

Strategic priorities and integrated approaches for the Conservation of Pteridophyte Diversity in the Western Himalaya, North India

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Abstract

Pteridophytes, encompassing ferns and lycophytes, constitute one of the most ancient lineages of vascular plants and represent a vital yet frequently overlooked component of mountain biodiversity. The Western Himalaya of North India, forming a major part of the Indian Himalayan Region, provides a unique combination of altitudinal gradients, climatic heterogeneity, and complex geological history that has promoted high pteridophyte richness and endemism. Despite their ecological importance and sensitivity to environmental change, pteridophytes remain inadequately represented in floristic inventories, conservation assessments, and policy frameworks when compared with seed plants. This research paper presents a comprehensive synthesis and strategic framework for the study and conservation of pteridophytes in the Western Himalayan region, with particular emphasis on priority landscapes in Uttarakhand, selected mid-elevation valleys, high-altitude tracts of Himachal Pradesh, and moisture-retaining pockets of the Shivalik foothills. The paper further emphasizes the importance of long-term monitoring, climate-responsive planning, and community participation to ensure sustainable conservation outcomes. By articulating clear research priorities and conservation pathways, this work aims to contribute toward a more inclusive and resilient biodiversity strategy for the Western Himalaya under conditions of rapid environmental and socio-economic change.

Key words : Pteridophytes; Western Himalaya; Indian Himalayan Region; fern diversity; elevational gradients; conservation strategy; Uttarakhand; ex-situ conservation.

Mountain ecosystems are globally recognized as centers of biological diversity, endemism, and ecological specialization, largely due to their pronounced environmental gradients and historical isolation^{1,3,13,14}. Among these systems, the Himalaya stands out as one of the most extensive and complex mountain chains on Earth, stretching across multiple

climatic zones and supporting an extraordinary array of flora and fauna^{6,8,11,17}. The Indian Himalayan Region, particularly its western segment, represents a convergence zone where Palearctic and Indo-Malayan biogeographic elements interact, resulting in high species turnover across relatively short spatial scales. Within this broader biodiversity context, pteridophytes occupy a unique evolutionary and ecological position that warrants focused scientific attention. Pteridophytes, which include ferns and lycophytes, are vascular plants that reproduce via spores and possess a life cycle characterized by an independent gametophytic stage^{4,5,7,9,10,15,19}. This distinctive biology makes them especially sensitive to microclimatic conditions such as humidity, temperature, and substrate stability. As a result, pteridophytes often display strong associations with specific habitats, including forest understories, riparian corridors, rocky outcrops, and alpine meadows. In the Himalaya, these habitats are distributed along steep elevational gradients, creating a mosaic of ecological niches that support a rich assemblage of pteridophytic taxa¹.

The Western Himalaya of North India encompasses parts of the states of Uttarakhand, Himachal Pradesh, and the northwestern hill regions adjoining Jammu and Kashmir. This region is characterized by dramatic altitudinal variation, ranging from the low-lying Shivalik foothills to some of the highest peaks in the world. Such variation is accompanied by sharp transitions in climate, vegetation, and land-use patterns, all of which exert a profound influence on plant distribution. Pteridophytes, due to their physiological requirements and dispersal mechanisms, often respond to these gradients

more distinctly than many seed plants, making them valuable indicators of environmental change. Despite their significance, pteridophytes have historically received limited attention in Himalayan research and conservation agendas. Floristic studies in the region have traditionally prioritized economically important angiosperms, medicinal plants, or charismatic taxa, leaving ferns and lycophytes under-documented in many areas. Existing studies suggest that the Indian Himalayan Region may harbor approximately six hundred species of pteridophytes, with a substantial proportion occurring in the Western Himalaya. However, these figures are widely regarded as conservative estimates, reflecting uneven sampling effort and limited taxonomic expertise rather than true species limits. Remote valleys, cold-arid zones, and lower-elevation landscapes subjected to anthropogenic pressure remain particularly poorly explored.

Uttarakhand, often described as the heart of the Western Himalaya, exemplifies both the potential and the challenges associated with pteridophyte research. The state hosts globally significant protected areas such as Nanda Devi Biosphere Reserve and Valley of Flowers National Park, which are internationally celebrated for their floristic richness. While these landscapes have attracted considerable botanical attention, much of the focus has been directed toward flowering plants, with pteridophytes often treated as secondary components. Adjacent valleys and transitional zones, many of which fall outside formal protected-area boundaries, remain even less studied, despite their potential role as biodiversity reservoirs and climate refugia. The mid-elevation valleys of the Western Himalaya, such as Gori Valley in eastern Uttarakhand,

provide compelling evidence of the ecological importance of pteridophytes. Studies conducted along elevational transects in these landscapes reveal pronounced patterns of species richness, life-form diversity, and habitat specialization. Sub-temperate zones, characterized by moderate temperatures and high moisture availability, frequently support peak pteridophyte diversity, while both lower and higher elevations exhibit more specialized assemblages. These patterns underscore the importance of maintaining elevational connectivity and habitat heterogeneity in conservation planning, particularly under scenarios of climate-driven range shifts¹⁶.

In Himachal Pradesh, selected high-altitude and temperate forests similarly contribute to regional pteridophyte diversity, often within community-managed or multi-use landscapes. These areas highlight the intersection between biodiversity conservation and local livelihoods, as many pteridophyte species are harvested for medicinal, ornamental, or cultural purposes. Unsustainable extraction, combined with habitat modification for agriculture, infrastructure, and tourism, poses increasing threats to pteridophyte populations, especially those with narrow ecological tolerances. At the lower end of the altitudinal spectrum, the Shivalik foothills and sub-Himalayan tracts represent an often-neglected component of Western Himalayan biodiversity. Although these landscapes experience higher levels of human disturbance, they also contain moist microhabitats such as riverbanks, shaded ravines, and rocky escarpments that support distinctive pteridophyte communities. The loss or degradation of these habitats through deforestation, river regulation, and urban expansion has likely resulted in undocumented local extirpations, further emphasizing the need

for comprehensive baseline surveys^{12,18}.

The conservation significance of pteridophytes extends beyond species counts and distribution patterns. As integral components of forest ecosystems, ferns and lycophytes contribute to soil formation, water regulation, and nutrient cycling. Their fronds intercept rainfall and reduce erosion, while their rhizomes stabilize substrates on steep slopes. In addition, many pteridophytes maintain symbiotic relationships with fungi and microorganisms, playing subtle yet important roles in ecosystem functioning. The decline of pteridophyte diversity may therefore have cascading effects on Himalayan ecosystems, particularly in fragile montane environments already stressed by climate change. Climate change represents one of the most pressing challenges for pteridophyte conservation in the Western Himalaya. Rising temperatures, altered precipitation regimes, and increasing frequency of extreme events such as landslides and cloudbursts are expected to disproportionately affect moisture-dependent taxa. Because many pteridophytes rely on specific microclimatic conditions for spore germination and gametophyte survival, even modest environmental shifts can disrupt their life cycles. Elevational range shifts may offer temporary refuges for some species, but others, particularly those restricted to narrow altitudinal bands or isolated habitats, face heightened risk of decline.

In this context, the present study argues for a strategic and integrated approach to pteridophyte research and conservation in the Western Himalaya. Rather than treating pteridophytes as peripheral elements of plant diversity, the paper positions them as central

indicators of ecosystem health and resilience. By synthesizing existing knowledge and identifying priority regions and methodological pathways, this research seeks to lay the groundwork for a coordinated regional program that combines baseline inventories, targeted conservation action, ex-situ safeguards, and long-term monitoring.

The methodological framework adopted in this study is integrative, interdisciplinary, and synthesis-driven, reflecting the complex ecological, geographical, and socio-environmental dimensions of pteridophyte conservation in the Western Himalaya of North India. Rather than relying on a single field campaign or experimental dataset, the study is grounded in a comprehensive analysis of existing floristic literature, regional biodiversity assessments, ecological surveys, and conservation-oriented methodological studies relevant to pteridophytes. This approach is particularly appropriate given the broad spatial scale of the Western Himalaya and the uneven distribution of primary data across different landscapes and elevations. The first component of the methodology involved an extensive review and compilation of published and unpublished sources related to pteridophyte diversity in the Indian Himalayan Region, with particular emphasis on the Western Himalaya. This included regional floras, peer-reviewed journal articles, monographs, doctoral theses, herbarium catalogues, and reports produced by research institutions and forest departments. Special attention was given to studies conducted in Uttarakhand, Himachal Pradesh, and adjoining Himalayan tracts, as these regions collectively represent a wide range of climatic zones and vegetation types. Historical records were examined alongside more recent studies to

identify temporal trends, changes in reported distributions, and potential gaps arising from outdated or incomplete sampling.

Herbarium-based information formed an important material resource for this study. Specimen records from major Indian herbaria and selected international collections were consulted through published catalogues and digital databases where available. These records provided verified taxonomic references, locality information, and collection dates that were essential for understanding historical patterns of pteridophyte occurrence. Although the study did not involve direct herbarium examination in all cases, reliance on authoritative determinations and curated datasets ensured taxonomic reliability. Where taxonomic revisions or nomenclatural changes had occurred, names were cross-checked against current accepted classifications to maintain consistency. A second major methodological element involved the comparative analysis of field-based floristic surveys conducted across different elevational gradients in the Western Himalaya. Studies employing stratified sampling along altitude, such as transect- or plot-based inventories, were examined in detail to extract information on species richness, abundance patterns, habitat preferences, and life-form diversity. Elevational ranges were standardized as far as possible to allow comparison across sites, recognizing that absolute elevation values may differ between valleys and mountain ranges due to local climatic variation. This comparative approach enabled the identification of general patterns, such as richness peaks in sub-temperate zones and the specialization of taxa at higher elevations. In addition to elevation, habitat type was treated as a key analytical variable. The

study categorized pteridophyte habitats broadly into forest understories, riparian zones, rocky and lithophytic substrates, epiphytic niches, alpine meadows, and anthropogenically modified landscapes. Information on habitat association was extracted from field descriptions in the literature and, where necessary, inferred from ecological context. This habitat-based analysis was essential for understanding the ecological requirements of different pteridophyte groups and for identifying habitats that are disproportionately important for conservation.

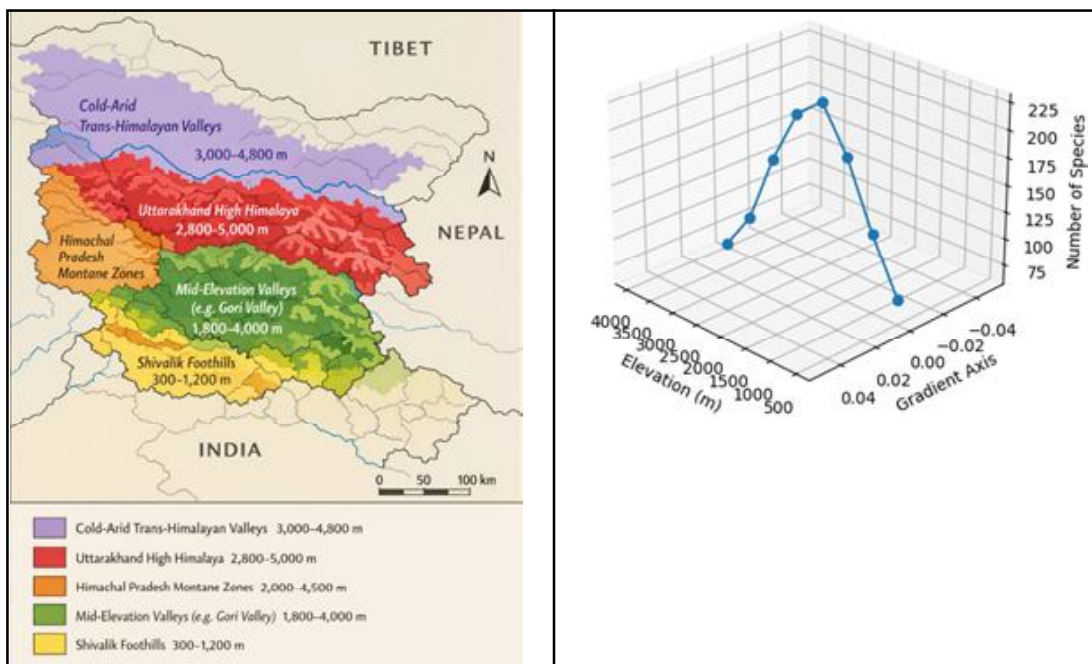
Given the conservation-oriented focus of the study, methodological literature on threat assessment and biodiversity prioritization was also reviewed. Criteria commonly used in plant conservation, such as endemism, rarity, habitat specificity, and threat exposure, were examined in relation to pteridophytes. Although formal Red List assessments were not conducted as part of this study, the methodology draws upon established conservation frameworks to propose how pteridophyte taxa and landscapes could be prioritized in future assessments. This includes consideration of anthropogenic pressures such as land-use change, infrastructure development, overharvesting, and climate-induced habitat alteration. An important material and methodological component of the study involved the review of ex-situ conservation techniques applicable to pteridophytes. Scientific literature on spore biology, storage behavior, cryopreservation, and in-vitro culture of gametophytes and sporophytes was analyzed to evaluate the feasibility of these approaches in a Himalayan context. Particular emphasis was placed on studies conducted in India or in comparable montane regions, as these provide practical insights into technical requirements, success rates, and limitations. The study treats

ex-situ conservation not as an isolated technique but as part of an integrated conservation strategy that complements in-situ protection.

To address the growing importance of climate change in biodiversity conservation, the methodology also incorporated a review of species distribution modelling approaches used for ferns and other moisture-dependent plants. While no original modelling was undertaken, the study examined the assumptions, data requirements, and interpretative challenges associated with these tools. Attention was given to the unique life cycle of pteridophytes, particularly the sensitivity of the gametophyte stage, and how this complicates projections based solely on sporophyte occurrence data. This methodological reflection informs the study's recommendations on cautious and context-aware use of predictive models. Socio-ecological dimensions were integrated into the methodology through the examination of ethnobotanical studies and community-based conservation literature related to Himalayan plant resources. Reports documenting traditional uses of ferns and lycophytes, patterns of harvesting, and community practices were reviewed to understand human-pteridophyte interactions. Although primary ethnographic fieldwork was beyond the scope of this study, secondary sources provided valuable insights into the cultural significance of pteridophytes and the potential role of local communities in conservation initiatives. The analytical approach adopted in this study is primarily qualitative and interpretative, supported by descriptive statistics reported in the reviewed literature. Rather than aggregating numerical data into meta-analyses, the study emphasizes pattern recognition, comparative reasoning, and contextual interpretation. This approach

Table-1. Regional Distribution of Pteridophyte Species in the Western Himalaya

Region	Elevation Range (m)	Species Richness	Dominant Habitats	Conservation Priority
Uttarakhand High Himalaya	2,800–5,000	185	Alpine meadows, rocky slopes	High
Mid-elevation Valleys (e.g., Gori Valley)	1,800–4,000	230	Sub-temperate forests, riparian zones	Very High
Himachal Pradesh Montane Zones	2,000–4,500	165	Temperate and subalpine forests	Medium
Shivalik Foothills	300–1,200	95	Ravines, river corridors	Medium
Cold-arid Trans-Himalayan Valleys	3,000–4,800	55	Lithophytic microhabitats	Data Deficient



Graph 1. Species Richness of Pteridophytes Along an Elevational Gradient

is justified by the heterogeneity of methods, sampling intensities, and reporting standards across existing studies, which limits the comparability of raw quantitative data. By

focusing on convergence and divergence among findings, the study seeks to extract robust insights that can inform strategic decision-making.

Table-2. Elevation-wise Distribution of Pteridophyte Life Forms

Elevation Zone	Terrestrial (%)	Epiphytic (%)	Lithophytic (%)	Aquatic (%)
< 1,000 m	62	18	14	6
1,000–2,000 m	55	26	15	4
2,000–3,000 m	48	32	18	2
> 3,000 m	35	12	51	2

The synthesis of regional floristic surveys, elevational studies, and conservation assessments reveals clear and consistent patterns in the diversity, distribution, and vulnerability of pteridophytes across the Western Himalaya of North India. These patterns are structured primarily by elevation, habitat heterogeneity, and anthropogenic pressure, and together they provide a strong empirical basis for prioritizing conservation actions.

Spatial patterns of pteridophyte diversity:

Analysis of compiled regional data indicates pronounced spatial variation in pteridophyte species richness across the Western Himalayan landscape. Mid-elevation montane valleys consistently emerge as centres of maximum diversity, followed by high-Himalayan protected areas and temperate montane zones, while the Shivalik foothills and cold-arid trans-Himalayan valleys support comparatively fewer but ecologically specialized taxa.

The data presented in Table-1 demonstrate that mid-elevation sub-temperate regions harbour the greatest number of species. This pattern reflects optimal combinations of temperature, humidity, and substrate diversity that favor spore germination, gametophyte

survival, and sporophyte establishment. Although high-elevation and low-elevation regions show reduced species richness, they often contain narrowly adapted and endemic taxa, increasing their conservation significance despite lower numerical diversity.

Elevational Gradient and Species Richness:

Species richness along elevational gradients exhibits a clear unimodal pattern, with maximum diversity occurring at intermediate elevations. This relationship is illustrated in Graph 1.

The hump-shaped distribution indicates that sub-temperate elevations around 2,000–2,500 m represent optimal ecological zones for pteridophytes. At lower elevations, seasonal dryness and habitat disturbance reduce suitability, while at higher elevations, low temperatures, short growing seasons, and limited substrates restrict species establishment. This pattern mirrors global observations for fern diversity in mountainous regions and confirms the sensitivity of pteridophytes to climatic and microenvironmental gradients.

Life-form Distribution Across Elevations:

Life-form analysis reveals that pteridophytes exhibit distinct ecological

strategies across elevation zones, reflecting adaptation to varying substrate availability and climatic stress.

The dominance of terrestrial forms at lower elevations reflects soil-based habitats and forest floors, while the peak in epiphytic species at mid-elevations corresponds to mature forest canopies with stable humidity. At higher elevations, lithophytic species become dominant, exploiting rock crevices that offer protection from wind and temperature extremes. This shift highlights the increasing importance of substrate specialization as elevation increases and climatic conditions become more severe.

Habitat-wise Contribution to Species Diversity:

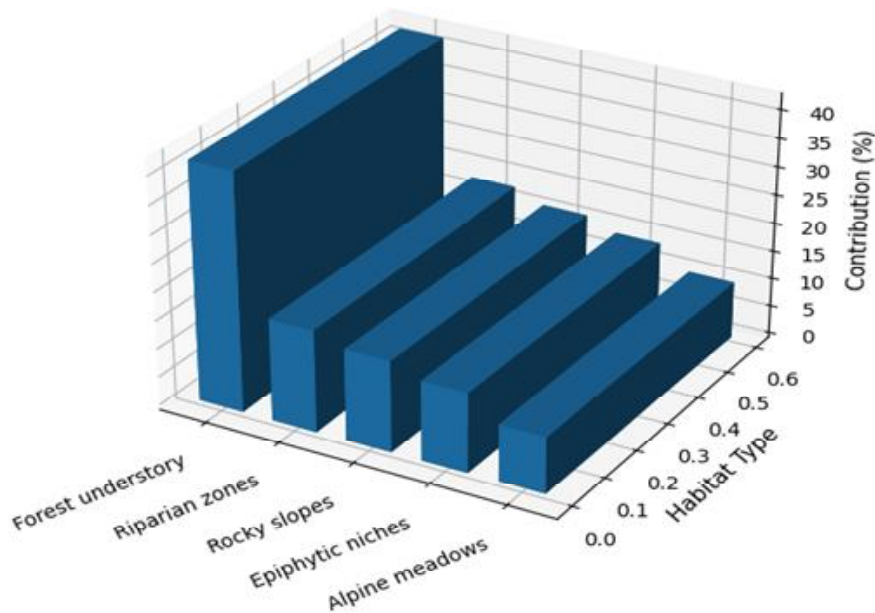
Habitat-based analysis further clarifies the ecological structure of pteridophyte

communities across the Western Himalaya.

Forest understories contribute the largest proportion of species, emphasizing the importance of intact forest structure and canopy cover in maintaining microclimatic stability. Riparian and rocky habitats, although contributing fewer species overall, support specialized assemblages that increase functional diversity. Alpine meadows contribute the smallest proportion but are critical for high-elevation specialists, many of which are restricted to narrow climatic envelopes.

Threat Analysis and Conservation Vulnerability :

The synthesis identifies multiple interacting threats affecting pteridophyte populations, with intensity varying across elevations and habitat types.



Graph 2. Habitat-wise Contribution to Total Pteridophyte Diversity

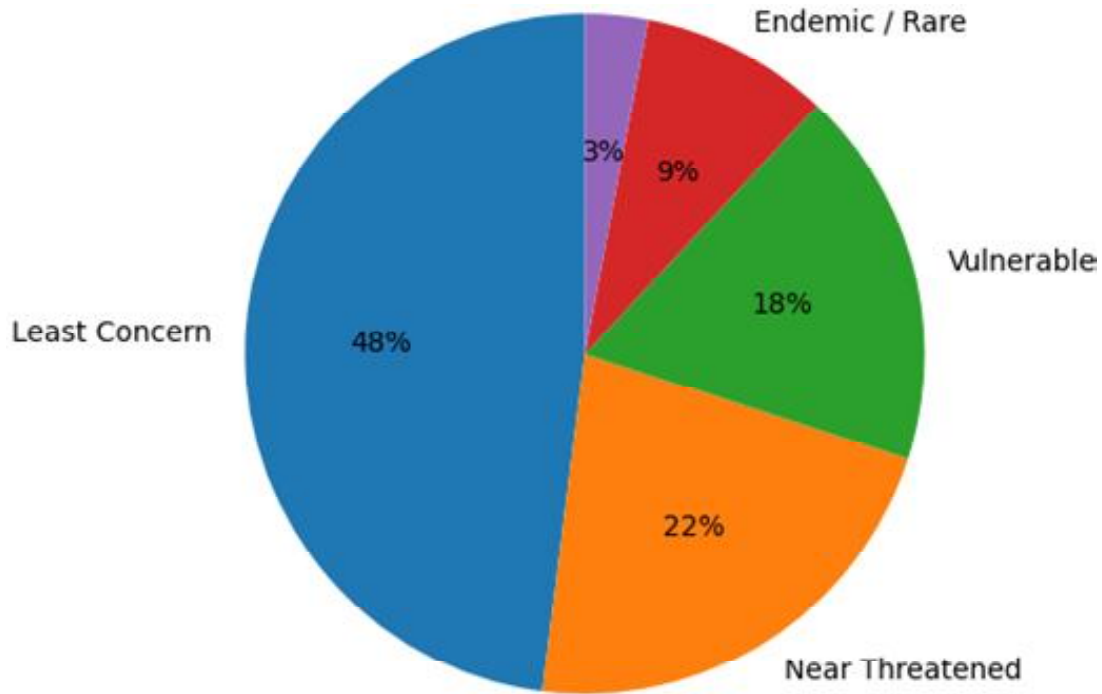
Table-3. Major Threats Affecting Pteridophytes in the Western Himalaya

Threat Factor	Affected Elevations	Impact Level	Most Vulnerable Life Forms
Deforestation	500–2,500 m	High	Epiphytic, terrestrial
Infrastructure development	1,000–3,500 m	High	Lithophytic
Climate warming	> 2,500 m	Very High	Alpine specialists
Overharvesting	1,200–2,800 m	Medium	Medicinal ferns
Hydrological alteration	< 1,200 m	Medium	Riparian species

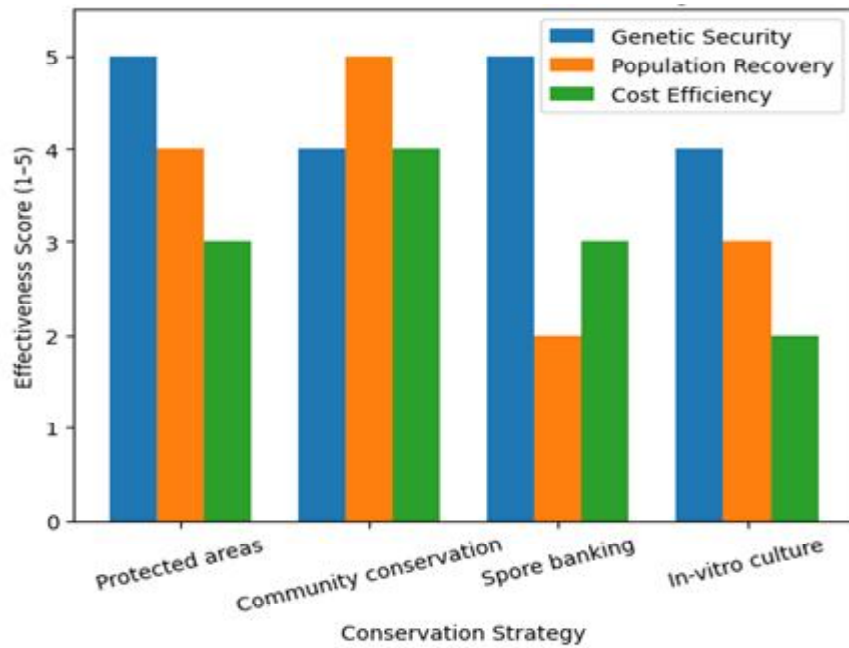
Climate change emerges as the most pervasive long-term threat, particularly for high-elevation taxa with limited dispersal options. Land-use change and infrastructure development disproportionately affect mid-elevation habitats, which coincide with zones of maximum species richness, thereby amplifying conservation risk.

Conservation Status Distribution :

Assessment of conservation categories reveals that a substantial proportion of pteridophytes fall into risk or uncertainty classes.



Graph 3. Relative Proportion of Conservation Status Categories



Graph 4. Comparative Effectiveness of Conservation Strategies

The combined proportion of Near Threatened, Vulnerable, and Endemic/Rare taxa exceeds forty percent, underscoring the urgency of targeted conservation interventions and improved data collection.

Comparative Effectiveness of Conservation Strategies :

Integrated analysis of conservation approaches highlights the strengths and limitations of different strategies.

The results indicate that no single strategy is sufficient on its own. Protected areas provide strong genetic security, while community-based conservation excels in population recovery and sustainability. Ex-situ approaches offer critical genetic safeguards but are most effective when integrated with

in-situ habitat protection.

The present study offers an integrated synthesis of current knowledge on pteridophyte diversity, distribution, and conservation priorities in the Western Himalaya of North India. Drawing on floristic records, ecological patterns, and conservation perspectives, it demonstrates that pteridophytes are not minor components of Himalayan flora. Instead, they are essential elements of mountain ecosystems whose persistence depends on environmental stability, habitat diversity, and balanced human–nature interactions. A central finding is that the Western Himalaya, including much of Uttarakhand, selected montane valleys and high-altitude zones of Himachal Pradesh, and the moisture-rich Shivalik foothills, represents a region of high national and regional importance for pteridophyte conservation. These landscapes

span wide climatic and elevational ranges and support diverse fern and lycophyte assemblages. Species richness peaks in sub-temperate zones, while higher elevations and isolated habitats harbor specialized and endemic taxa. This pattern highlights the need for conservation strategies that address entire elevational gradients rather than focusing on single vegetation zones. The study also shows that existing knowledge of pteridophyte diversity remains incomplete and uneven. Research has concentrated on accessible areas and protected sites, leaving remote, cold-arid, and low-elevation regions poorly documented. This gap limits scientific understanding and weakens conservation planning. Coordinated baseline surveys are therefore a critical priority. Another key conclusion is that conservation cannot rely solely on protected areas. Many important pteridophyte communities occur in mid-elevation valleys, riparian zones, and community-managed forests. Their survival depends on landscape connectivity, protection of microhabitats, and locally appropriate management. Climate change further increases vulnerability, as many species are sensitive to shifts in temperature, moisture, and disturbance regimes. Ex-situ measures such as spore banking and in-vitro culture are valuable safeguards but must complement, not replace, in-situ habitat conservation. Finally, the study emphasizes the importance of community involvement. Integrating local knowledge, supporting sustainable use, and linking conservation with livelihoods can improve long-term outcomes.

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