 2017). To investigate the relationship between soil characteristics and diversity indices in protected and unprotected areas, fifty (25 x 2) soil samples (depth: 0-25 cm) were taken from the center and four corners of each quadrat (Figure 1C). In the laboratory, the soil samples were partially air-dried and cleaned to remove debris before being sieved through a 2.0 mm mesh for uniform particle sizes. The processed samples were stored in plastic bags for further analysis.

Soil physicochemical properties, including calcium carbonate ($CaCO_3$), organic matter (OM), total nitrogen (N_2), phosphorus (P), and potassium (K), were measured following the procedures outlined by Hussain (1989) and (Lü et al. 2019). Electrical conductivity (EC) and pH were also determined using soil-water extracts analyzed with conductivity and pH meters.

Statistical analysis

The Mann-Whitney U test was applied to evaluate differences in stem density, species richness, and diversity indices between the protected and unprotected areas. Additionally, variations in soil variables between the two land-use types were assessed for statistical significance. Pearson's correlation coefficient (r)/Pearson product-moment correlation coefficient (PPMCC) was used to examine relationships among ecological variables. Statistical analyses and data visualization of ecological, vegetation, soil, and spatial data were conducted using Microsoft Excel, SPSS version 16.0 (Dhaou et al. 2010) and ArcGIS.

Results

Vegetation structure and diversity in protected and unprotected areas

A total of 67 medicinal and aromatic plant species were identified across the study plots, comprising 10 trees, 18 shrubs, and 39 herb species. Among tree species (with a diameter at breast height of ≥ 12 cm), six were common to both land-use types, while four were exclusive to the protected area. Similarly, 12 of 18 shrub species were common, with the remaining 06 in the protected area.

The study revealed significant differences in herb diversity, density, and herbaceous cover between the protected and unprotected areas. The protected area supported a greater diversity of plant species, with 38 distinct species recorded, while 11 species were absent in the unprotected region. Additionally, the protected area exhibited greater herb density and cover per quadrat. In contrast, fewer herb species resulted in poor herb density and cover in unprotected areas.

The administrative department of KUST established the protected area as an ecological conservation park by planting seedlings and saplings of *Senegalia modesta, Dalbergia sissoo, Olea ferruginea*, and *Eucalyptus camaldulensis*, which have demonstrated rapid regeneration (Figure 2). A fourfold difference in tree species richness was observed between the protected area (78.5%) and the unprotected area (19.15%) in terms of species richness (n 100 m^{-2}).

Significant differences in plant consumption,

Table 1 General aspects of two types of land used in District Kohat

Attributes	Protected area (PA)	Unprotected area (UA)
Total study area (ha)	81.23	> 81.23
Fodder contribution to livestock (%)	00%	100%
Land use	Little or no human interference for 10 years	Extensive human pressure continues
Administrative status	Controlled area under the Kohat University of Science & Technology jurisdiction with barbed wire	Un-controlled area under public use with no protection
Slope (%) (mean)	31	24
Northern aspect (%)	45	38
Distance (km) to highway	1	1
Distance (km) to the nearest community	0.5	0.5
Distance (km) to security guards	0-1	No security
Total types of tree species (25 plots)	10 (4)	6
Total types of shrub species (25 plots)	18	12
Total types of herbs species (25 plots)	38	27
Altitude of study plots (m ASL) (range)	558	504
Total no. of tree species (25 plots)	1132	204
Total no. of shrub species (25 plots)	2210	632
Total no. of herb species (25 plots)	3549	1496
Total no. of saplings (25 plots)	565	0
Total no. of seedlings (25 plots)	460	51

such as fodder, were also noted. No consumption was observed in the protected area, while the unprotected areas experienced 100% fodder consumption (Table 1). These ecological surveys highlighted substantial differences regarding vegetation structure between the two land-use types. The protected area featured a healthy forest canopy, a diverse bushy layer, and a rich ground cover. Native plant species in the protected area fostered a varied and well-balanced ecosystem.

In contrast, the unprotected area exhibited significant vegetation degradation. Sparse canopy cover and low tree density allowed invasive species to dominate the shrub and ground layers. The protected area supported more native plant species diversity and ecological stability.

The Shannon-Wiener index values further confirmed the differences, with the protected area displaying more evenly distributed and diverse plant communities. However, the unprotected area exhibited lower species richness and was predominantly dominated by non-native invasive species. The diversity indices suggest native plant species in the unprotected area are at risk of extinction due to anthropogenic pressures.

Shannon Index values in this study ranged between 1.5 and 3.5, which is typical. Higher values, rarely exceeding 4.5, indicate more evenly distributed plant populations, while values of 4.6 suggest an equal distribution of individuals across all species.

The protected area exhibited significantly higher species richness, with 66 distinct plant species compared to 45 species in the unprotected area. This notable difference highlights the greater diversity of native species within the protected area. These findings underscore the positive impact of protection measures on enhancing and preserving plant diversity in District Kohat.

Tree variables and structural parameters

Tree variables and stand parameters were assessed for individual species across both land-use types. Of the ten recorded tree species, only six were found in both regions, while the remaining four were absent in unprotected areas (Table 2).

Tree species with higher basal area, such as *V. nilotica, S. modesta,* and *C. sinensis*, were reported exclusively in the protected area. Additionally, *G. optiva* and *S. mascatense* were identified as the

Table 2 Tree and stand structural features of two land-use types.

Species name (Family)	**DBH** (cm) **Mean** (SD)			**Basal area** (m^2/ha) **Mean** (SD)			**Stem density** (n/ha) **Circum. ≥ 12.4** (SD)			**Stem density** (n/ha) **Circum. < 12.4** (SD)		
	PA	**UA**	**MWUt**	**PA**	**UA**	**MWUt**	**PA**	**UA**	**MWUt**	**PA**	**UA**	**MWUt**
Celtis sinensis Pers. (Cannabaceae)	12.60 (1.47)	02.32 (1.07)	p<0.01	01.16 (0.85)	0.08 (0.40)	p<0.01	02.88 (0.73)	0.16 (0.37)	p<0.01	4.64 (0.91)	0.64 (0.49)	p<0.01
Dalbergia sissoo Roxb. (Fabaceae)	12.40 (1.87)	0.04 (0.20)	p<0.01	01.56 (0.92)	0	p<0.01	0.80 (0.41)	0	NS	19.04 (2.05)	0	p<0.01
Eucalyptus camaldulensis Dehnh. (Myrtaceae)	03.04 (1.17)	0.32 (0.48)	p<0.01	01.52 (0.96)	0	NS	0.23 (0.41)	0	NS	4.2 (1.00)	0	p<0.01
Ficus drupacea Thunb. (Moraceae)	14.16 (2.19)	02.96 (1.46)	p<0.01	02.92 (1.32)	0.23 (0.50)	p<0.01	0.64 (0.95)	0	NS	1.4 (0.50)	0	p<0.01
Grewia optiva J.R.Drumm. ex Burret (Malvaceae)	05.76 (1.39)	01.12 (0.97)	p<0.01	06.04 (0.93)	0.52 (0.59)	p<0.01	4.01 (1.53)	0	p<0.01	5.28 (0.61)	0.32 (0.48)	p<0.01
Olea ferruginea Wall. ex Aitch. (Oleaceae)	12.48 (2.33)	02.92 (1.55)	p<0.05	01.36 (0.91)	0.16 (0.37)	p<0.01	4.80 (0.91)	0	p<0.01	6.28 (0.73)	0.48 (0.51)	p<0.01
Senegalia modesta (Wall.) P.J.H. Hurter (Fabaceae)	13.72 (1.43)	04.04 (1.34)	p<0.01	05.76 (1.16)	0.44 (0.51)	p<0.01	15.20 (1.08)	1.12 (0.53)	p<0.01	47.36 (2.12)	5.44 (0.58)	p<0.01
Sideroxylon mascatense (A. DC.) T.D. Penn. (Sapotaceae)	10.44 (2.02)	01.64 (0.99)	p<0.05	02.36 (1.11)	0.20 (0.41)	p<0.01	7.20 (1.71)	0.82 (0.65)	p<0.01	14.08 (0.81)	1.12 (0.53)	p<0.01
Vachellia nilotica (L.) P.J.H. Hurter & Mabb. (Fabaceae)	13.52 (1.33)	04.52 (1.05)	p<0.05	05.92 (0.91)	01.52 (0.96)	p<0.01	15.68 (1.82)	3.84 (1.28)	p<0.01	44.16 (2.41)	15.52 (0.87)	p<0.01
Ziziphus jujuba Mill. (Rhamnaceae)	07.08 (1.58)	01.36 (0.91)	p<0.05	0	0	0	16.32 (1.03)	1.60 (1.04)	p<0.01	40.96 (0.68)	11.36 (1.47)	p<0.01

Note: MWUt: MWU test; Circum.: circumference; PA: protected area; UA: unpotected area

Table 3 Tree stands structural parameters of individual species on both land-use types. Mean and standard deviation, n = 25 plots per land-use type.

Parameters	Protected area Mean (SD)	Unprotected area Mean (SD)	Mann-Whitney U test
Species diversity (no. of species)	10	06	
Stem density (≥ 12 cm DBH) (n ha-^{1})	163.49 (0.50)	30.70 (0.48)	p<0.01
Basal area (m^2 ha^{-1})	10.52 (0.40)	2.12 (1.00)	p<0.01
Tree species richness (n 100 m^{-2})	314.6 (53.49)	76.6 (23.00)	p<0.01
Tree Simpson index (D)	0.98 (0.03)	0.99 (0.02)	NS
Tree Shannon index (H′)	1.65 (N/A)	1.50 (N/A)	p<0.01
Tree Shannon evenness (E_H)	0.76 (N/A)	0.68 (N/A)	NS

most prevalent tree species within the protected area (Table 3).

On average, the basal area of plots in the protected area (40.35 m^2 ha^{-1}) was nine times greater than in the unprotected area (2.95 m^2 ha^{-1}). Diversity indices further highlighted the stark differences between the two land-use types. The protected area had significantly higher Simpson and Shannon indices, with values of 0.98 (0.03) and 1.65 (0.25), respectively. In contrast, the unprotected areas exhibited lower diversity, with a Simpson index of 0.69 (0.02) and a Shannon index of 1.50 (0.12).

Furthermore, the protected area demonstrated a more uniform distribution of individuals, with the high stem density recorded at 163.49 (0.50), a basal area of 40.35 m²/ha, and a density of 81.23/ha (Table 2).

Total and species-specific densities of shrubs across both land-use types

The average density of shrub species was four times greater in the protected area than in the unprotected area. The mean density across both land use types was 2628.8 (355.10), with the difference being statistically significant ($p < 0.01$). Shrub species were identified as dominant plants in the protected area, comprising 30-41% of the vegetation cover.

Notably, *R. stricta* and *W. coagulans* exhibited the highest mean densities in the protected area, with 175 (18.8) and 173 (17.5) values, respectively. Other prominent shrub species in the protected area included *P. aphylla* 118 (7.7), *C. procera* 115.2 (10.2), *J. adhatoda* 111.36 (6.7), *D. viscosa* 110.08 (7.5), and *G. royleana* 86.4 (11.6) respectively (Table 4).

Table 4 Species-specific densities of studied shrub plants on both land-use types.

Species name/ Family name	Protected area (n/ha) **Mean** (SD)	Unprotected area (n/ha) **Mean** (SD)	Mann-Whitney U test
Abutilon grandifolium (Willd.) Sweet (Malvaceae)	48.01 (9.05)	14.08 (3.31)	p<0.05
Buxus wallichiana Baill. (Buxaceae)	32.04 (4.80)	12.04 (1.70)	NS
Calotropis procera (Aiton) Dryand. (Apocynaceae)	115.20 (10.24)	34.56 (3.60)	p<0.01
Dodonaea viscosa (L.) Jacq. (Sapindaceae)	110.08 (7.52)	31.36 (4.22)	p<0.01
Drosera rotundifolia L. (Droseraceae)	28.16 (3.81)	7.68 (1.32)	NS
Erigeron canadensis L. (Asteraceae)	25.60 (4.23)	12.16 (1.60)	NS
Gymnosporia royleana Wall. ex M.A. Lawson (Celastraceae)	86.43 (11.60)	15.05 (1.50)	p<0.01
Indigofera heterantha Wall. Ex Brandis (Fabaceae)	62.08 (13.52)	11.52 (1.81)	P<0.01
Justicia adhatoda L. (Acanthaceae)	111.36 (6.70)	31.36 (4.23)	p<0.01
Nannorrhops ritchiana (Griff.) Aitchison (Arecaceae)	13.41 (2.90)	7.68 (1.33)	p<0.05
Periploca aphylla Decne. (Apocynaceae)	34.05 (3.24)	14.72 (1.50)	NS
Prosopis cineraria (L.) Druce (Fabaceae)	35.02 (4.52)	17.12 (1.53)	NS
Rhazya stricta Decne. (Apocynaceae)	175.04 (18.80)	43.51 (2.32)	p<0.01
Rydingia limbata (Benth.) Scheen & V.A. Albert (Lamiaceae)	47.43 (8.70)	37.12 (3.22)	P<0.05
Sageretia thea (Osbeck) M.C. Johnst. (Rhamnaceae)	27.03 (4.06)	13.02 (2.06)	NS
Withania coagulans (Stocks) Dunal (Solanaceae)	173.03 (17.51)	19.24 (2.11)	p<0.01
Withania somnifera (L.) Dunal (Solanaceae)	51.82 (5.43)	16.61 (1.90)	p<0.05
Ziziphus nummularia (Burm.f.) Wight & Arn (Rhamnaceae)	31.03 (2.91)	20.03 (1.61)	p<0.05

These findings highlight the significant impact of protection measures on the density and abundance of shrub species. The results strongly suggest minimizing disturbances through protection efforts can enhance shrub density and biodiversity.

Diversity of herbaceous vegetation and their canopy coverage

A total of 39 species of vascular herbs were identified across 50 square quadrat plots in both land use types. The mean herb density was recorded as 14.60 (1.89), with notable species such as *E. serrata, S. arvensis, P. harmala,* and *A. viridis* showing significantly higher density in the plots of the protected area. These findings suggest that the protected area supports greater herbaceous species abundance and diversity.

The percentage of canopy coverage for most herb species was minimal in both land use types. However, a few species demonstrated relatively higher canopy coverage in the protected area, including *P. hysterophorus* (16.96%), *E. serrata* (13.93%), and *A. viridis* (10.07%), respectively (Table 5).

Assessment of vulnerability and conservation status of native plant species

The Rapid Vulnerability Assessment (RVA) provided a preliminary overview of the vulnerability and conservation status of native plant species in the study area. Among the 67 recorded plant species, 22 were identified as being on the brink of extinction. According to the IUCN Red List, *W. coagulans* and *G. royleana* were classified as critically endangered, with RVA scores of 18 and 19, respectively, while the remaining species were deemed moderately vulnerable (Table 6).

There were many vulnerable plant species among these, with herbs accounting for the largest proportion (16.41%), followed by shrubs (9%) and trees (6%), respectively. A comparative analysis of the conservation status of the identified species with national and international databases, including the IUCN Red List and supplementary data (see Supplementary Table S1), corroborates these findings.

The RVA results highlight the precarious status of *W. coagulans* and *G. royleana*, critically endangered and nearly threatened, respectively.

Conversely, these species, along with others classified as endangered or threatened, were observed to be thriving within the protected area.

The findings affirm that protected zones serve as essential refuges, offering a secure habitat for native species and mitigating the threats posed by anthropogenic activities in unprotected regions. These insights emphasize the importance of ongoing conservation efforts in safeguarding District Kohat's ecological landscape.

Soil characteristics in both land-use types

Soil samples were collected from each plot and analyzed to evaluate their profile, texture, and organic and nutritional components across the two land use types. The analysis was conducted at the Agricultural Research Institute, Tarnab Peshawar. Both land-use types were predominantly characterized by loamy soils; however, the concentrations of organic compounds and nutrients varied significantly.

In the protected area, nitrogen (N), zinc cation (Zn^{+2}), and iron (Fe^{+2}) were observed at notable higher levels. Conversely, at $p < 0.05$, the unprotected area exhibited significantly higher concentrations of $CaCO_3$, Potassium (K), and pH values, with a difference of 5.23%. Both land-use types showed similarities in their soil organic matter (SOM), electrical conductivity (EC), total soluble salts (TSS), phosphorus (P), and copernicium (Cn) concentrations (Table 7).

A clear correlation was observed between soil characteristics and the diversity of specific plant species in the study plots. Soil nutrient content, particularly in the protected area, was pivotal in shaping plant diversity. Higher soil nutrient levels correspond to greater diversity, as indicated by the Shannon-Wiener and Simpson's diversity indices, which showed vivid plant diversity in nutrient-rich plots. Additionally, spatial variations in the soil parameters were found to influence the composition of plant communities.

Table 5 Diversity of herbaceous vegetation and their canopy coverage overall between land-use types, mean and standard deviation, n = 25 plots per land-use type.

Species name/ Family name	Herbs density ($n/6.25m^2$)			Herbs coverage ($n/6.25m^2$)		
	Protected area Mean (SD)	Unprotected area Mean (SD)	MWU test	Protected area Mean (SD)	Unprotected area Mean (SD)	MWU test
Achyranthes aspera L. (Amaranthaceae)	13.12 (1.74)	5.44 (1.16)	NS	4.48 (0.65)	2.24 (0.72)	NS
Aerva javanica (Burm. f.) Juss. (Amaranthaceae)	9.32 (1.07)	4.48 (0.82)	NS	3.04 (0.73)	2.08 (0.70)	NS
Ajuga bracteosa Wall. (Lamiaceae)	7.36 (0.71)	5.44 (0.71)	NS	3.28 (1.13)	1.72 (0.84)	NS
Amaranthus viridis L. (Amaranthaceae)	28.32 (1.93)	8.64 (0.86)	p<0.05	10.08 (0.91)	3.22 (0.91)	p<0.05
Argemone mexicana L. (Papaveraceae)	6.08 (1.52)	3.52 (0.87)	NS	2.68 90.80)	0.76 (0.44)	NS
Argyrolobium roseum (Camb.) Jaub. & Spach (Fabaceae)	6.56 (1.23)	2.92 (0.71)	NS	2.56 (0.58)	1.36 (0.57)	NS
Asparagus officinalis L. (Asparagaceae)	9.28 (1.06)	4.22 (0.90)	NS	3.56 (0.58)	1.92 (0.64)	NS
Calamagrostis arenaria (L.) Roth (Poaceae)	6.72 (0.84)	4.80 (0.82)	NS	2.24 (0.66)	1.63 (0.58)	NS
Calamagrostis breviligulata (Fernald) Saarela (Poaceae)	14.41 (1.12)	13.60 (1.01)	NS	4.81 (0.65)	3.88 (1.62)	NS
Cenchrus ciliaris L. (Poaceae)	18.72 (1.28)	8.96 (0.98)	NS	6.61 (0.91)	2.52 (0.82)	NS
Cenchrus setosus subsp. *setosus* (Poaceae)	27.84 (1.72)	4.82 (0.91)	NS	9.60 (0.65)	1.76 (0.72)	NS
Cleome brachycarpa Vahl ex DC. (Cleomaceae)	13.12 (1.32)	6.23 (1.41)	NS	4.64 (0.99)	1.68 (0.63)	NS
Cymbopogon citratus (DC.) Stapf (Poaceae)	21.12 (1.09)	6.72 (1.28)	NS	6.16 (1.10)	2.08 (0.70)	NS
Cymbopogon flexuosus (Nees ex Steud.) Will. Watson (Poaceae)	9.92 (1.04)	4.36 (0.99)	NS	4.68 (0.95)	2.32 (0.75)	NS
Cynodon dactylon (L.) Pers. (Poaceae)	31.84 (1.41)	8.32 (0.75)	NS	9.48 (1.98)	2.76 (1.05)	NS
Datura stramonium L. (Solanaceae)	11.84 (1.03)	4.96 (0.88)	NS	5.12 (1.01)	2.08 (0.70)	NS
Delphinium uncinatum Hook. f. & Thomson (Ranunculaceae)	8.64 (0.99)	4.01 (1.15)	NS	2.88 (0.88)	1.44 (0.51)	NS
Dianthus anatolicus Boiss. (Caryophyllaceae)	9.28 (1.4)	4.32 (1.07)	NS	2.88 (1.01)	1.76 (0.66)	NS
Dianthus deltoides L. (Caryophyllaceae)	8.16 (1.31)	4.82 (1.16)	NS	2.88 (0.73)	1.76 (0.66)	NS
Echinops echinatus Roxb. (Asteraceae)	7.04 (1.51)	4.96 (0.79)	NS	2.23 (0.65)	1.76 (0.59)	NS
Elymus repens (L.) Gould (Poaceae)	21.28 (1.82)	3.04 (0.61)	NS	6.56 (0.87)	1.12 (0.67)	NS
Euphorbia hirta L. (Euphorbiaceae)	8.64 (0.49)	5.76 (1.02)	NS	3.28 (1.13)	1.92 (0.64)	NS
Euphorbia serrata L. (Euphorbiaceae)	41.92 (1.32)	7.36 (0.95)	p<0.01	13.92 (0.90)	2.16 (0.75)	p<0.01
Forsskaolea tenacissima L. (Urticaceae)	11.84 (1.34)	3.20 (0.76)	NS	4.76 (0.78)	1.44 (0.58)	NS
Gentiana olivieri Grisebach (Gentianaceae)	14.08 (0.76)	0.64 (0.64)	NS	4.64 (0.91)	0.52 (0.51)	NS
Inula britannica L. (Asteraceae)	5.12 (0.83)	3.72 (0.98)	NS	1.76 (0.66)	0.12 (0.33)	NS
Jurinea heteromalla (D.Don) N.Garcia, Herrando & Susanna (Asteraceae)	6.08 (1.15)	2.24 (0.92)	NS	1.62 (0.58)	0.64 (0.49)	NS
Malva neglecta Wallr. (Malvaceae)	22.88 (1.33)	9.12 (0.78)	NS	7.96 (0.84)	2.68 (0.69)	NS
Nanorrhinum ramosissimum (Wall.) Betsche (Plantaginaceae)	4.83 (0.87)	2.56 (0.82)	NS	1.64 (0.57)	0.72 (0.54)	NS
Parthenium hysterophorus L. (Asteraceae)	52.48 (2.85)	22.08 (1.66)	p<0.01	16.96 (1.21)	8.48 (0.82)	NS
Peganum harmala L. (Nitrariaceae)	9.28 (1.92)	6.88 (0.88)	P<0.01	3.23 (1.04)	2.56 (0.65)	NS
Plantago australis subsp. *cumingiana* (Fisch. & C.A. Mey.) Rahn (Plantaginaceae)f	8.21 (0.70)	3.20 (0.80)	NS	4.84 (0.82)	1.28 (0.61)	NS
Ptilimnium capillaceum (Michx.) Raf. (Apiaceae)	9.28 (0.98)	5.92 (0.76)	NS	3.36 (0.86)	2.41 (0.87)	NS
Pupalia lappacea (L.) Juss. (Amaranthaceae)	5.28 (0.79)	2.72 (0.68)	NS	2.08 (0.64)	1.12 (0.73)	NS
Rumex hastatus D. Don (Polygonaceae)	2.44 (0.62)	1.60 (0.91)	NS	2.12 (0.62)	0.64 (0.49)	NS
Silybum marianum (L.) Gaertn. (Asteraceae)	18.4 (1.25)	4.71 (0.83)	NS	6.32 (1.11)	1.48 (0.71)	NS
Solanum americanum Mill. (Solanaceae)	15.36 (0.81)	3.40 (0.76)	NS	5.44 (0.87)	1.12 (0.78)	NS
Sonchus arvensis L. (Asteraceae)	42.56 (1.36)	11.84 (1.40)	p<0.01	12.8 (1.98)	2.96 (1.41)	NS
Zygophyllum indicum (Burm.f.) Christenh. & Byng(Zygophyllaceae)	6.56 (1.42)	4.24 (0.83)	NS	2.64 (0.73)	1.92 (0.76)	NS

Table 6 Rapid Vulnerability Assessment of the studied plant species under both land-use types

Botanical name	H/ Lf	H	Pu	Uv	Ps	Rr	Sc	Qc	Ts	TS
A.aspera	1	5	3	2	5	1	2	4	2	25
A.viridis	3	2	1	3	2	1	2	4	2	20
A.grandifolium	5	5	3	2	4	1	2	5	2	29
A. integrifolia	4	5	5	4	1	1	1	3	2	26
A. javanica	1	5	3	4	5	2	2	3	2	27
A. mexicana	1	5	3	2	5	1	2	4	2	25
A. officinalis	3	2	1	3	2	1	2	4	2	20
A. roseum	1	5	3	4	5	2	2	3	2	27
B. wallichiana	1	3	4	3	3	2	2	5	1	24
C. arenaria	3	2	2	1	3	2	2	4	2	21
C. brachycarpa	5	5	1	2	4	1	2	5	2	27
C. breviligulata	3	5	4	3	4	2	1	2	1	25
C. ciliaris	3	5	4	3	4	2	1	2	1	25
C. citrates	5	1	2	2	1	2	2	5	2	22
C. dactylon	5	1	4	4	1	1	2	1	1	20
C. flexuosus	3	5	4	3	4	2	1	2	1	25
C. procera	5	4	2	1	2	1	2	4	2	23
C. setosus	3	5	4	5	4	2	2	5	2	32
C. sinensis	4	2	1	3	2	1	2	5	2	22
D. anatolicus	4	5	5	4	1	1	1	3	2	26
D. deltoids	3	5	4	3	4	2	1	2	1	25
D. rotundifolia	5	5	1	2	4	1	2	5	2	27
D. sissoo	4	5	5	4	1	1	1	3	2	26
D. stramonium	3	5	4	3	4	2	1	2	1	25
D. uncinatum	5	5	1	2	4	1	2	5	2	27
D. viscosa	1	1	3	4	3	2	1	5	1	21
E. camaldulensis	4	4	2	3	2	1	2	5	2	25
E. canadensis	5	2	2	1	2	2	2	5	2	23
E. echinatus	5	5	3	5	3	2	2	5	2	32
E. hirta	4	5	3	1	2	1	2	3	2	23
E. repens	5	2	1	3	2	1	2	4	2	22
E. serrate	4	5	5	1	4	1	2	4	2	28
F. drupacea	2	4	5	3	5	2	2	5	2	30
F. tenacissima	5	1	4	4	1	1	2	1	1	20
G. olivieri	2	4	5	3	5	2	2	5	2	30
G. optiva	5	3	4	4	2	1	2	4	1	26
G. royleana	5	3	1	1	2	1	2	3	1	19
H. heteromalla	5	5	3	5	3	2	2	5	2	32
I. Britannica	4	5	3	1	2	1	2	3	2	23
I. heterantha	5	2	1	3	2	1	2	4	2	22
J. adhatoda	4	4	2	1	4	2	2	1	1	21
M. neglecta	5	2	1	3	2	1	2	5	1	22
N. ramosissimum	5	5	4	5	5	2	2	5	2	35
N. ritchiana	5	5	2	4	5	2	1	4	2	30
O. ferruginea	4	5	3	1	2	1	2	3	2	23
P. aphylla	2	4	5	3	5	2	2	5	2	30
P. capillaceum	3	5	1	2	1	1	1	3	1	18
P. cineraria	5	3	4	4	2	1	2	4	1	26
P. harmala	1	3	3	4	2	2	2	3	2	22
P. hysterophorus	3	4	1	1	3	1	2	4	2	21
P. lappacea	3	4	1	1	3	1	2	4	2	21
P. ovate	2	4	5	3	5	2	2	5	2	30
R. hastatus	5	3	4	4	2	1	2	4	1	26
R. limbata	3	4	1	1	3	1	2	4	2	21
R. stricta	3	5	4	3	5	2	2	4	1	29
S. americanum	1	3	3	4	2	2	2	3	2	22
S. arvensis	3	4	1	1	3	1	2	4	2	21
S. marianum	2	4	5	3	5	2	2	5	2	30
S. mascatense	3	4	1	1	3	1	2	4	2	21
S. modesta	4	5	2	1	4	1	2	4	2	25
S. thea	1	3	3	4	2	2	2	3	2	22
V. nilotica	4	5	2	1	3	1	2	5	2	25
W. coagulans	3	4	1	1	2	1	2	3	1	18
W. somnifera	2	4	5	3	5	2	2	5	2	30
Z. indicum	5	1	2	2	1	2	2	5	2	22
Z. jujuba	1	3	3	4	2	2	2	3	2	22
Z. nummularia	3	4	1	1	3	1	2	4	2	21

Note: HLf: Habit/ Life form; H: habitat; Pu: Parts used; Uv: Use value; Ps: Population size; Rr: Regeneration rate; Sc: Season of collection; Qc: Quantity collected (kg/year); Ts: Threat status; TS: Total score

The findings underscore the critical role of local soil conditions in structuring plant communities and emphasize the importance of integrating plant and soil data when assessing biodiversity and ecological relationships. Such an approach provides valuable insights into developing conservation strategies considering ecological factors and dynamic interactions between plants and their soil environments.

Table 7 Soil analysis in both land-use types.

Parameters	Protected area Mean (SD)	Unprotected area Mean (SD)	Mean-Whitney U-test
Soil texture	Silt Loam	Silt Loam	----
Calcium carbonate ($CaCO_3$) (%)	05.23 (0.07)	5.92 (0.18)	$p < 0.01$
Copernicium (Cn^{++}) (ppm)	50.46 (3.94)	49.82 (2.44)	NS
Electric conductivity (dS/m)	00.11 (0.03)	0.31 (0.33)	NS
Iron (II) ion (ppm)	36.52 (1.65)	31.6 (1.75)	$p < 0.01$
Nitrogen (ppm)	00.13 (0.07)	0.02 (0.01)	$p < 0.05$
pH	07.27 (0.62)	8.62 (0.77)	$p < 0.05$
Phosphorus (ppm)	07.02 (0.24)	6.56 (0.62)	NS
Potassium (ppm)	99.88 (3.80)	112.4 (5.59)	$p < 0.01$
Soil organic matter (SOM) (%)	00.14 (0.03)	0.25 (0.05)	NS
T.S.S (Total Suspended solids) (%)	0.04 (0.005)	0.03 (0.01)	NS
Zinc (II) ion (ppm)	16.24 (2.48)	17.70 (2.26)	$p < 0.05$

Discussion

The results of this study highlight substantial differences between protected and unprotected areas, underscoring the importance of a comprehensive understanding of these distinct settings. Protected areas demonstrated significantly higher species diversity and plant abundance, likely due to controlled access and proactive conservation initiatives. Contrariwise, unprotected areas showed reduced plant abundance and were often dominated by invasive species.

A study of Kohat Pass has previously documented diverse plant growth forms characteristic of both land-use types (Shinwari et al. 2011). In the current study, herb species were the most dominant in protected areas, with shrubs and trees following in diversity. This trend suggests that shrubs and trees may exert less competitive pressure on herbs compared to other plant growth forms (Gómez et al. 2004). The high species diversity observed in the protected area, particularly among endemic plant species, is vital in maintaining ecosystem sustainability and supporting various life forms.

The proactive measures in the protected area, such as the plantation of seedlings and saplings, control of soil erosion, and management of invasive alien species, have contributed to the stability and recovery of ecological systems. These interventions not only safeguard biodiversity but also ensure the preservation of indigenous plant species critical for the long-term ecological health of the region (Galabuzi et al. 2014).

Conversely, the unprotected areas showed evidence of extensive overexploitation of natural vegetation. Anthropogenic practices have significantly affected Indigenous plant diversity, disrupting the ecological complexity of ecosystems (Hamilton et al. 2016). Over half of the unprotected area has lost approximately 35% of its Indigenous plant diversity and disrupted the ecological complexity of the ecosystem, and over a quarter has experienced a 47% decline in plant diversity.

This study emphasizes the necessity of conservation measures to mitigate the adverse impacts of human activities on plant diversity. Further, the findings revealed a significant decline in stem density and species diversity in the unprotected area, closely linked to various anthropogenic activities in the study area. These activities included cutting wood for fuel and income, harvesting silage for livestock, extracting timber, and engaging in infrastructural development. Additionally, practices such as grazing, browsing, deforestation, and soil erosion further exacerbated these issues.

These recurrent anthropogenic practices strongly disrupt forest structure and composition, leading to gradual yet profound changes in tree density and the area's overall ecological balance (Khan & Musharaf 2015). The protected area, in contrast, benefits from conservation measures that mitigate the impacts of such destructive activities, emphasizing the critical role of protected areas in preserving forest integrity and biodiversity.

Our study revealed notable differences in plant diversity and abundance between protected and unprotected areas. These findings align with research conducted in Afghanistan, where protected areas exhibited greater vegetation resilience, higher diversity, and species abundance (Breckle 2007). Similar studies in Pakistan have also highlighted the significant positive impact of conservation efforts on plant regeneration and biodiversity (Ali et al. 2005, Adnan et al. 2015).

The current vegetation structure in our study area is particularly vulnerable to pressures such as population growth, infrastructure development, and the increasing awareness of traditional plant uses (Ali et al. 2005). These pressures pose substantial risks to plant diversity, particularly medicinal and aromatic plants, many of which are already under threat of extinction.

This study provides crucial insights into the concentration status of native plant species and their vulnerability to anthropogenic disturbances. In this context, it underscores the importance of protected areas as biodiversity reservoirs and critical habitats for the sustainable preservation of medicinal and aromatic plants. The decline in sapling and seedling density of native plant species in unprotected areas, driven by anthropogenic interruptions, aligns with the findings of Adnan & Hölscher (2010). These disturbances contribute to tree density reduction and species' overall basal area. Such activities not only lower the number of trees but also impede the regeneration potential of native vegetation. Previous studies, including (Adnan et al. 2015) have similarly reported that areas subject to heavy anthropogenic pressures exhibit drastically lower tree densities than protected, regenerated, or minimally disturbed regions.

Our findings also emphasize the significantly higher species richness and density observed in the protected area, where natural and planted seedlings and saplings flourished.

The regeneration of native plant species in protected zones highlights the crucial role of ecological restoration. Measures such as fencing, active planting, and protection from human activities can serve as a practical framework for ecological restoration and biodiversity conservation in regions affected by anthropogenic pressures.

Based on the calculated basal area values, the protected area (28.43 m^2ha^{-1}) demonstrated a markedly better vegetation status and canopy cover compared to the highly disturbed unprotected area (2.96 m^2ha^{-1}), as similarly reported (Traoré et al. 2013). The unprotected area exhibited a higher density of small-diameter trees (3.01 m^2ha^{-1}), whereas the protected area showcased a greater density of large-diameter trees (10.99 m^2ha^{-1}), indicating regeneration of the forest (Keeley et al. 2003).

Among the dominant species, *O. ferruginea* had the highest basal area (14.2 m^2ha^{-1}) in the protected area, followed by *Z. nummularia* (6.022 m^2ha^{-1}), *V. nilotica* (5.92 m^2ha^{-1}) and *S. modesta* (5.76 m^2ha^{-1}). However, these species were at significant risk in the disturbed, unprotected area (Table 2). This indicates the absence of adequate laws or regulations to curb deforestation, which has led to unregulated environmental destruction.

The lack of conservation measures has directly contributed to land degradation and critical vegetation conditions in unprotected areas. This aligns with the findings (Hussain et al. 2013) with similar outcomes due to the absence of conservation strategies and enforcement mechanisms.

Shrub cover growth in the protected area (30-41%) was significantly higher than in the unprotected area (8-10%). These observations align with findings (Eldridge et al. 2011) reported shrub vegetation cover ranging from 15% to 30% under varying biotic and abiotic conditions. The unprotected area exhibited only a moderate diversity index, which may be attributed to the shrubs' resistance to grazing (Nacoulma et al. 2011). However, this resistance does not reflect the success of conservation strategies.

While the protected area exhibited rich shrub abundance and diversity, the distribution of shrub species was similar across both land-use types (Bunalema et al. 2014). These findings underscore the correlation between the protection status and the shrub density, indicating that conservation measures significantly contribute to sustaining within protected areas.

Comparative analysis between protected and unprotected areas highlighted a high density of species such as *R. stricta, W. coagulans, P. aphylla, C. procera,* and *D. viscosa* in the protected region. In contrast, shrub density in the unprotected area was severely degraded due to anthropogenic practices, including overgrazing and land degradation.

Implementing effective vegetation conservation measures and promoting systematic flora utilization are imperative to mitigate the loss of indigenous shrub density.

Most herbs in protected and unprotected areas were identified as weeds. Over the past two decades, locals, IDPs, and nomadic groups have heavily grazed the unprotected area. With the influx of IDPs and nomadic populations, the number of grazing animals has exceeded sustainable limits despite locals initially owning a limited number of domestic animals, such as goats, sheep, and cattle. This overgrazing by increasing animal units (AUs) has had a profound impact on unprotected areas, severely affecting vegetation cover, reducing soil fertility, and consequently diminishing biodiversity.

Additionally, overgrazing has contributed significantly to soil erosion and desertification. Other anthropogenic activities, such as browsing, chopping, and extracting stones and sand, have further restricted herbaceous species in unprotected areas (Ebrahimi et al. 2014).

In contrast, the higher mean densities of herbs in the protected area can be attributed to restricting harmful factors, such as agricultural activities, human interference, and overgrazing (Huffman et al. 2015). These conservation measures have created a safer environment for herbaceous vegetation to thrive.

Prior studies have documented the detrimental effects of human activities and overgrazing on plant reproduction, particularly on processes like flowering and seed production (Lalita & Kumar 2018). Such pressures in unprotected areas likely hinder herbaceous species' natural regeneration and sustainability, further emphasizing the critical role of protection in preserving biodiversity.

In addition to negatively affecting plant abundance and diversity, anthropogenic pressures alter soil fertility and precipitation gradients (Koerner et al. 2018) resulting in shallow floral coverage and herb diversity in unprotected areas. Soil analysis of the study area revealed significant variability in nutrient availability, which plays a crucial role in supporting plant life. Despite these differences, both land-use types share a silt loam texture.

Soil phosphorus levels emerged as a key determinant of biodiversity, influencing the structure and composition of plant communities. While some studies indicate that nutrient-poor soils can lead to declining plant stand characteristics (Lal et al. 2018) other research suggests that nutrient-deficient ecosystems may support higher species richness (Schröder & Kiehl 2020).

A substantial increase in $CaCO_3$, potassium, and pH was observed in unprotected areas compared to the protected zone due to human and livestock practices (trampling, consumption, excreta deposition, redistribution) that may positively affect soil nutrient behavior (Gilmullina et al. 2020). However, soil organic matter, phosphorus, Copernican, electrical conductivity, and total soluble salts did not differ significantly between the land-use types.

Overgrazing, particularly trampling, accelerates soil erosion in unprotected areas by increasing surface compaction and reducing water infiltration. However, livestock waste (excreta) is essential in maintaining soil properties, contributing essential nutrients that sustain soil health. In semi-arid and humid regions, calcium salt accumulation due to water scarcity can fix phosphorus, making it less available for plants (Jiang et al. 2022). This further highlights the intricate relationship between soil composition and plant growth.

Protecting endangered and threatened plant species depends on effective conservation measures. The success of protected areas in maintaining biodiversity reinforces the importance of their long-term preservation. Future land management strategies should integrate plant-soil interactions to enhance understanding of species distribution and ecosystem stability.

Conclusions

This study highlights the decline in native plant diversity and tree stand structures, including species richness, shrub density, and herbaceous cover, primarily due to increased anthropogenic activities. However, the protected area demonstrated significant growth of saplings and seedlings, indicating successful restoration efforts. Despite fertile soil textures, deficiencies in essential macronutrients were observed, affecting overall plant health. These findings establish a baseline for tracking vegetation changes over time and emphasize the urgency of conserving plant diversity by mitigating overgrazing and promoting reforestation.

To address these challenges, we recommend large-scale conservation programs to mitigate overgrazing, control deforestation, and promote the natural regeneration of native seedlings. We also recommend actively involving local communities, including farmers, herders, respected elders, and religious leaders, through workshops, awareness programs, and reforestation initiatives. We encourage politicians and stakeholders to support balanced conservation policies integrating local needs with ecosystem sustainability. Further ecological, ethnobotanical, and pharmacological studies are recommended for a comprehensive approach to conservation in the Kohat region.

Conflict of interest

No financial or personal interests could influence the authors' work.

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Data availability

Data supporting the findings of this study are included in the manuscript.

Author contribution statement

MZ designed the study, conducted the fieldwork, and prepared the draft manuscript for publication. SB helped compile and analyze the data. MA and WM supervised the study at all stages and contributed to the manuscript draft. MZ and SK contributed to developing the supplementary table and reviewed the entire manuscript draft for improvement. We are pleased to announce that all authors have read and approved of the final manuscript.

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