Research Article

Phytoclimatic Patterns and Seasonal Variation in Plant Life Forms and Leaf Size Spectra in District Dir Lower, Pakistan

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Abstract | A year-long ecological investigation was conducted in District Dir Lower (Timergara, Fazal, and Tehsil Munda), Pakistan, to assess seasonal variation in plant life forms and leaf size spectra. The objective of this study was to evaluate phytoclimatic patterns and ecological responses of vegetation using Raunkiaer's life form classification and leaf size spectra across seasons. The study was carried out from spring 2022 to winter 2023 across eight ecologically distinct sites selected based on variation in vegetation structure, soil characteristics, and floristic composition. A total of 145 species were recorded in spring, 131 in summer, 126 in autumn, and 77 in winter, indicating clear seasonal fluctuations in species richness. Therophytes were the dominant life form throughout the year, with the highest proportion observed in spring (66.3%), followed by hemicryptophytes and megaphanerophytes, while geophytes, chamaephytes, and other phanerophytic classes (nano, micro, and mesophanerophytes) were less frequent. Leaf size spectra showed the predominance of microphyllous species (35.0–45.8%) across all seasons, followed by nanophylls, leptophylls, mesophylls, and a few aphyllous species. The dominance of therophytes and microphylls reflects adaptation to environmental stress conditions, likely influenced by overgrazing, deforestation, and anthropogenic disturbances. These findings highlight the phytoclimatic sensitivity of the region and emphasize the need for sustainable management and conservation strategies. Future studies incorporating long-term climatic data and functional trait analysis are recommended to better understand vegetation responses under changing environmental conditions.

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Introduction

District Dir Lower, part of the Malakand Division in Khyber Pakhtunkhwa, was established as a separate administrative district in 1996. It lies between 71°31′ and 72°14′ East longitude and 34°37′ and 35°07′ North latitude (Ali *et al*., 2018; Bano *et al*., 2018; Gul *et al*., 2018). The district is bordered by

Bajaur in the northwest, Swat in the northeast, Upper Dir in the north, and Malakand and Mohmand in the south (Jamil et al., 2022). The total area of District Dir Lower is approximately 1,586 square kilometers and is characterized by rugged mountainous terrain interspersed with narrow valleys and cultivated plains (Angyalossy *et al.*, 2022; Flores-Argüelles *et al.*, 2022; Wani *et al.*, 2022b; Watts *et al.*, 2022). Timergara is the district headquarters, while Fazal and Tehsil Munda are among the prominent administrative units of the region (Farooq *et al.*, 2019; Khan and Badshah, 2019; Ca *et al.*, 2020; Wani and Pant, 2021; Wani *et al.*, 2022a).

The climate of Dir Lower is moderately temperate, with cold winters and relatively hot summers. Temperatures begin to rise from April, peaking in June and July, while the coldest months are December and January (Li et al., 2021; Zhao *et al.*, 2021). Rainfall occurs throughout the year, with two peaks: one during winter due to western disturbances and another during the monsoon season (July–August) (Wani *et al.*, 2021; Su *et al.*, 2022; Wani and Pant, 2022). The climatic variability and altitudinal differences across the district create diverse microhabitats supporting a wide range of vegetation types (Asif et al., 2020).

According to Takhtajan (1969a) and Ali and Qaiser (1986), there are three phytogeographical regions in Pakistan, i.e., Irano-Turanian, Saharo-Sindian, and the Indian regions (Khan et al., 2020). But Hara (1966) also recognized the Sino-Japanese region. Thus, four phytogeographical regions are recognized in Pakistan. Each region is delimited based on certain criteria, apart from others, by Zohary (1950), and characterized by the presence of a component of the flora or phytogeographical elements (Zohary, 1950).

Ecologically, the region experiences four distinct seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February), each characterized by variations in temperature, light intensity, and moisture availability (Takhtajan, 1969b). These seasonal changes play a significant role in influencing plant growth, flowering, reproduction, and species composition. Seasonal variation in ecological parameters such as temperature and precipitation affect not only the distribution and abundance of plant species but also their physiological and morphological adaptations (Zohary, 1950).

Flora refers to the total plant life in a given region and serves as a key indicator of ecological health and environmental conditions (Hara, 1966). The structure and composition of plant communities reflect adaptations to local climatic factors. Life forms, as defined by Raunkiaer (1934), provide insight into how plant species survive under specific environmental conditions (Haq *et al.*, 2020). The concept of the "biological spectrum" helps to analyze the proportion of different life forms in a region, offering clues about its phytoclimatic nature (Axelrod and Raven, 1978). Phytoclimate refers to the prevailing climate within plant communities and can be studied through life form and leaf size spectra to understand environmental pressures and ecological resilience (Eig, 1931).

Table 1: *Climatic data of District Dir Lower, Khyber Pakhtunkhwa, Pakistan.*

Months	Temperature (°C)			Precipitation (mm)	Average humidity (%)
	Maximum	Minimum	Average		
January	17.7	2.8	10.2	55	27
February	19.4	6	12.7	58	41
March	24.4	10.6	17.5	69	38
April	30.1	15.3	22.7	47	34
May	36.1	20	28	23	25
June	41	24.9	32.9	25	24
July	38	25.7	31.8	110	44
August	36	24.8	30.4	137	51
September	35	21.9	28.4	58	43
October	31.7	15.1	23.4	14	29
November	25.5	8.3	16.9	12	29
December	19.7	3.8	11.7	31	24
Annual	29.5	14.9	22.2	53.2	34.0

Source: Climate data. org., 2023

Phytoclimate analysis through seasonal monitoring of life form and leaf size spectra provides valuable insights into the adaptive strategies and ecological dynamics of plant communities. In District Dir Lower, the flora exhibits marked seasonal variation, reflecting responses to fluctuating climatic conditions such as temperature, precipitation, and humidity (Table 1; Manan *et al.*, 2025). Life form classification based on Raunkiaer's system reveals the dominance of therophytes, short-lived annual plants, across all seasons, indicating an environment under considerable ecological stress, possibly due to overgrazing and deforestation (Ahmad *et al.*, 2016;

Amri *et al*., 2019; Ur Rahman *et al*., 2021; Ali *et al*., 2022). Hemicryptophytes and various categories of phanerophytes also contribute to the vegetation structure, although to a lesser extent. Leaf size spectra consistently show a predominance of microphylls, which are small leaves adapted to reduce water loss, further underscoring the region's adaptation to variable and often challenging environmental conditions (Bridson and Forman, 1998). Seasonal shifts in species richness and leaf morphology highlight the intricate relationship between plant functional traits and the prevailing phytoclimate, emphasizing the importance of these parameters in assessing ecosystem health and guiding conservation efforts (Nasir and Ali, 1972).

Plant species can be classified into five main life form categories according to Raunkiaer's system: phanerophytes, chamaephytes, hemicryptophytes, cryptophytes, and therophytes. The combined percentages of these life forms and leaf size classes form the biological spectrum, which serves as a useful tool to predict both microclimatic and macroclimatic conditions (Brummitt *et al*., 2001). Leaf size spectra, reflecting physiological traits of plant communities, also provide insights into plant–environment interactions and ecological adaptations (Abbas *et al*., 2021; Ahmad *et al*., 2022b; Anwar *et al*., 2022; Haq *et al*., 2022). Together, life form and leaf size spectra are important physiognomic indicators that reveal the ecological amplitude and tolerance of species in response to climatic factors and human disturbances (Longo et al., 2019).

Studying phytoclimatic patterns is essential not only for understanding ecological responses but also for informing conservation strategies (Yang *et al*., 2022). Changes in species composition and life form dominance can serve as bioindicators of anthropogenic pressure, such as overgrazing and deforestation. Therefore, a deeper investigation into the seasonal dynamics of flora and phytoclimate in District Dir Lower is critical for developing long-term conservation plans and managing biodiversity under changing environmental conditions (Khan *et al*., 2017; Ahmad *et al*., 2021, 2022a; Iqbal *et al*., 2021; Ali *et al*., 2022a, b).

The primary objective of this study was to investigate the seasonal variation in the phytoclimate of District Dir Lower by analyzing the distribution of plant life forms and leaf size spectra across different seasons. Specifically, the research aimed to (i) document seasonal variation in floristic diversity, (ii) classify plant species according to Raunkiaer's life form system, and (iii) analyze leaf size spectra in relation to environmental conditions (Hussain *et al*., 2022; Khan *et al*., 2022). Furthermore, the study aimed to identify indicators of ecological stress, such as the dominance of therophytes and microphyllous leaves, which may reflect the impact of anthropogenic factors, including overgrazing and deforestation. Ultimately, the findings are intended to provide baseline data for understanding vegetation dynamics and to support biodiversity conservation and sustainable ecosystem management in the region.

Materials and Methods

Field survey and site selection

This study was conducted in District Dir Lower, including the areas of Timergara, Fazal, and Tehsil Munda, over four consecutive seasons, spring, summer, autumn, and winter from 2022 to 2023. A total of eight ecologically diverse stands were selected based on variations in physiognomy, floristic composition, and edaphic (soil-related) characteristics to comprehensively assess the ecological features of the regional flora (Ahmad *et al*., 2019; Ahmed *et al*., 2019; Anwar *et al*., 2019; Hussain *et al*., 2019; Kamran *et al*., 2020). "Plant material collection was conducted in accordance with institutional, local, and national regulations. The studied species are common and widely distributed, and no specific permits were required."

Life form spectra (biological spectra)

Following the classification framework of Raunkiaer (1934) and Hussain (1989), plant species from the study area were categorized into five main life form classes based on the position of their perennating buds relative to the ground surface (Abbas *et al*., 2019):

- *Phanerophytes:* Plants with perennating buds located more than 25 cm above the ground surface, including trees and shrubs. This category is further subdivided into:
- *Megaphanerophytes:* Tall trees with buds located above 30 m.
- *Mesophanerophytes:* Small trees with buds located between 7.5 and 30 m.
- *Microphanerophytes:* Small trees and shrubs with

buds located between 2 and 7.5 m.

- *Nanophanerophytes:* Perennial shrubs with buds located between 0.25 and 2 m.
- *Chamaephytes:* Woody or semi-woody plants with perennating buds located less than 25 cm above the ground surface, including under shrubs and cushion plants.
- *Hemicryptophytes:* Herbaceous perennial plants with buds situated at or just below the soil surface; aerial parts typically die back during unfavorable seasons.
- *Geophytes:* Plants with underground perennating buds, such as bulbs, tubers, rhizomes, and corms.
- *Therophytes:* Annual plants that complete their life cycle within a single growing season, with perennating structures in the form of seeds.

The life form spectra percentage for each class was calculated as: Raunkiaer's life form spectra were calculated as;

$$\text{Raunkiaer's life form spectra} = \frac{\text{Number of species belonging to a specific life form class}}{\text{Total number of all species in a stand}} \times 100$$

Leaf size spectra

Leaf size classification of plant species from District Dir Lower was performed following Raunkiaer (1934), in which species were grouped into six categories based on leaf area (Kamran *et al*., 2020):

- *Leptophylls:* Leaf area < 25 mm^2
- *Nanophylls:* 25–225 mm^2
- *Microphylls:* 225–2025 mm^2
- *Mesophylls:* 2025–18,225 mm^2
- *Macrophylls:* 18,225–164,025 mm^2
- *Megaphylls:* Leaf area > 164,025 mm^2
- Leaf area was calculated using the formula of Cain and Castro (1959):

Leaf size/area = Leaf length (mm) × Leaf breadth (mm) × 2/3

The relative abundance of each leaf size class was calculated as:

$$\text{Raunkiaer's leaf size spectra} = \frac{\text{Number of species belonging to a specific leaf size class}}{\text{Total number of all species in a stand}} \times 100$$

Statistical analysis

Descriptive statistics were used to summarize seasonal variation in life form and leaf size spectra. The percentage of each category was calculated for all seasons. Pearson's correlation analysis was performed to evaluate the relationships among seasonal percentages. Correlation coefficients (r) were computed to assess the strength and direction of associations between seasons, and the results were visualized using a heatmap. All analyses were conducted using R software (R Core Team, 2023).

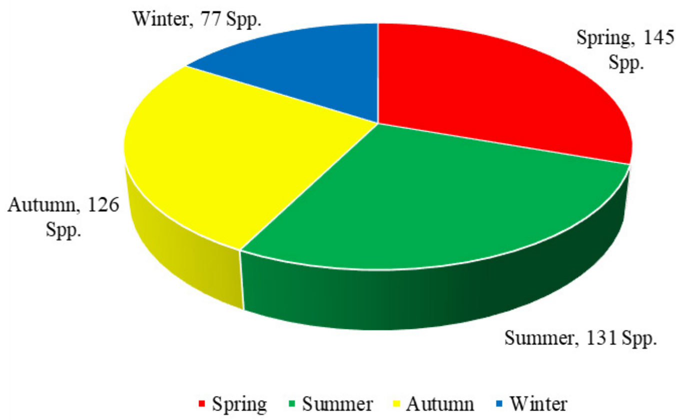

Figure 1: *Seasonal variation in the flora of District Dir Lower.*

Results

Life form spectra

A total of 145 plant species were recorded during the spring season (Figure 1). Seasonal analysis of life form spectra revealed a clear dominance of therophytes, which constituted 96 species (66.3%), indicating a strong prevalence of short-lived annuals under favorable spring conditions. Hemicryptophytes represented the second most abundant group with 17 species (11.7%), followed by megaphanerophytes with 10 species (6.9%). Geophytes, nanophanerophytes, and microphanerophytes were each represented by 6 species (4.1%). Mesophanerophytes were comparatively less frequent, with 3 species (2.1%), while parasites were represented by a single species (0.7%) (Shah et al., 2021). In summer, a total of 131 species were recorded (Figure 1). Although therophytes remained the dominant life form, their proportion declined to 64 species (48.8%), reflecting seasonal shifts in vegetation structure. Hemicryptophytes increased to 25 species (19.1%), suggesting improved persistence of perennial herbs under relatively favorable summer conditions. Nanophanerophytes and megaphanerophytes were equally represented, each contributing 10 species (7.7%). Geophytes accounted for 9 species (6.8%),

Table 2: *Seasonal variation in life form spectra of flora of district dir lower, pakistan.*

S.No.	Ecological attributes	Spring		Summer		Autumn		Winter	
		No.	% Age	No.	% Age	No.	% Age	No.	% Age
1.	Therophytes	96	66.3	64	48.8	64	50.8	36	46.7
2.	Hemicryptophytes	17	11.7	25	19.1	20	15.9	12	15.6
3.	Geophytes	6	4.1	9	6.8	8	6.3	1	1.3
4.	Nanophanerophytes	6	4.1	10	7.7	11	8.7	7	9.1
5.	Megaphanerophytes	10	6.9	10	7.7	10	7.9	10	13.0
6.	Microphanerophytes	6	4.1	6	4.6	6	4.8	6	7.8
7.	Mesophanerophyte	3	2.1	4	3.1	4	3.2	3	3.9
8.	Chamaephytes	0	0.0	2	1.5	3	2.4	1	1.3
9.	Parasite	1	0.7	1	0.7	0	0	1	1.3
Total		145	100	131	100	126	100	77	100

followed by microphanerophytes with 6 species (4.6%) and mesophanerophytes with 4 species (3.1%). Chamaephytes were represented by 2 species (1.5%), while parasites remained rare, with only 1 species (0.7%) (Ullah and Badshah, 2017; Bedair *et al.*, 2021).

During autumn, 126 species were recorded (Figure 1), with therophytes maintaining dominance at 64 species (50.8%). Hemicryptophytes were the second most abundant group, comprising 20 species (15.9%). Nanophanerophytes contributed 11 species (8.7%), followed by megaphanerophytes with 10 species (7.9%). Geophytes accounted for 8 species (6.3%), while microphanerophytes remained stable with 6 species (4.8%). Mesophanerophytes and chamaephytes were represented by 4 species (3.2%) and 3 species (2.4%), respectively. These patterns indicate a transitional phase in vegetation composition associated with declining temperature and moisture availability. In winter, species richness declined markedly to 77 species (Figure 1), reflecting harsh environmental conditions. Therophytes continued to dominate, but at a reduced proportion of 36 species (46.7%). Hemicryptophytes followed with 12 species (15.6%), while megaphanerophytes showed relatively higher representation with 10 species (13.0%). Nanophanerophytes accounted for 7 species (9.1%), and microphanerophytes for 6 species (7.8%). Mesophanerophytes were represented by 3 species (3.9%), whereas geophytes, chamaephytes, and parasites were each represented by a single species (1.3%) (Table 2; Figure 2).

Overall, the life form spectra across all seasons demonstrate consistent dominance of therophytes, accompanied by notable seasonal fluctuations in other life form categories. Species richness showed a clear seasonal trend, with maximum diversity in spring (145 species) and minimum in winter (77 species), reflecting strong climatic control on vegetation dynamics. The increased proportion of hemicryptophytes during summer indicates favorable conditions for perennial herbs, while the relatively stable presence of phanerophytic elements suggests structural continuity of woody vegetation throughout the year Table 2.

Geophytes maintained low but consistent representation, highlighting their adaptation through underground storage organs to survive unfavorable conditions. Chamaephytes and parasites remained rare across all seasons, indicating limited ecological distribution within the study area. The dominance of therophytes, along with seasonal variation in life form composition, reflects strong phytoclimatic influence, particularly the effects of temperature fluctuations, moisture availability, and anthropogenic disturbances such as overgrazing and deforestation. The data demonstrate a consistent dominance of therophytes across all seasons, highlighting their adaptability and prevalence in the study area's varying climatic conditions. The proportion of therophytes peaked during spring (66.3%) when conditions favor rapid growth and reproduction of annual species (Ullah and Badshah, 2017; Bedair *et al.*, 2021). This dominance gradually decreased through summer and autumn but remained significant, indicating that annual plants form a major component of the local flora year-round. Hemicryptophytes, which typically consist of perennial herbaceous plants with buds near the soil surface, showed an opposite trend, increasing in relative abundance during the warmer months, likely benefiting from more stable soil moisture and temperature conditions (Manan *et al.*, 2025).

Phanerophytes, particularly megaphanerophytes and nanophanerophytes, maintained a steady presence throughout the year, reflecting the persistence of woody vegetation adapted to the region's ecological conditions (Khan *et al.*, 2013). The presence of geophytes and chamaephytes, although lower in percentage, suggests the occurrence of species adapted to survive unfavorable seasons through underground storage organs or low-stature growth forms (Sher and Khan, 2007). The reduction in total species richness during winter (77 species) compared to other seasons aligns with harsher climatic conditions that limit plant growth and reproduction. However, the presence of all life forms during winter indicates a resilient flora capable of surviving seasonal extremes (Hussain *et al.*, 2015). These seasonal variations in life form spectra not only reflect adaptive strategies of the plant community but also provide insight into the ecological and climatic influences shaping vegetation dynamics in District Dir Lower. The dominance of short-lived therophytes, particularly, may also suggest ecological disturbances such as grazing pressure or land use changes, which tend to favor fast-growing, opportunistic species (Hussain *et al.*, 2015).

Leaf size spectra

The analysis of leaf size spectra in District Dir Lower revealed a consistent dominance of microphyllous species across all seasons, indicating a strong adaptive response of the local flora to prevailing environmental conditions. In spring, microphylls constituted 40.0% of the total flora, followed by nanophylls (33.1%), suggesting that smaller leaf sizes are well suited to the moderate temperature and moisture conditions characteristic of this season (Haas et al., 2018). The presence of leptophylls and mesophylls in relatively lower proportions further reflects the limited occurrence of extreme leaf size strategies under these conditions (Figure 2).

During summer, the proportion of microphylls increased to 45.8%, while nanophylls declined to 29.0%, highlighting a shift toward smaller leaf sizes under increasing temperature and evapotranspiration stress. This pattern suggests that plants with reduced leaf area are better adapted to minimize water loss through transpiration, thereby enhancing survival under dry and warm conditions. Similar trends have been reported in arid and semi-arid environments, where microphyllous species dominate due to their efficient water-use strategies (Nasir and Sultan, 2002). The persistence of leptophylls and mesophylls in moderate proportions indicates that some species maintain broader leaf structures, possibly in microhabitats with relatively higher moisture availability (Figure 2).

In autumn, microphylls remained dominant (44.5%), with nanophylls contributing 32.5%, reflecting continuity in adaptive strategies despite seasonal transitions. The equal representation of leptophylls and mesophylls (11.1% each) suggests a balancebetween drought-tolerant and moderately moisture-

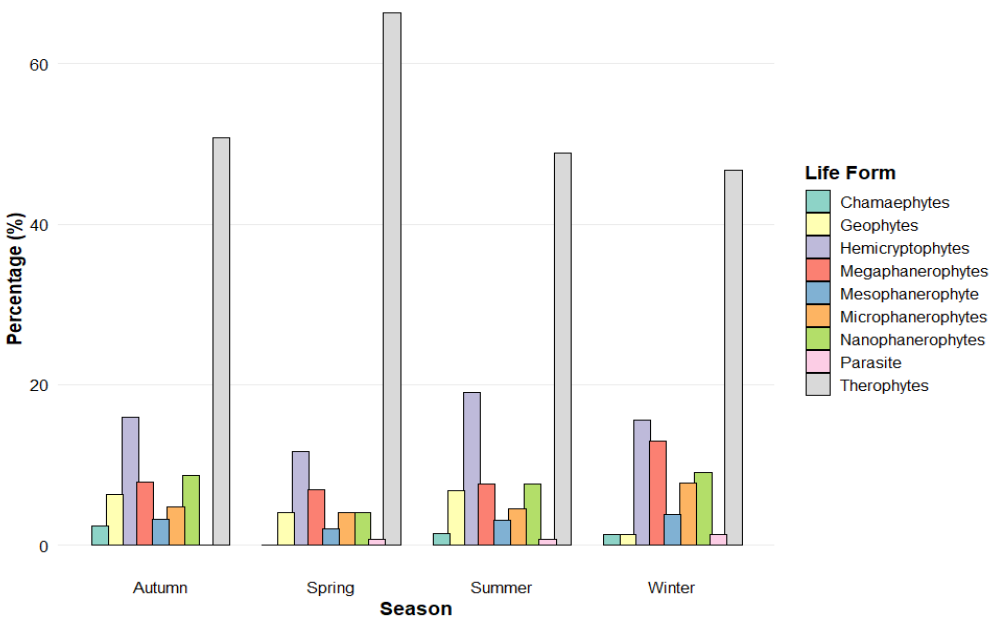

Figure 2: *Seasonal variation in life form spectra of the flora of district dir lower.*

demanding species. This transitional phase likely corresponds to decreasing temperature and variable moisture conditions, allowing the coexistence of different leaf size classes (Figure 2).

In winter, the proportion of microphylls declined to 35.0%, while nanophylls remained relatively stable (33.8%), and mesophylls increased to 16.9%. This shift indicates a partial relaxation of water stress and a greater contribution of species with larger leaf areas adapted to cooler and relatively moist conditions. The increase in mesophyllous species during winter may be associated with reduced evapotranspiration rates, allowing plants with broader leaves to maintain photosynthetic activity more efficiently (Figure 2).

The consistent dominance of microphyllous species across all seasons strongly supports the interpretation that the flora of District Dir Lower is adapted to water-limited and environmentally stressful conditions. Smaller leaves reduce surface area, thereby minimizing water loss and enhancing resistance to heat and drought stress (Sher and Khan, 2007). The substantial presence of nanophylls further reinforces this adaptation, indicating that a significant proportion of species exhibit intermediate strategies for balancing water conservation and photosynthetic efficiency (Figure 2).

Seasonal variation in leaf size spectra reflects the dynamic nature of plant functional traits in response to environmental fluctuations (Figure 1). Plants in this region appear to optimize leaf morphology to balance water-use efficiency and carbon assimilation under varying climatic conditions. The coexistence of multiple leaf size classes suggests ecological heterogeneity and the presence of diverse microhabitats supporting species with different adaptive strategies (Sher and Khan, 2007).

Overall, the leaf size spectra provide strong evidence of phytoclimatic control over vegetation structure in District Dir, Lower Table 3. The predominance of small-leaved species, coupled with seasonal shifts in leaf size distribution, highlights the influence of

Table 3: *Seasonal variation in leaf size spectra of flora of district dir lower, pakistan.*

S.No.	Ecological attributes	Spring		Summer		Autumn		Winter	
		No.	% Age	No.	% Age	No.	% Age	No.	% Age
1.	Microphylls	58	40.0	60	45.8	56	44.5	27	35.0
2.	Nanophylls	48	33.1	38	29.0	41	32.5	26	33.8
3.	Leptophylls	21	14.5	17	13.0	14	11.1	9	11.7
4.	Mesophylls	16	11.0	14	10.7	14	11.1	13	16.9
5.	Aphyllous	2	1.4	2	1.5	1	0.8	2	2.6
Total		145	100	131	100	126	100	77	100

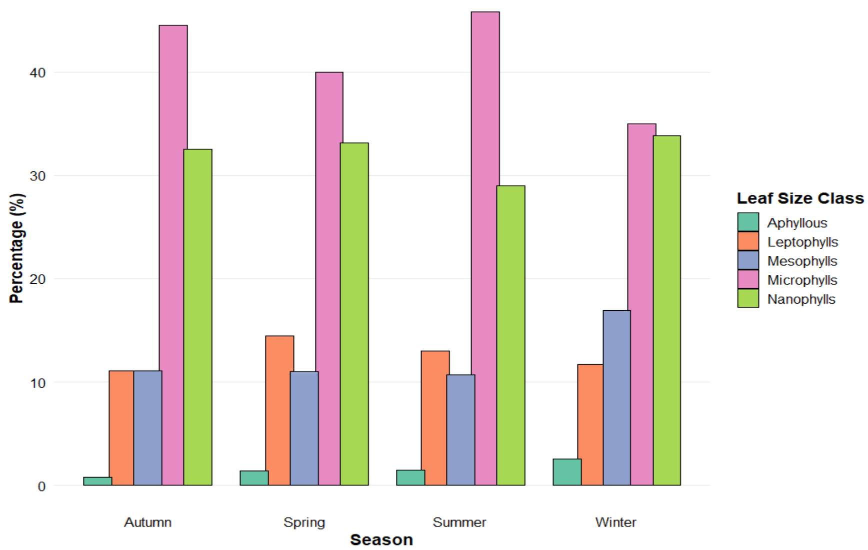

Figure 3: *Seasonal variation in leaf size spectra of the flora of district dir lower*

temperature, moisture availability, and anthropogenic pressures on plant adaptation. These findings emphasize the ecological significance of leaf size as a functional trait for assessing environmental stress and vegetation dynamics in mountainous ecosystems (Table 3; Figure 3).

Correlation analysis

Correlation analysis of seasonal percentages revealed a strong positive relationship among all seasons (Figure 4). The highest correlations were observed between winter, summer, and autumn, with correlation coefficients reaching 1.00, indicating nearly identical patterns among these seasons. Spring also showed strong positive correlations with the other seasons, with values ranging from 0.98 to 0.99. Overall, the consistently high correlation values (0.98–1.00) suggest that seasonal variation in the studied parameter is highly synchronized across all seasons, with only minor differences observed in spring compared to the other seasons. This indicates a stable and closely related pattern of variation throughout the year.

Discussion

Seasonal variation represents predictable changes in environmental conditions throughout the year, primarily driven by fluctuations in temperature, precipitation, and other climatic factors (Tareen and Qadir, 1993; Badshah *et al*., 2013; Ullah *et al*., 2025a). These variations exert a profound influence on plant communities by regulating their growth patterns, physiological processes, chemical composition, and overall ecological performance (Takhtajan, 1986; Zeb *et al*., 2021; Khan *et al*., 2022; Ullah and Shakir, 2023). Vegetation physiognomy, which reflects the structural and functional interaction of plants with their environment, can be effectively interpreted through plant life forms. Raunkiaer's life form classification, based on the position and protection of perennating buds during unfavorable conditions, remains a robust and widely accepted framework for understanding plant adaptation to climatic regimes (Ullah *et al*., 2015).

In the present study conducted in District Dir Lower, life-form analysis revealed a consistent dominance of therophytes across all seasons, with a particularly high proportion in spring (Ullah *et al*., 2023). Therophytes, as annual plants completing their life cycle within a short period, are well adapted to environments characterized by seasonal variability and ecological disturbance. Their dominance in spring reflects favorable conditions for rapid germination, growth, and reproduction, allowing them to exploit transient resources efficiently (Siadati *et al*., 2010). This pattern is consistent with previous studies conducted in similar ecological zones (Ejaz *et al*., 2022) and strongly suggests the influence of biotic pressures such as overgrazing, deforestation, and land-use changes, as also reported by Pandit et al. (2012).

The ability of therophytes to persist under harsh climatic conditions, including drought and low temperatures, further explains their widespread

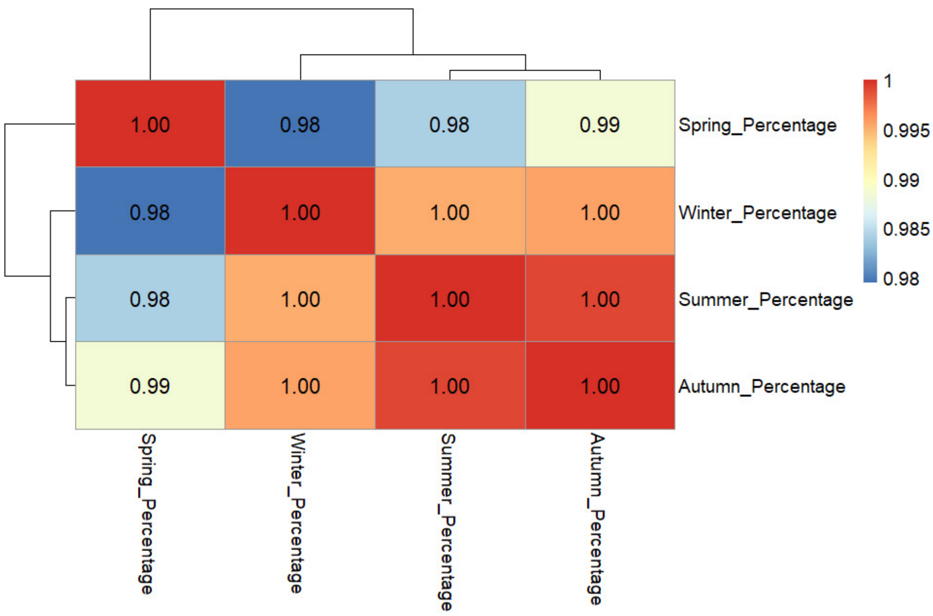

Figure 4: *Correlation analysis of the percentage of seasonal variation*

occurrence, as highlighted by (Abbas *et al*., 2021; Ahmad *et al*., 2022b; Anwar *et al*., 2022; Haq *et al*., 2022; Yang *et al*., 2022; Shakir *et al*., 2023a, b).

Seasonal fluctuations in other life form categories, including hemicryptophytes, geophytes, and phanerophytes, reflect the dynamic ecological responses of vegetation to changing environmental conditions (Khan *et al*., 2017; Ahmad *et al*., 2021, 2022a; Subhan *et al*., 2024). Hemicryptophytes showed increased representation during favorable seasons, particularly summer, indicating their ability to maintain growth under moderate climatic conditions through perennating buds located at the soil surface (Khan *et al*., 2018c). Geophytes, though limited in number, demonstrate an important adaptive strategy through underground storage organs, enabling survival during adverse periods and regeneration during favorable seasons (Ullah *et al*., 2025b). Phanerophytes, including woody trees and shrubs, maintained a relatively stable representation throughout the year, highlighting their structural role in the ecosystem and resilience to seasonal climatic stress (Manan *et al*., 2025). These patterns underscore the importance of diverse survival strategies, such as dormancy, seed persistence, and vegetative reproduction, in shaping plant community composition (Khan *et al*., 2018b; Iqbal *et al*., 2021; Ali *et al*., 2022a, b; Hussain *et al*., 2022; Khan *et al*., 2022; Ullah *et al*., 2024a).

The analysis of leaf size spectra further enhances the understanding of plant adaptive strategies in the study area. Microphylls were consistently dominant across all seasons, followed by nanophylls, leptophylls, and mesophylls. This predominance of smaller leaf sizes aligns with findings from similar ecological regions (Abbas *et al*., 2019; Ahmad *et al*., 2019; Ahmed *et al*., 2019; Anwar *et al*., 2019; Hussain *et al*., 2019; Kamran *et al*., 2020; Khan, 2022) and reflects adaptation to environmental stress conditions, particularly water limitation and high evapotranspiration. Smaller leaves reduce surface area, thereby minimizing water loss and thermal stress, making them advantageous under semi-arid and disturbed conditions. The dominance of microphylls in this study supports observations by (Angyalossy *et al*., 2022; Flores-Argüelles *et al*., 2022; Wani *et al*., 2022b; Watts *et al*., 2022; Ullah *et al*., 2024), who associated smaller leaf sizes with areas experiencing significant anthropogenic disturbance, further indicating that human activities are influencing vegetation structure in District Dir Lower.

Climatic factors, particularly temperature gradients and altitude, play a crucial role in determining the distribution of leaf size. Microphylls are typically associated with regions exhibiting moderate climatic conditions and environmental variability, as reported by Haq *et al*. (2020). Seasonal changes in leaf size classes observed in this study can also be attributed to the differential responses of annuals, perennials, and geophytes, which employ distinct adaptive strategies under varying environmental conditions. These findings are consistent with those of Zhao *et al*. (2021), who documented similar seasonal trends in leaf size spectra in neighboring regions. Despite the strong ecological significance of leaf size, it alone cannot fully explain plant adaptation to climatic conditions. Other morphological and physiological traits, including plant habit, root architecture, and reproductive strategies, also contribute significantly to vegetation responses along environmental gradients (Ullah *et al*., 2025c). Therefore, a comprehensive understanding of plant adaptation requires integration of multiple functional traits (Ali *et al*., 2018; Bano *et al*., 2018; Gul *et al*., 2018).

Collectively, life form and leaf size spectra serve as powerful physiognomic indicators of phytoclimate and anthropogenic influence on vegetation (Asif *et al*., 2025). The predominance of therophytes and microphyllous species observed in this study reflects ecological stress conditions and highlights the combined effects of climatic variability and human disturbance. These traits provide valuable insights into the ecological amplitude, resilience, and adaptive capacity of plant species (Khan *et al*., 2018a). The phytoclimatic spectrum derived from these characteristics is essential for assessing ecosystem health and for developing effective conservation and management strategies aimed at preserving plant biodiversity in the District Dir Lower.

Conclusions

This study assessed the flora of District Dir Lower (Timergara, Fazal, and Tehsil Munda) across four seasons in 2022–2023, revealing significant seasonal variations in life form and leaf size spectra. Therophytes dominated throughout the year, especially in spring, reflecting their adaptability to climatic extremes and biotic pressures like overgrazing. Hemicryptophytes, geophytes, and phanerophytes also contributed, indicating diverse survival strategies. The prevalence of microphyllous leaves highlights adaptations for water efficiency, while other leaf sizes reflect habitat diversity. These patterns serve as important indicators of the region's phytoclimate and ecological health. The findings suggest that anthropogenic stress threatens local flora, underscoring the need for targeted conservation and further research to ensure sustainable management of the region's biodiversity.

Recommendations

Sustainable management of vegetation in District Dir Lower requires controlling overgrazing and deforestation to reduce ecological stress. Conservation and restoration of native plant species should be prioritized through afforestation programs. Long-term monitoring of vegetation patterns is recommended to assess the impacts of climate change. Additionally, community awareness and participation are essential for effective biodiversity conservation and sustainable resource use.

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Novelty statement

This study provides the first comprehensive seasonal phytoclimatic assessment of vegetation in District Dir Lower, Pakistan, integrating life form and leaf size spectra across four seasons. By combining Raunkiaer's classification with detailed field-based observations, the research reveals clear patterns of ecological adaptation, particularly the dominance of therophytes and microphyllous species under environmental stress and anthropogenic disturbance. The study offers baseline ecological data and novel insights into seasonal vegetation dynamics, contributing to improved understanding of plant–climate relationships and supporting biodiversity conservation and sustainable ecosystem management in mountainous regions.

Author's Contributions

Falak Naz, Mohammad Sohail, Sajid Ali, Hasnain Khan, and Azmat Noreen: Were responsible for field surveys, data collection, and preliminary data organization.
Lubna Shakir: Contributed to data analysis and assisted in manuscript drafting and revision.
Shakir Ullah: Conceived and designed the study, performed data analysis, supervised the research work, and led the writing of the manuscript.
Shah Alam Khan: Contributed to data analysis and assisted in manuscript drafting and revision.
All authors critically reviewed and approved the final manuscript.

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The authors declare that no generative AI was used in the creation of this manuscript.

Conflict of interest
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