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SAFEGUARDING THE HIDDEN MYCOBIOTA OF SWAT, PAKISTAN: EVIDENCE GAPS, THREATS, CLIMATE VULNERABILITY AND PROPOSED CONSERVATION FRAMEWORK

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Abstract

Fungi are one of the least protected elements of the biodiversity in the Hindu Kush Himalayan region. District Swat, Pakistan, has a good representation of macrofungal diversity comprising morels (Morchella spp.), commercially harvested wood-decay Polyporales, ectomycorrhizal communities and some recently described species. Although taxonomic documentation of fungi has improved, there has bee a lag in fungal conservation compared to plant and vertebrate conservation. Systematic evidence synthesis that critically reviews the published information about the mycobiota of Swat. Taking the PRISMA approach, papers were searched from key databases and studies were selected that contained taxonomic and ecological data, ethnomycological data or threat relevant data relevant to Swat or its immediate environs. Identify and compile evidence of documented diversity, vulnerabilities by habitat, anthropogenic and environmental pressures and climate related risk amplifiers. Distinguish three evidence categories: demonstrated (Swat-specific), supported (regionally transferable) and hypothesized (mechanistically plausible but not locally quantified). Fungal Conservation Priority Index (FCPI) is mathematically formulated using standardized criteria, explicit weighting options and recommended sensitivity analysis. A spatial prioritization framework for multiple criteria was outlined for possible future GIS implementation. Conservation-gap matrix quantifies gaps in knowledge at the taxonomy, distribution, population trends, climate response, harvest sustainability and protected-area coverage levels. The resulting Swat Fungal Conservation Model combines inventory, DNA identification, GIS mapping, threat assessment, vulnerability assessment, FCPI scoring, habitat protection, community involvement, sustainable harvesting, ex-situ measures and long term monitoring. This review offers a way to go from a largely narrative literature to an evidence-base and transparent, quantitative prioritization process to actionable conservation for Swat mycobiota.

Introduction

The fungal diversity is one of the most widespread but poorly officialised parts of the mountain terrestrial biodiversity. District Swat (Khyber Pakhtunkhwa Province, Pakistan) is located in the Hindu Kush ranges with an elevation range from 700 m up to >6000 m and has subtropical, moist temperate, subalpine and alpine zones. These gradients host a variety of mixed broadleaf–conifer forests, pure coniferous stands, oak woodlands and high elevation meadows, that create a variety of fungal niches [1–3]. At least 34 wild edible medicinal mushroom species have been observed during ethnomycological surveys and Morchella (Guchhi) is of special commercial value [4–5]. Molecular phylogenetic studies have resulted in the addition of new species and national records such as Phlebia swatensis, Xanthoperenniporia pileata, Cortinarius swatensis, Russula swatica and some taxa of Postia [6–9]. There are more than 1200 species of macrofungae in Pakistan national checklist, western Himalayan broadleaf and subalpine conifer forests are the richest ecoregions in Pakistan [3,10–12]. Although there has been a taxonomic advance, the fungal conservation in Swat is still underdeveloped. The pressures are deforestation, fragmentation, commercial harvesting of morels, fire, infrastructure development and microclimatic instability due to climate change. Many fungi are host and/or substrate specialists, and these pressures can result in fast local declines, which are only inadequately represented by traditional biodiversity monitoring. The impact of climate-related risk on the food system is mediated mostly indirectly, rather than through one common climate driver (moisture extremes, fire weather, infrastructure failure) [13–17]. This systematic evidence synthesis highlights five questions: (1) What fungal diversity is reported in Swat? (2) What are the most vulnerable taxa/habitats? (3) What pressures face them and when? (4) What are the priorities for conservation, and what are they quantitative? (5) What should be the policy that should be implemented in Swat? The review compiles the existing literature into a coherent and well-structured evidence base, sets out a mathematical Fungal Conservation Priority Index (FCPI) and introduces a spatial prioritization framework, along with a working conservation model.

Materials and Methods

This review has been carried out in accordance with the general principles for reporting systematic reviews as outlined in the PRISMA 2020 statement [18]. Given this variability in methods and outcomes reported in the literature, a structured narrative synthesis (richness tallies, threat frequencies, evidence-quality scoring) was used instead of formal meta-analysis.

Literature Search Strategy

A search was conducted from 2025 in Scopus, Web of Science Core Collection, PubMed (supplementary) and Google Scholar. Primary search strings in the form of combinations of geographic terms and taxonomic or thematic terms were used exactly (to be reported in full in Supplementary S1). Core Boolean structure: ("Swat" OR "Hindu Kush" OR "Khyber Pakhtunkhwa" OR "KPK") AND (fungi OR fungus OR mushroom

OR mycobiota OR "macrofung" OR Morchella OR Polyporales OR ethnomycolog OR "wild edible") other strings focused on conservation, climate, threat, and space. For the core synthesis, only English-language, peer-reviewed articles and high quality taxonomic and ethnomycological studies were retained and used for harvest statistics when confirmed by selected grey literature.

Eligibility Criteria (PICOS-adapted)

Population: Fungal taxa/communities collected from District Swat or from adjoining localities in Hindu Kush. Threat/Exposure: Any threat or harvest regime, habitat change, climate variable, or conservation action reported. Comparator: Not required; where available, comparisons across habitats, elevations or time were removed. Outcomes: Taxonomic lists, richness, habitat associations, ethnomycological use, threat observations, population or harvest data, conservation recommendations. Study design: Field surveys, Taxonomic descriptions, Ethnomycological studies, Ecological observations, Molecular phylogenetic papers and relevant papers and reviews with primary Swat data.

Study Selection and PRISMA Flow

Automated and manual deduplication, then screening of titles and abstracts and finally full text assessment. The number of records identified in databases is approximately 280-350, with duplicates removed being approximately 90-120, and full-text assessed records being approximately 80-110, and the number of studies eligible for inclusion and providing extractable data being approximately 55-70 (illustrative numbers based on the search scope; final numbers to be determined in the completed extraction). The final figures will be included in a formal PRISMA 2020 flow diagram (figure 1), when the extraction database is finalized.

Data Extraction Framework

Structured extraction matrix is recorded for each included study, and includes bibliographic metadata, study locality and precision, sampling design and effort, taxonomic identity and certainty (morphology/molecular), elevation, habitat, host/substrate, functional guild, ethnomycological and economic use, reported threats and intensity, population or harvest evidence and evidence-quality indicators. This matrix (Supplementary S2) transforms this literature into an evidence database that can be queried.

Evidence Hierarchy and Quality Assessment

Every major claim is assigned to one of three evidence levels: Each key argument is rated at one of three levels of evidence: Level A (Demonstrated) evidence from Swat. Transferability of evidence from neighbouring Khyber Pakhtunkhwa or Pakistan-wide studies at Level B (Supported). Level C (Hypothesized) Mechanically plausible inference based on the broader literature on fungi from the Himalayas or elsewhere, but not yet quantified locally. A Fungal Evidence Quality Index (FEQI) is defined as a weighted combination of taxonomic verification, geographic precision, molecular confirmation,

population evidence and replication. High FCPI scores with low FEQI are identified as high priority, low confidence targets, and need immediate primary data collection.

Mathematical Definition of the Fungal Conservation Priority Index (FCPI)

For each species (or habitat unit) i the FCPI is defined as the weighted sum of ten standardized criteria Xij $\in [0,1]$:

$FCPI_i = \Sigma_{j=1}^{10} w_j \cdot X_{ij}$ where $\Sigma_j w_j = 1$ and $w_j \geq 0$

The ten criteria are: (1) rarity (2) endemism/restricted distribution (3) habitat specificity (4) population/distribution status (5) threat intensity (6) climate vulnerability (7) ecological/functional importance (8) ethnomycological importance (9) economic importance (10) inverse of existing formal protection. An explicit rubric (Supplementary S3) is used to score each criterion. There are 3 recommended weighting scenarios:

a. Model A — Equal weights ($w_j = 0.10$).

b. Model B — Conservationist (higher weights on rarity, habitat specificity, threat, climate vulnerability).

c. Model C — Socio-ecological (higher weights on ecological, ethnomycological and economic importance).

The three models are ranked in order of sensitivity, using rank correlation (Spearman). Priority tiers: Critical (≥0.80), Very high (0.65–0.79), High (0.50–0.64), Moderate (0.35–0.49), Low/monitoring (<0.35).

Spatial Prioritization Framework

A multi-criteria GIS overlay is specified using: (i) georeferenced occurrence records, (ii) forest cover and vegetation type, (iii) elevation, (iv) land-use change, (v) climate variables (current + projected), (vi) water availability, and (vii) anthropogenic pressure proxies. Weighted overlay creates continuous priority surfaces from which Fungal Conservation Hotspots, Ecological Corridors, Threatened Habitats and Priority Conservation Zones are generated. A necessary next step of analysis is the full implementation and resulting maps; this paper provides the conceptual and data-layer specification.

Transparency and Protocol Status

The review protocol did not need to be pre-registered in PROSPERO, sice the main focus of the review is not clinical outcome, but environmental mycology and biodiversity conservation. A priori, the eligibility criteria and search strategy and synthesis approach were defined. Final PRISMA counts, the complete extraction matrix and FCPI scores will be deposited as supplementary data upon completion of the full extraction.

Result

Study Selection Summary

The literature search returned a basic list of studies providing primary or high quality secondary data on Swat fungi (final number will be determined when the extraction database is finalised). Most are taxonomic

descriptions, ethnomycological surveys and ecological notes, while in-depth conservation evaluations are limited. A significant rise in publications, mainly because of molecular phylogenetic research and ethnomycological documentation formal conservation or population studies are less common.

Documented Fungal Diversity

At least 34 species of wild edible and medicinal plants in 31 genera and 1 families, (Level A evidence) are recorded in Ethnomycological surveys [4–5]. Uses are dominated by the Hymenochaetaceae, Polyporaceae, Lycoperdaceae, Morchellaceae and Agaricaceae. Morels (Morchella esculenta, M. elata, M. conica, M. semilibera and related taxa) are the most commercially exploited species, with annual production estimates of several tonnes of dried material, and thousands of collectors (Level A/B) [4,19–20]. There are additional species and national records based on molecular studies Phlebia swatensis, Xanthoperenniporia pileata, Cortinarius swatensis, Russula swatica and several Postia s.lat. taxa (Level A) [6–9]. Western Himalayan forests are one of the richest ecoregions in Pakistan based on national checklist data (Level B) [3,10–12]. The "hidden mycobiota", as framed, applies to the lack of macrofungal and functional documentation, not a total lack of documentation for all fungal lineages. The "hidden mycobiota" concept is mostly about the lack of documentation of macrofungi and functional groups, and not a complete lack of documentation for all fungal lineages.

Habitat-Specific Vulnerabilities

Habitat-specific vulnerabilities are abbreviated in Table 1. Moist temperate mixed forests and subalpine conifer stand have the greatest number of known ectomycorrhizal and wood-decay taxa and face the highest level of host removal and fragmentation (Level A/B). Morel productive sites are small in size and have very specific environmental conditions, with heavy harvesting for business (Level A). There is a high risk of specialists loss in fragmented and edge forests (Level B/C).

Table 1. Habitat-specific vulnerabilities and dominant fungal groups in Swat (evidence levels indicated).

Habitat	Main Composition	Dominant Fungal Groups	Primary Decline Mechanisms	Evidence Level
Moist temperate mixed forest	Quercus–Pinus–broadleaf	ECM agarics, Polyporales, morels	Host loss, fragmentation, dead-wood reduction	A/B
Subalpine / pure conifer	Abies, Picea, Pinus	Wood-decay Polyporales, ECM	Logging, fire, climate envelope shift	A/B
Morel productive sites	Specific soil–host–microclimate	Morchella spp.	Overharvesting + habitat degradation	A

Oak woodlands	Quercus-dominated	Russulaceae, Boletaceae, Cortinariaceae	Conversion, grazing, fuelwood	B
Fragmented / edge forests	Altered microclimate	Generalists; loss of specialists	Desiccation, intensified use	B/C

Threat Frequency and Evidence Classification

Table 2 displays the Threat x Vulnerability matrix, explicitly labeled with evidence levels. Deforestation, fragmentation and climate related instability are considered as Critical urgency because of Level A/B evidence of habitat change, and known fungal dependence on host and substrate continuity. Insufficient population-level data are available to support a fully established commercial pressure (Level A) for overharvesting of morels. Fire, urbanization and pollution are ranked as High and Moderate.

Table 2. Threat × Vulnerability matrix with evidence-level classification.

Threat	Exposure	Vulnerable	Urgency	Evidence Level	Notes
Deforestation	High	High	Critical	A/B	Host & dead-wood loss
Habitat fragmentation	High	High	Critical	A/B	Network isolation
Climate instability (high elev.)	High	High	Critical	B/C	Envelope & phenology
Overharvesting (Morchella)	Mod–High	High	High	A (pressure); C (decline)	Demographic data limited
Forest fires	Moderate	High	High	B	Substrate loss
Urbanization / infrastructure	High	Moderate	High	A/B	Direct conversion

Conservation Gap Analysis

Table 3 measures gaps in knowledge. Taxonomic documentation of macrofungi moderate–high and increasing; microfungi, population trends, climate-response models, quantitative harvest monitoring and fungal layers in protected area planning very low. Such gaps directly affect the confidence in the possible priority ranking and the research agenda that needs to be addressed prior to considering FCPI scores as high-confidence management instruments.

Table 3. Conservation gap analysis for Swat mycobiota.

Knowledge Domain	Current Evidence	Principal Gap	Conservation Consequence
Taxonomic diversity (macrofungi)	Moderate–High	Microfungi & hypogeous taxa poorly known	Hidden diversity under-estimated
Distribution / georeferencing	Low–Moderate	Few precise coordinates	Poor spatial prioritization
Population trends	Very Low	No long-term plots	Cannot confirm decline
Climate response	Very Low	Species-specific models absent	Uncertain future risk
Harvest pressure quantification	Moderate	Limited monitoring of offtake	Unknown sustainability
Protected-area fungal coverage	Low	No fungal layers in PA design	Conservation mismatch
Functional / trait data	Low	Few trait datasets	Functional loss overlooked

FCPI Application Status and Worked Illustration

All documented taxa for FCPIs, it is necessary to complete the extraction matrix and expert/automated assignment of the ten criteria. The mathematical framework (Section 2.6) is completely defined in the meantime and can be applied. Once scores are generated, a small subset of high-profile taxa will be ranked illustratively for the three weighting models and sensitivity will be quantified by rank-correlation analysis. For the time being FCPI is being shared as a tool that is transparent, repeatable, and not as a finished list of all the mycobiota sorted by priority.

Spatial Prioritization Status

No GIS-based multi-criteria analysis has been done for this review. The data layers, weighting logic and output products (hotspots, corridors, threatened habitats, priority zones) are completely defined in Section 2.7. Existing occurrence density and forest integrity are hypothesized to be priority forest complexes in the upper Swat (Kalam, Malam Jabba, Miandam and similar mid to high elevation forest complexes) which will need quantitative spatial testing.

Discussion

The synthesis reveals that the mycobiota of Swat is not fully documented and mycologically significant biota of ecological, cultural and economic significance are part of it. The taxonomic discovery process has been furthered with the description of Russula swatica from morphological, microscopic and ITS molecular

data from the Swat Valley [9] and the description of Phlebia swatensis and Xanthoperenniporia pileata from morphological data and ITS + nrLSU phylogenetic analysis from the Hindukush Mountains of Swat [6]. The recent description of Cortinarius swatensis in Tehsil Kabal, Swat based on its morphology, microsclerotia and phylogenetic data from the ITS of the fungus agrees with the previous findings of the same area as a taxonomic discovery [8]. The molecular-taxonomic study of Postia s.lat. in Swat also included five new records of brown-rot polypores for Pakistan showing the incompleteness of the existing inventory of fungi in the region [7]. The results validate the concept that conservation planning does not have to wait until a thorough fungal flora is completed, since fungal conservation is always limited in its scope due to imperfect knowledge of the rarity, distribution, habitat requirements and conservation risk of fungal species. This review contribution aims to: (i) present a coherent picture of the diversity of the evidence and create an explicit evidence hierarchy; (ii) define a mathematically expressed Fungal Conservation Priority Index (FCPI); (iii) establish a component of sensitivity analysis for the FCPI; and (iv) develop a conservation-gap matrix and an operational management plan. The components are designed to increase reproducibility, to make uncertainty explicit and to make known threats clear, particularly in the area of fungal conservation, where assessment is available, but where significant knowledge gaps and geographical and taxonomic biases exist [21–23]. Despite this, the current evidence base for the Swat area is still quite limited in scope: there is no spatial or taxonomic uniformity in sampling effort, occurrence data are not georeferenced, data on species' populations trends are limited and there are no assessments of species vulnerability to climate change in the Swat mycobiota. The present synthesis is not intended to present a complete overview of the regional mycobiota, but it does include microfungi, which are known to be an important part of the fungal diversity and are not included in the existing Swat evidence base in a systematical manner [24–26]. The FCPI classification, therefore, should be interpreted as a conservation prioritisation result, and should be considered with a degree of uncertainty, rather than a formal extinction risk assessment based on the IUCN Red List framework [21,23,27]. The FEQI and evidence level tagging generated in this review is not intended to imply that weak, sparse or indirect evidence leads to a high conservation priority for a low quality numerical FCPI score. The review does not limit the discussion to the economically important taxonomic group of fungi, but rather includes edible and commercially important fungi, wood-decay fungi and ectomycorrhizal fungi [4-5, 28-29]. This wide concept is consistent with the fact that wood-decay fungi are important in ecosystem services (e.g., lignocellulose degradation, forest carbon and humus cycling) [29–31]. The ecological importance component of the FCPI can be further reinforced as functional traits, substrate associations and host-specificity data are systematically collected, and subsequently analyzed using habitat and spatial analyses [32,33,34]. To progressively decrease uncertainty and improve spatial conservation prioritization, future versions of the framework should include

standardized occurrence records, georeferenced sampling, habitat variables, functional traits and climate projections [35–39].

The Swat Fungal Conservation Model

Systematic inventory using standardized sampling plots and repeatable field protocols [2,40] will be followed by a combination of DNA barcoding and morphological identification, enabling phylogenetic analysis and improved taxonomic resolution of species in need of conservation [41–42]; a georeferenced GIS database will be developed to integrate occurrence, habitat and environmental data [35,37,43]; evidence-based threat assessment with explicit evidence-level tagging will help distinguish documented threats from inferred or uncertain threats [21–22]; climate-vulnerability screening based on species-distribution, habitat-suitability and climate-exposure information will be used to evaluate the conservation value of sites [16–17,44]; FC This framework has a modular design that is expected to allow future application and testing within the adjacent districts of the Hindu Kush region, as long as biodiversity and environmental data collected locally supports it.

Conclusions

Swat fungi are a relatively neglected but ecologically significant part of regional biodiversity and fungi play a role in processes of decomposition, nutrient cycling, symbiotic relationships, and ecosystem function [33–34,51–52]. The documented diversity of fungi in the area of Swat is also very high and is growing with the ongoing taxonomic research which resulted in the description of Russula swatica, Phlebia swatensis, Xanthoperenniporia pileata and Cortinarius swatensis and other polypore records which were previously not documented in Pakistan [6–9]. However, there is insufficient evidence available to make robust population level conclusions for most of the Swat fungal taxa. Therefore, pressures like habitat loss, forest disturbance, fragmentation, environmental change (caused by climate changes), harvesting etc. should be distinguished from reported pressures based on the strength of available evidence and not interpreted as proven declines in the population of species [21-22]. This review follows the principles of PRISMA 2020 for transparent reporting [18] and an explicit evidence hierarchy, a mathematically defined FCPI with sensitivity analysis, a conservation-gap matrix and a conservation management framework, ensuring that the process is structured and can be reproduced. The FCPI and associated FEQI have been proposed tools developed during the present review, and should therefore not be considered as an alternative or replacement for formal IUCN Red List assessments [21, 23, 27]. The first methodological tasks needed to make the proposed framework fully quantitative results of conservation priority are the completion of the Evidence extraction database, the calculation of the FCPI scores and the implementation of the planned GIS overlay. Uncertainty ranges and evidence classification should be preserved in the interpretation of those results to avoid assigning a numerical priority score as a standalone extinction-risk assessment [21,53]. Coordinated collaboration between mycologists, forest and protected-area managers, local

communities, conservation organizations and relevant policy makers, combined with iterative monitoring and adaptive management is needed to implement the resulting conservation priorities [54–57].

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