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Review article

Systematic review of fungi, their diversity and role in ecosystem services from the Far Eastern Himalayan Landscape (FHL)

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A R T I C L E I N F O

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A B S T R A C T

Fungi are morphologically and ecologically diverse kingdom but less explored in the global perspective. This systematic review of mainly higher fungi (mushrooms) and lichenized fungi (lichens) was aimed to convey comprehensive knowledge on these understudied taxa, especially considering diversity, research trends, taxonomic/geographic knowledge gaps, and their contribution to ecosystem services. We investigated literature from the Far Eastern Himalayas and adjacent areas. We followed the PRISM (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework for the evidence synthesis and reporting. Search strings were used to explore literature both in English and Chinese databases. Publications were validated examining the title, locality, abstract and full text. We included 75 eligible studies after screening 12,872 publications. The result on species diversity extrapolated from literature was consolidated as a species checklist and published on the Global Biodiversity Information Facility (GBIF) portal. This review demonstrates a significant shortage of research work on fungi, and a lack of quantitative data on diversity, ecology, and ecosystem services. Mycological inventories with multidisciplinary perspectives are urgent in the Landscape to better understand the importance of fungi in conservation and sustainable development science. This review is especially useful when global environmental and climate concerns are focused on the use of nature-based solutions, and fungi as integral part of all ecological processes, could play important role in enhancing ecosystem services and therefore benefits coming to people as natural solutions.

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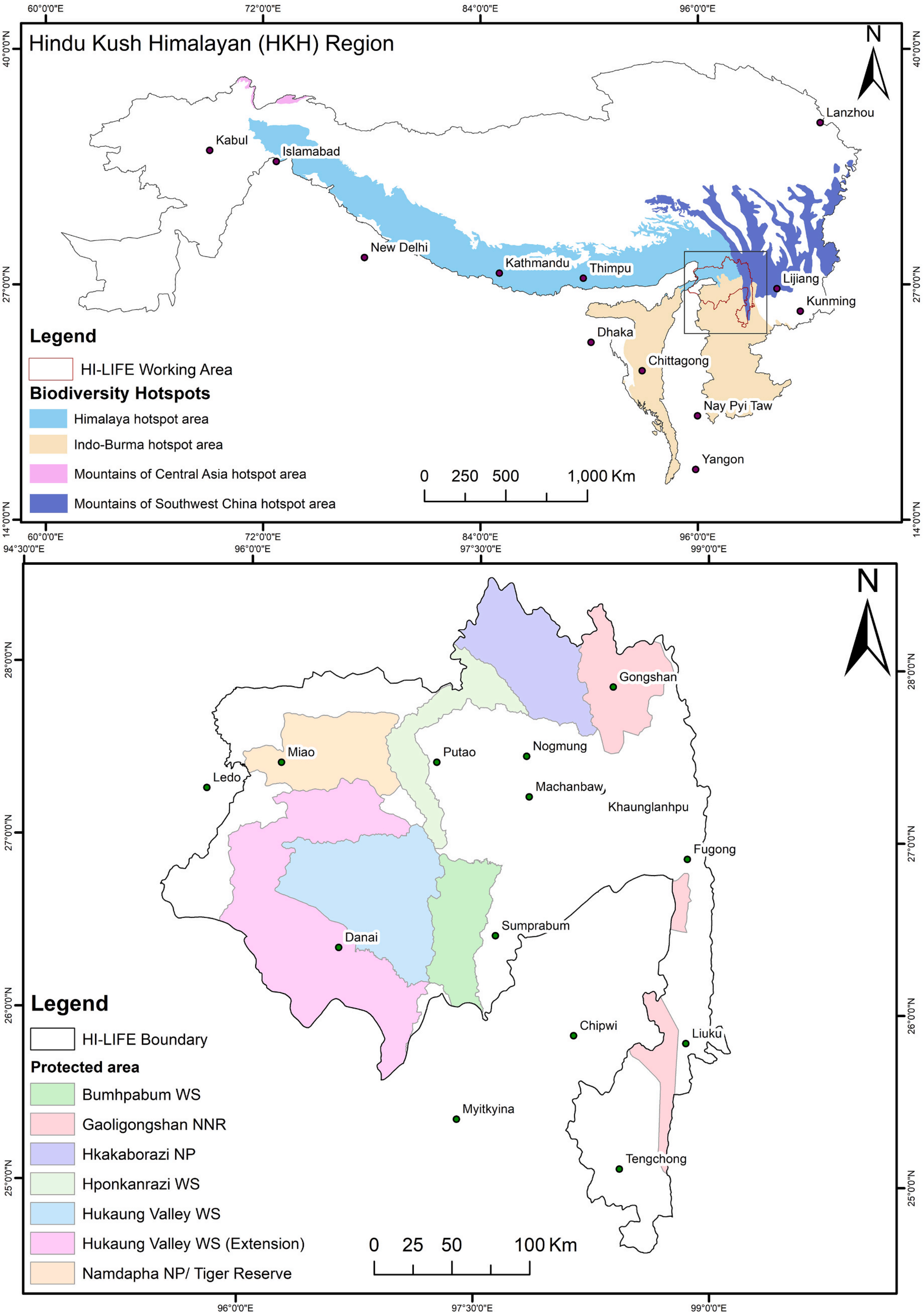

(caption on next page)

Fig. 1. Far-Eastern Himalayan Landscape and surroundings.

1. Introduction

Fungi are immensely diverse and include taxa ranging from microscopic, single-celled yeasts, and aquatic chytrids to macroscopic multicellular mushrooms and lichenized fungi [1,2]. Although their worldwide species diversity estimate goes from at least 2.2–3.8 million [3–5] to 165.6 million [6], only 151,381 species have been named and classified (Species Fungorum, http://www.speciesfungorum.org/Names/Names.asp, accessed on July 25, 2022). There are relatively sparse, and fragmentary scientific publications dealing with systematic review and assessment fungi at local, regional and global levels [7–14]. Studies have mostly focused on highlighted the roles fungi play in ecosystem functioning as decomposer, symbionts, pathogens, foods, nutraceuticals and, carbon cycling [10,15–17]. Research has also confirmed that climate change and its consequences on fungal growth have considerable knock-on effects for ecosystem functions and services [5,18].

Ecosystem services, commonly categorized into provisioning, regulating, cultural, and supporting ecosystem services are underpinned by the state of biodiversity, and which directly contribute to human well-being ([19]. Fungi, too are part of all essential ecosystem services - from primary production (nutrient making, nutrient enhancing), secondary production (food providing, fungal and faunal interactions), and population/community regulation [5,10,20–22]. Being heterotrophic organisms, fungi establish relations with almost all known organisms (eg. as mutualists with cyanobacteria and algae in lichens and inhabit different extreme environments) and provide a multitude of ecosystem services importantly the regulatory services [10,23]. Furthermore, being a major constituent of soil biodiversity, fungi function in nutrient cycling, carbon transformation and biological regulation in globally [17].

The conservation value of the Himalayan region and the need for regional collaboration picked up momentum when the International Center for Integrated Mountain Development (ICIMOD) and its partners designated the six (Kailash, Kangchenjunga, Far-Eastern Himalaya, Hindu Kush Karakoram Pamir, Everest, and Cherrapunjee-Chittagong) transboundary landscape across the Hindu Kush Himalayan region [24–26]. The Far-Eastern Himalayan Landscape (Fig. 1) which spreads over 71, 452 km^2 lies at the confluence of three global biodiversity hotspots: the Indo-Burma, the Himalaya, and the Mountains of Southwest China. It comprises the Nujiang–Gaoligongshan areas of China (22%), parts of northern Myanmar (66%), and parts of Changlang district of northeast India (12%) [27]. About 213,600 people mostly from different ethnic and linguistic groups with their historical, cultural and traditional beliefs reside in this landscape. Chakma, Lisu, Singpho and Rawan are examples of ethnic communities with a well-developed Traditional/Local Environmental Knowledge (TEK/LEK) reliance on biological resources [28,29].

The review of biodiversity in the FHL, reported higher species level publications (73.6%), followed by ecosystems (25%) and genetics (1.4%), and among the species, mammals were the most studied taxa (22.6%), followed by arthropods (15.6%), angiosperms (14.8%), insects (13.4%), and birds (10.8%) [27]. According to Basnet et al., 2019, only 1.5% (11 studies) were on fungi. In general, scarcity of studies and research on biodiversity could be due to inaccessibility and remoteness in most parts of the landscape [29]. Many areas remain to be fully explored, species inventoried, and ecosystem services recorded (Shakya et al., 2020). For that reason, the species diversity of wild mushrooms, and lichens of the FHL fungal communities are still largely unknown. As the evidence-based knowledge on their diversity and uses is severely lacking, we aim at a systematic review of the fungal species (wild mushrooms and lichens) diversity and their contributions to ecosystem services for the FHL. In the FHL, while several protected areas (See Fig. 1) have been established to support the objective of biodiversity conservation, areas outside the protected area are equally rich in species diversity [30]. For this review, given very limited publication from with FHL, we also selected surrounding areas, including the whole of Arunachal, Kachin and North-West parts (Baoshan, Dali Bai, Dehong Dai and Jingpo, Diquing Tibetan, Lijiang and Nujiang) of Yunnan province. This geographical scope for the review was framed at the virtual inception meeting among the three-country partners from China, India, Myanmar; and ICIMOD. A team of scientists representing partner countries with knowledge on fungi, local people and ongoing conservation actions was formed to take forward the review work. This balanced multidisciplinary and multinational team enriched the review process, in searching, screening and analyzing literature in Chinese and Burmese language publications.

The objective of this proposed review was to collate the spatially explicit evidence on the fungi (wild mushrooms and lichens) and their role in ecosystem services in FHL and to raise the conservation priority profile of the FHL. In addition, this work will also create an avenue for collaborative three-country research in fungi. The review was designed to answer the following research questions: What are the diversity of fungi and the spatio-temporal extent of their research? What are the ecosystem services (including Traditional/Local Environmental Knowledge provided by fungi in general; and What are potential areas of future fungi research in the FHL?

2. Methodology

This systematic review followed the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses of Diagnostic Test Accuracy [31]. The PRISM checklist [32] with an updated guideline for this review is provided as a Supplementary file (1).

2.1. Searching for articles and databases

Articles were searched from the global databases of Web of Science Core Collection (all years search within Topic until January 2022) and Scopus (article title, abstract and keyword search with no further limitations applied) as contributors are well aware of the limited work done in the FHL The subscriptions for the databases are made by some of the authors' institutions. The search strings, were generated, tested and finalized after discussion with project team members using Boolean operators "OR" and "AND" as summarized in Scopus format (Supplementary file 2). The performance of each string was tested using a test list of 15 articles collated from experts (Supplementary file 3). Search strings only with key terms were used when the search interface did not provide the whole search.

To supplement the search and to bring additional information on species diversity, gray literature and periodicals were searched on Google in English and on CNKI (https://oversea.cnki.net/index/) for Chinese literature sources, translating important information for analysis and interpretation. Together with known sources of potential literatures, relevant organizational websites of universities, professional research organizations, and local/regional/global fungal databases were also searched to prepare species checklists. Books, book chapters, master's and Ph.D.'s dissertations were also searched to collect species details from the subject area to ensure that all potentially relevant published and unpublished work has been searched to comprehensively include all additional species information. All searched scientific articles were exported and managed into the free and accessible reference manager Mendeley (https://www.mendeley.com/reference-management/mendeley-desktop).

2.2. Literature screening process

Articles found by database searches and search engines were screened at four stages: (i) title screening, (ii) locality screening, (iii) abstract screening, and (iv) full text. Other articles found through supplementary searches were screened in full text whenever available. Each article was assessed by three reviewers at the title and abstract screening stages, except for those found in Chinese databases that were assessed by the native reviewer. In case of uncertainty, the article was passed on for the next round of screening. Furthermore, articles through Google Scholar or from local/regional sources were screened for both title and abstract by an independent reviewer and, after such review, were included in our database once deemed applicable. Search records were collated, and the articles were screened manually.

Once accepted through the title and abstract screening stages, articles were assessed for their geographical locality. Locality screening was based on geographical coordinates provided in the text, extracted from maps provided in the publication, or extracted from Google Earth based on study location names mentioned in the articles. To delimit the study region of FHL, we used the Arunachal, Kachin - Myanmar and Western Yunnan. We also included the southern belt of Arunachal and south-west Yunnan in order to maximize species occurrences.

Moreover, all taxon names and authorities were rechecked according to the records updated by July 24, 2022 in the authentic mycological databases, Index Fungorum (http://www.indexfungorum.org/) and MycoBank Database (http://www.mycobank.org/). Thus, articles and species lists included in this review were critically appraised accounting for heterogeneity and potential effect modifiers. The species checklist from our study area (not species richness and abundances) is published on 25 July 2022 in the open-access Global Biodiversity Information Facility (GBIF) using the DarwinCore standard [33].

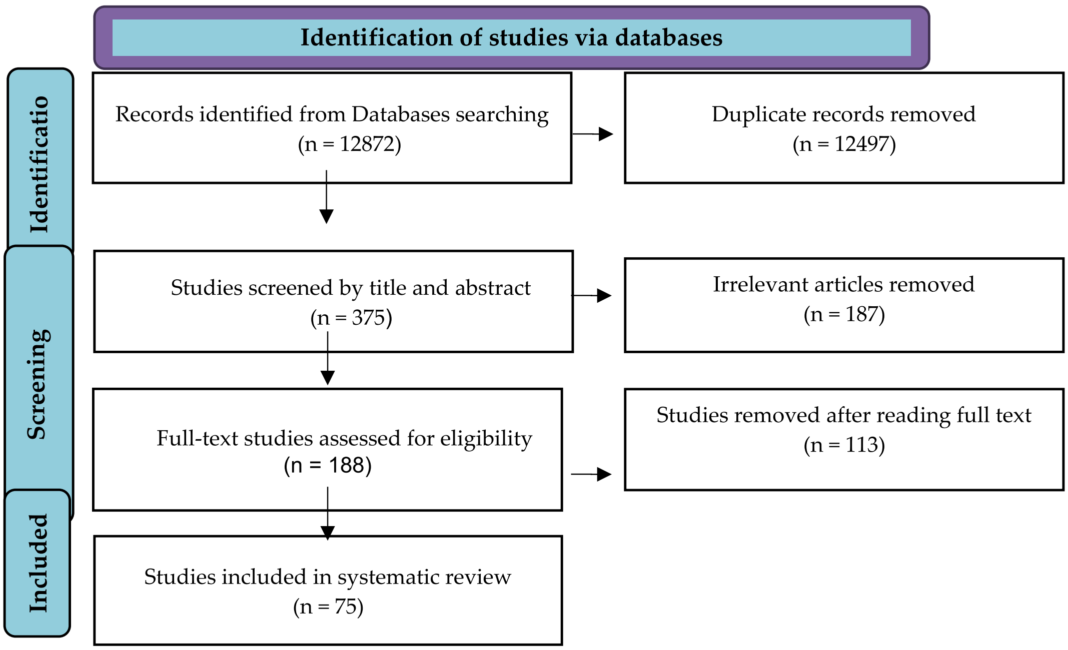

Fig. 2. Characterization of search strategy using PRISMA adapted from Ref. [32]. This flowchart represents the search and screening workflow and the eligibility criteria applied to the studies.

2.3. Data extraction and synthesis

Duplicate articles and data were appraised and removed following [34]. In those articles where all species are listed together with wild mushrooms or lichens, only needed species details (Species name, localities, uses if any) were extracted. In the dearth of published data, personnel communications were made with experts of the project in-charge for any additional information or relevant details. For e.g.- personnel communication has been established with Dr. Yoshihito Ohmura (Email: hmura-y@kahaku.go.jp), National Museum of Nature and Sciences, Japan who is a research member of the international cooperative project "The Natural History Research of Myanmar and the foundation of an International Research Center" together with the Forest Department, Ministry of Natural Resources and Environmental Conservation, Myanmar.

The PRISM flow diagram following [35] has also been utilized to summarize the literature search and review process with clear separation into identification, screening, eligibility, and inclusion stages (Fig. 2). In order to bring species diversity (not species richness and abundances) and descriptive knowledge on their ecosystem services, we have not applied statistically rigorous meta-analysis. Instead, a non-statistical meta-analysis was utilized. Only a chi-square test was performed to see if there were any variation in the articles published between the years 1965–2021. Extracting all the ecological variables would be a useful project to understand the nature of environmental influences on individual species, their populations, and communities, on ecoscapes and ultimately at the level of the entire landscape.

3. Results

3.1. Spatio-temporal extent of publication

Our searches returned 12,872 records. After removing duplicates from these records, we screened the titles and abstracts of 375 records, 188 of which underwent a full-text screening, Finally, a total of 75 articles were selected for review (narrative and data syntheses). For a full reference list of all articles included in our review are presented in supplementary file S4. Most articles in our review (48%, n = 36) were conducted in China, followed by 44% (n = 33) in India, 7% (n-5) in the Kachin state of Myanmar and a single publication from the FHL landscape. This review demonstrates that India has the highest number of publications on lichens, whereas China leads with publications on wild mushrooms.

The included articles were published between 1965 and 2021, with increasing frequency through the decades. We found a significant variation among reviewed articles published between years ($\chi^2 = 33.52$; df = 20; $p < 0.05$), showing an increasing publication trend during the study period. Information meeting our objectives were extracted through journal articles ($n = 62$), book chapters (n = 7), reports (n = 3) and books (n = 3). "The Lichenologist" journal had the highest number of articles on lichens (n = 6) followed by the journals "Mycosystema", and "The Bryologist" (n = 3). Considering the thematic areas, approximately, 52% of the articles focused on mushrooms, whereas 41% covered lichens. Similarly, approximately 56% of articles focused on taxonomy, 17% on ethnomycology, 12% on fungi in general, 8% on taxonomy + ethnomycology 5% on ethnolichenology and 1% on species distribution.

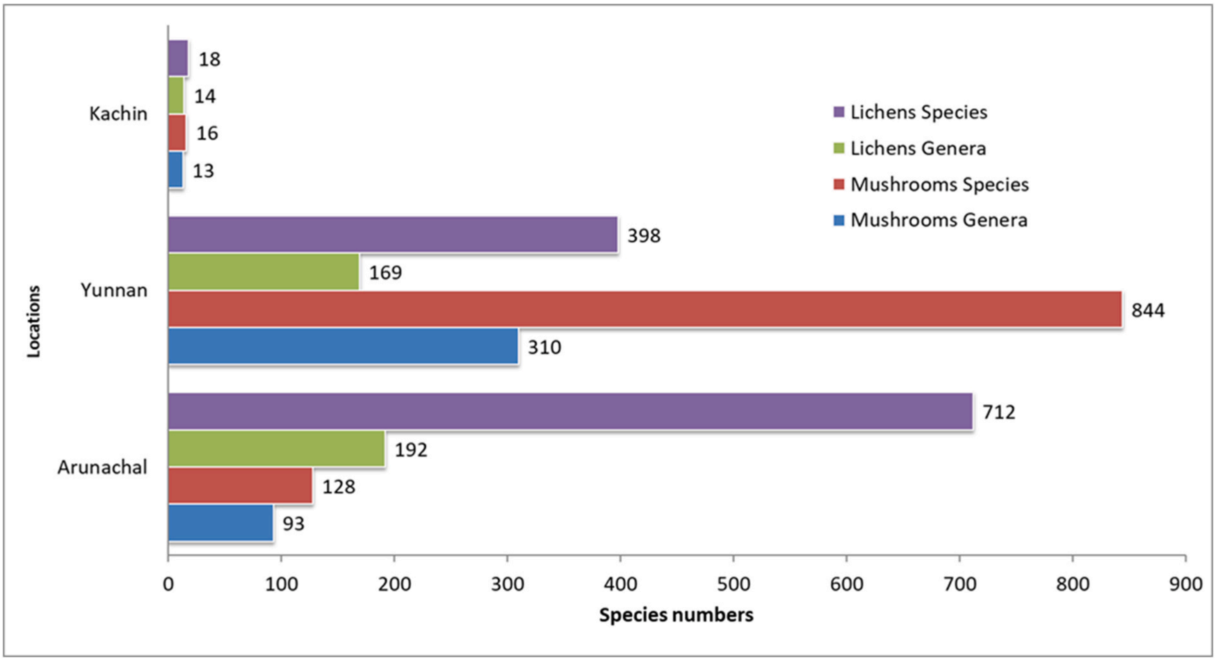

Fig. 3. The number of lichens and mushrooms families, genera and species reported from FHL and surroundings.

3.2. Fungal communities and checklist on the GBIF portal

In total 1937 species (Higher fungi 932 of 118 families and lichens 1005 of 79 families) have been extracted tracing the old record from the year 1780 until 2021 and published on the Global Biodiversity Information Facility (GBIF) online portal [36]. The open access dataset can be updated/revised and used for future research. The details of species with their available scientific name, collection date, location (county, state/province, country, locality), collector(s), bibliographic citations and links to their publications to dig deep into the species have been provided. The summary of the findings is reflected in Fig. 3, Table 1.

The top five mushrooms families are Polyporaceae (89 species), Hymenochaetaceae (74 species), Russulaceae (57 species), Boletaceae (47 species), Gomphaceae (37 species), and the top five lichens families are Parmeliaceae (177 species), Graphidaceae (147 species), Cladoniaceae (53 species), Pertusariaceae (51 species) and Physciaceae (47 species) Fig. 4 (a, b). Country wise, the higher number of mushrooms species ($n = 844$) are reported from China while 712 lichens species are reported from India. Higher inconsistencies or data deficient appeared in Myanmar part both in terms of mushrooms ($n = 16$) and lichens ($n = 18$) species diversity.

3.3. Species endemicity and cross-border availabilities: a reflection from the checklist

This review has revealed species endemicity of reported species showing 804 species of mushrooms only reported from China and 608 lichens species are only recorded from India. Myanmar harbours only nine and three unique mushrooms and lichens species respectively. Only two mushrooms species (*Schizophyllum commune* Fr., *Trametes versicolor* (L.) Lloyd) and eight lichens species (*Cetraria* Ach., *Cladonia* P. Browne, *Hypotrachyna cirrhata* (Fr.) Divakar, A. Crespo, Sipman, Elix & Lumbsch, *Hypotrachyna nepalensis* (Taylor) Divakar, A. Crespo, Sipman, Elix & Lumbsch, *Leptogium trichophorum* Müll. Arg., *Parmotrema* A. Massal., *Stereocaulon* Hoffm., *Sticta* (Schreb.)) Ach. are being shared among three countries. There are equally good numbers of species being shared in between China and India. Interestingly, none of the mushroom species are shared between India and Myanmar where only three (*Dibaeis birmensis* Kalb & Gierl, *Thamnolia* Ach. ex Schaer., *Usnea firmula* (Stirt.) Motyka) lichens species are being shared. Species details are provided in Table 2 and the GBIF checklist [36].

This review revealed two interesting fungal remains of earliest known mushrooms, *Palaeoagaricites antiquus* Poinar & R. Buckley [37] and *Palaeogaster micromorphus* Poinar Alfredo & Baseia [38] in Early Cretaceous and Early-Mid Cretaceous from the Amber mine in sandlestone limestone deposits in the Hukawng Valley, southwest of Maingkhwan, Kachin State ($26^0 20^0$N, $96^0 36^0$E). Amber piece contains complete or partial fruiting bodies in various developmental stages. *P. micromorphus* represents the first-ever fossil member of the oldest known gasteroid fungus.

3.4. Fungi and the extent of ecosystem services

Most of the publications mentioned use of mushrooms either as edible or inedible and poisonous-elaborating mainly their

Table 1
Distribution of lichens and mushrooms species in different locations of FHL and surroundings.

Locations	Localities	Lichens	Mushrooms
Myanmar	Kachin	18	16
Yunnan	Baoshan	1	141
	Dali Bai	277	37
	Dehong Dai and Jingpo	0	3
	Diquing Tibetan	70	349
	Lijiang	192	521
	Nujiang	10	5
Arunachal	Anjaw	2	0
	Arunachal (General)	137	58
	Basar	0	19
	Changlang	55	6
	Dibang	57	1
	East Kameng	32	0
	East Siang	19	0
	Lohit	25	0
	Lower Dibang Valley	263	0
	Lower Subansiri	40	1
	Namsai	13	0
	Papampure	24	2
	Siang	1	0
	Tawang	70	3
	Tawang-West Kameng	77	0
	Tirap	45	0
	Upper Siang	31	0
	Upper Subansiri	73	0
	West Kameng	118	32
	West Siang	90	30

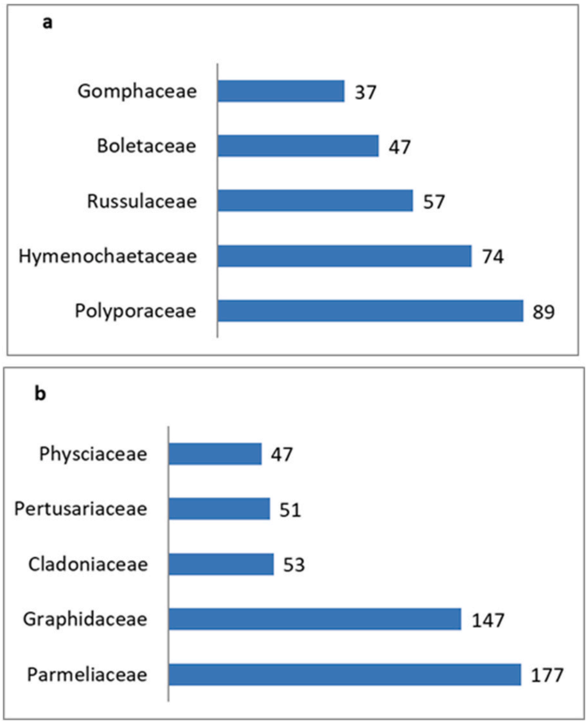

Fig. 4. Top five families (a. Mushrooms; b. Lichens) with their respective species numbers.

Table 2
Unique (available only in mentioned countries) and their cross-border availability.

Mushrooms		
Arunachal[a]	81	
Yunnan[a]	804	
Kachin	9	*Byssomerulius corium* (Pers.) Parmasto, *Chlorophyllum molybdites* (G.Mey.) Massee, *Chlorosplenium* Fr., *Favolaschia manipularis* (Berk.) Teng, *Marasmiaceae* Roze ex Kühner, *Palaeoagaricites antiquus* Poinar & R. Buckley[b], *Palaeogaster micromorphus* Poinar Alfredo & Baseia[b], *Trametes tephroleuca* Berk., *Xylaria fockei* (Miq.) Cooke
Yunnan - Arunachal[a]	45	
Yunnan - Kachin	5	*Dacryopinax spathularia* (Schwein.) G.W.Martin, *Flaviporus liebmannii* (Fr.) Ginns, *Heterobasidion insulare* (Murrill) Ryvarden, *Stereum ostrea* (Blume & T. Nees) Fr., *Trametes vernicipes* (Berk.) Zmitr., Wasser & Ezhov
Arunachal - Kachin[a]	0	
Arunachal-Yunnan-Kachin	2	*Schizophyllum commune* Fr., *Trametes versicolor* (L.) Lloyd
Lichens		
Arunachal	608	
Yunnan[a]	291	
Kachin	3	*Dibaeis birmensis* Kalb & Gierl, *Thamnolia* Ach. ex Schaer., *Usnea firmula* (Stirt.) Motyka
Yunnan - Arunachal	98	
Yunnan - Kachin	2	*Heterodermia* Trevis., *Hypogymnia* (Nyl.) Nyl.
Arunachal - Kachin	5	*Bulbothrix* Hale, *Byssocorticium* Bondartsev & Singer, *Heterodermia leucomelos* (L.) Poelt, *Parmotrema zollingeri* (Hepp) Hale, *Usnea dasaea* Stirt.
Arunachal-Yunnan-Kachin	8	*Cetraria* Ach., *Cladonia* P. Browne, *Hypotrachyna cirrhata* (Fr.) Divakar, A. Crespo, Sipman, Elix & Lumbsch, *Hypotrachyna nepalensis* (Taylor) Divakar, A. Crespo, Sipman, Elix & Lumbsch, *Leptogium trichophorum* Müll. Arg., *Parmotrema* A. Massal., *Stereocaulon* Hoffm., *Sticta* (Schreb.) Ach.

[a] Please refer [36],to access species details.
[b] Fossil Basidiomycota.

contribution to food provisioning services. Only a few published publications from FHL and surroundings have dissected their relationship with culture, society and market. Although no studies were specifically dedicated to defining ecosystem services-from fungi, many services can be extrapolated from their research in ethnomycology, ethnolichenology and taxonomy. (Table 3).

Table 3
Reported fungi role in ecosystem services: Cases from the FHL and surrounding districts only.

Services	Contributions	Common species	References
Provisioning	Food source (Edibility)	***Lichens*** *Letharielia cashmeriana* Krog, *Letharielia sernanderi* (Mot.) Obermayer, *Letharielia sinensis* Wei & Jiang, *Lobaria isidiophora* Yoshim., *L. kurokawae* Yoshim., *L. yoshimurae* Kurok. & Kashiw., *Ramalina conduplicans* Vain., *R. sinensis* Jatta, *Thamnolia vermicularis* (Sw.) Schaer., *T. subuliformis* (Ehrh.) W.L. Culb. ***Mushrooms***[a] *Agaricus* L., *Amanita hemibapha* (Berk. & Broome) Sacc., *Auricularia auricula-judae* (Bull.) Quél., *A. delicata* (Mont. ex Fr.) Henn, *Auricularia polytricha* (Mont.) Sacc., *Boletus* L. *B. edulis* Bull., *Cantharellus* Adans. ex Fr., *Clavulinopsis* Overeem, *Cordyceps* Fr., *Crinipellis* Pat., *Favolus* Fr., *Fomes* (Fr.) Fr., *Fomitopsis pinicola* (Sw.) P. Karst *Ganoderma applanatum* (Pers.) Pat., *G. lucidum* (Curtis) P. Karst., *Gomphus clavatus* (Pers.) Gray, *Hericium erinaceus* (Bull.) Pers., *Hydnum repandum* L., *Inonotus* P. Karst., *Lactarius deliciosus* (L.) Gray, *Lactifluus volemus* (Fr.) Kuntze, *Lentinula edodes* (Berk.) Pegler, *Lenzites betulinus* (L.) Fr., *Lepiota* (Pers.) Gray, *Lycoperdon* P., *Macrolepiota* Singer, *Morchella* Dill. ex Pers., *Ophiocordyceps sinensis* (Berk.) G.H. Sung, J.M. Sung, Hywel-Jones & Spatafora, *Oudemansiella* Speg., *Pleurotus* (Fr.) P. Kumm. *Polyporus* P. Micheli ex Adans., *Pseudocraterellus, undulatus* (Pers.) Rauschert, *Russula* Pers., *Schizophyllum commune* Fr., *Schizopora* Velen., *Suillus sibiricus* (Singer) Singer, *Termitomyces microcarpus* (Berk. & Broome) R. Heim, *Trametes gibbosa* (Pers.) Fr., *Tricholoma* (Fr.) Staude, *Tricholoma matsutake* (S. Ito & S. Imai) Sinfer, *Volvariella* Speg	***Lichens*** [98] ***Mushrooms*** [43,72,74, 75,83,99–108]
	Medicinal	***Lichens*** *Cladonia rangiferrina* L.). F.H. Wigg. *Lethariella* spp. ***Mushrooms***** *Ganoderma lucidum* (Curtis) P. Karst. *Ophiocordyceps sinensis* (Berk.) G.H. Sung, J.M. Sung, Hywel-Jones & Spatafora	***Lichens*** [49,98] ***Mushrooms*** [43,72,74]
Regulating	Mycorrhizal[a]	*Amanita* spp., *Boletus* spp., *Cantharellus* spp., *Chroogomphus* spp., *Clavulina* spp., *Cortinarius* spp., *Craterellus* spp., *Entoloma* spp., *Gomphidius* spp., *Gomphus* spp., *Hebeloma* spp., *Helvella* spp., *Hydnellum* spp., *Hygrophorus* spp., *Inocybe* spp., *Laccaria* spp., *Lactarius* spp., *Lactifluus* spp., *Leccinum* spp., *Lyophyllum* spp., *Phylloporus* spp., *Piloderma* spp., *Pseudotomentella* spp., *Ramaria* spp., *Russula* spp., *Sarcodon* spp., *Suillus* spp., *Thelephora* spp., *Tricholoma* spp., *Tylopilus* spp., *Xerocomus* spp.	[9,44,50,74,100,104, 106–113]
	Regulation of plant diseases	*Antrodia mappa* (Overh. & J. Lowe) Miettinen & Vlasák *Antrodia sinuosa* (Fr.) P. Karst. *Asterostroma cervicolor* (Berk. & M.A. Curtis) Massee *Bjerkandera adusta* (Willd.) P. Karst *Bondarzewia mesenterica* (Schaeff.) Kreisel *Botryobasidium olivaceum* Boidin & Gilles *Botryobasidium danicum* J. Erikss. & Hjortstam *Calcipostia guttulata* (Sacc.) B.K. Cui, L.L. Shen & Y.C. Dai *Ceraceomyces borealis* (Romell) J. Erikss. & Ryvarden *Cerioporus varius* (Pers.) Zmitr. & Kovalenko *Cerrena caperata* (Berk.) Zmitr. *Conohypha grandispora* Dhingra *Coriolopsis occidentalis* (Klotzsch) Murrill *Cylindrobasidium evolvens* (Fr.) Jülich *Daedalea xantha* (Fr.) A. Roy & A.B. De *Daedalea quercina* (L.) Pers. *Dendrophlebia crassispora* Dhingra & Priyanka *Dichomitus leucoplacus* (Berk.) Ryvarden *Earliella scabrosa* (Pers.) Gilb. & Ryvarden *Efibula tuberculata* (P. Karst.) Zmitr. & Spirin *Favolus grammocephalus* (Berk.) Imazeki *Fibrodontia gossypina* Parmasto *Fomes fomentarius* (L.) Fr. *Fomitiporia robusta* (P. Karst.) Fiasson & Niemelä *Fuscoporia torulosa* (Pers.) T. Wagner & M. Fisch. *Fuscoporia ferrea* (Pers.) G. Cunn *Ganoderma applanatum* (Pers.) Pat. *Ganoderma lucidum* (Curtis) P. Karst. *Gloeophyllum sepiarium* (Wulfen) P. Karst. *Gloeophyllum sepiarium* (Wulfen) P. Karst. *Gloeophyllum subferrugineum* (Berk.) Bondartsev & Singer *Grammothele fuligo* (Berk. & Broome) Ryvarden *Hyphoderma setigerum* (Fr.) Donk	[110]

(*continued on next page*)

Table 3 (*continued*)

Services	Contributions	Common species	References
		Inonotus albertinii (Lloyd) P.K. Buchanan & Ryvarden *Kurtia argillacea* (Bres.) Karasi?ski *Lentinus arcularius* (Batsch) Zmitr. *Lenzites eximius* Berk. & M.A. Curtis *Lenzites betulinus* (L.) Fr. *Licrostroma subgiganteum* (Berk.) P.A. Lemke *Microporus* P. Beauv. *Microporus xanthopus* (Fr.) Kuntze *Onnia tomentosa* (Fr.) P.Karst. *Osteina undosa* (Peck) Zmitr. *Oxyporus corticola* (Fr.) Ryvarden *Peniophora limitata* (Chaillet ex Fr.) Cooke *Peniophorella pubera* (Fr.) P. Karst. *Peniophorella rude* (Bres.) K.H. Larss. *Peniophorella praetermissa* (P. Karst.) K.H. Larss *Phaeophlebiopsis himalayensis* (Dhingra) Zmitr. *Phanerochaete sordida* (P. Karst.) J. Erikss. & Ryvarden *Phellinus allardii* (Bres.) Ahmad *Phellinus caryophylli* (Racib.) G. Cunn. *Phellinus setulosus* (Lloyd) Imazeki *Phlebiopsis gigantea* (Fr.) Jülich *Picipes badius* (Pers.) Zmitr. & Kovalenko *Porodaedalea pini* (Brot.) Murrill *Radulomycetopsis cystidiata* Dhingra, Priyanka & J. Kaur *Serpula himantioides* (Fr.) P. Karst. *Subulicystidium meridense* Oberw. *Tomentella scobinella* G. Cunn *Trametes flavida* (Lév.) Zmitr., Wasser & Ezhov *Trametes versicolor* (L.) Lloyd *Trametes gibbosa* (Pers.) Fr. *Truncospora ochroleuca* (Berk.) Pilát *Tubulicrinis glebulosus* (Fr.) Donk *Xenasma tulasnelloideum* (Höhn. & Litsch.) Donk *Xylobolus peculiare* (Parmasto, Boidin & Dhingra) Ryvarden *Xylodon flaviporus* (Berk. & M.A. Curtis ex Cooke) Riebesehl & Langer *Xylodon nesporii* (Bres.) Hjortstam & Ryvarden *Xylodon sambuci* (Pers.) ?ura, Zmitr., Wasser & Spirin	
	Air quality regulation	Lichens exhibit air cleaning activity by capturing pollutants	[114,115]
Supporting	Soil formation (pedogenesis)	Several lichen species play a vital role in accelerating weathering processes of rock surface minerals.	[116]
	Nutrient cycling	Several lichens as primary colonizers and mushrooms (as decomposers) support soil nutrient enrichment and stabilization.	[116]
Cultural	Recreational value; inspiration for culture, art and design	*Ganoderma lucidum* (Curtis) P. Karst.	[117]

As this review revealed more than 300 species of Ectomycorrhizal and Endomycorrhizal fungi, only some common genera are provided herewith.
** [43] have reported 417 edible mushrooms species from the Yunnan province - so, here only major medicinal mushrooms names are provided.
[a] Some representative edible mushrooms only.

4. Discussion

This systematic review was challenged by the proportion of obtaining relevant articles by the search strings. The volume of the relevant article was low in the FHL and surrounding areas. A similar condition but with successful revision was presented by Ref. [39]. We discuss below some potential of fungi research and their implications for the science of conservation and development, especially looking at the unexplored species diversity that await inventorying in the landscape; and existing relationship with ILK.

4.1. The FHL - A potential reservoir of fungi and ILK

The FHL has been recognized by botanists as the "epicentre of evolution", "centre of plant diversity", and "Eastern Asiatic regional centre for endemism" [28]. Owing to unique geological diversity and climate, Yunnan province (southwestern China) is recognized as of the one world's 34 biodiversity hotspots including fungi [40]. More than 1241 new species of wild macromycetes (macrofungi) and lichens have been published between 2010 and 2019 using type specimens from China and among these, 34.6% (429 species) were from Yunnan [41]. As three segments of Gaoligongshan National Nature Reserve (hereafter GNNR) and the intervening areas between them in North-west Yunnan falls under the FHL landscape with highly variable climate, luxuriant vegetation and other biotic and abiotic factors, this area also harbors enormous possibilities in terms of fungal diversity [42]. have compiled 2753 species of macrofungi in Yunnan province of which 417 are found to be utilized for medicinal purposes [43]. In Lijiang, Northwestern Yunnan.

Several local ethnic communities use *Lobaria kurokawae., Lobaria yoshimurae., Ramalina conduplicans* and *Ramalina sinensis* as food and ethnic culinary delicacy and *Lethariella cashmeriana, Lethariella sernanderi, Lethariella sinensis, Thamnolia vermicularis* and *Thamnolia subuliformis* as health-promoting teas. The nutritional values of many such species are well elaborated by Wang et al. (2001).

Arunachal regionis the cradle of speciation and center of origin for many species. Namdapaha National Park (NNP) located in Changlang district is one of the phytogeographically rich areas with greater endemism [44,45]. An earlier study by Ref. [46], has reported 78 lichens species from NNP. This national park has altitudinal variation from 260 m to 450 m asl with different habitats in the land of populated by indigenous communities *Lisu, Miju Mishmi, Lama and Chakma* who depends on fuel wood, NTFPs collection, hunting and fishing is still unexplored interms of lichens, mushrooms, bryophytes and other cryptic species [47]. In West Kameng, Arunachal, dried thalli powder (of a half teaspoon) of *Cladonia rangiferrina* together with boiling water has been used medicinally, by local tribes (Monpa, Aka, Sherdukpen, and Miji) to remove kidney stones [48,49]. Mushrooms inventory in Arunachal and in core zone of FHL is still very preliminary and prospects for discovery of new species is considered high [50].

For Myanmar, though Hkakaborazi National Park (HNP) and Hukaung valley in northern Myanmar comprised diverse habitats from the broadleaf forest, grassland, temperate forest, coniferous forest and shrubland [28,51,52], there is a dearth of data on lichens and mushrooms, as shown from the results in Fig. 3, Table 1. Myanmar and North-east Indian landscape share long border and ecosystems in the east, likewise in the west, there are contiguous landscape between Myanmar and China. This implies that many fungal species from India and China could be present in Myanmar. At the time of this review, only a few publications were available from Myanmar (Kachin Part) thus less numbers of fungal species are recorded. Collaborative research between China, India and Myanmar would be very useful to understand the extent of common species and ethnobotanically connected species, even new species - especially from Myanmar which needs more research interventions compared to Indic and China.

A report by Ref. [52] mentioned the appearance of parasitic and saprophytic fungi on the stumps of trees near village sites in HNP but did not identify their species. Similarly [53], mentioned about a variety of vegetation, from forest trees, algae and lichens in the Hkakaborazi region in Kachin State, without species identification [54]. also mentioned the unavailability of published information for Myanmar even though there exists strong cultural links to China, a country rich in ethnomycological knowledge. Recently [55], characterized a total of 22 species of mushrooms based on newly generated DNA barcoding using the internal transcribed spacer (ITS) region of nuclear ribosomal DNA. A total of 18 species, including *Lactarius austrotorminosus*, are newly reported from Myanmar. All the species were collected from Mandalay, Yangon, Bo Cho Island and Moeyungyi areas but none from the Kachin state. Irrespective of scarce data, HNP, Kachin is the largest consumer of plant products being immensely used as food and as ingredients in Traditional Chinese Medicines (TCM) [56].

Furthermore, the availability of fossilized fungi [37,38] in FHL, from Early Cretaceous and Early-Mid Cretaceous in the Hukawng Valley, Kachin State is an interesting finding though Kachin is poorly explored in terms of fungal species diversity. Being fragmentary or subtle in nature, such fossilized fungi lack distinguishing features that are diagnostic of extant taxa [57]. Fungi that lack rigid morphology have fewer chances of being fossilized but preserved fossilized specimens is a boon to scientific knowledge [58].

Weather conditions, soil acidity, substrates/vegetations composition, canopy coverage, are major determinant for the abundance of higher fungi and lichenized fungi (Andrew et al., 2018; Bidartondo et al., 2018; Coxson & Stevenson, 2007; Gauslaa, 2014; Radies et al., 2009). Identification of the ecological processes that govern or structure fungal communities and the consequences for ecosystem function is another interesting research question to answer.

4.2. Ecosystem services: A lesson and perspectives on fungus-based tourism

Among the non-extractive use of wild mushrooms, "Fungus based Tourism" or "Mycological Tourism" or "Mycotourism" is also a prominent component of local/rural economy and conservation awareness as observed in Spain [59], Mexico [60,61], China [62], and Australia [63]. Tourism in general and ecotourism in particular are usually regarded as cultural ecosystem services [64]. Such recreational services play a vital role in preserving or achieving sustainable use of wild fungi, though such activities should be carefully tailored to the local context ensuring that local communities are benefiting, and the use is indeed sustainable [60], and that there is good awareness on type of fungi, especially on differentiation between edible and poisonous species.

The GNNR is located only by 600 km west of Chuxiong Yi Autonomous prefecture - also known as "the City of Fungi" and has shared similar habitat, picturesque valley and scenic mountains. Chuxiong Yi is well appraised for the rich fungal resources and local ethnic minorities have wealth of mycophilic knowledge on Fungi [62]. Structurally, mushrooms shaped streetlamps, mushrooms murals covering building facades and construction of mushrooms shaped houses have been made in Nanhua County, Chuxiong [65]. Similarly, hanging bag fungus steel frame shed, fungus museum, and fungus amusement park are set up in sightseeing areas are other ways to boost fungus theme tourism [66]. Apart from structures, wild mushrooms festivals, clubs' activities, musical programmes, street food festivals, and other mushrooms related activities could draw more attention and boost up the local economy if such programmes are implemented in prominent areas of FHL. Within the last decade, the Himalayas and southwestern parts of China have become popular regions for domestic tourism and the sale of fungi (including lichens species) for health-promoting teas, has increased remarkably [14].

The *Chakmas* ethnic group - the third largest ethnic group in Arunachal and other ethnic and linguistic groups such as Lisu, Singpho and Rawang residing in the northwestern adjacent periphery of Namdapaha Tiger Reserve, Changlang are extremely knowledgeable on local resources and wild species [27,45] but while making this review, we did not find any documentation related to ethno-mycological knowledge within these groups. The ethno-mycological knowledge can be useful entry point to build a connection to different indigenous communities. This can be utilized to promote Fungi-based tourism in Namdapaha National Park or conservation bodies in the FHL, which would add fungi as an additional component of their attractions.

4.3. *Ophiocordyceps sinensis: the flagship fungus for building rural economy*

The world's most precious fungi valued up to USD 145, 000 per kilogram [67] is reported from the alpine ecosystem of China [68], India [69], Nepal [70] and Bhutan [71]. There are no scientific publications describing presence and distribution ecology from the core FHL area and only a few reports are available from the surrounding areas. In Arunachal, it is reported from Dihang-Dibang Biosphere Reserve [72,73], West - Siang district [74] and from West Siang, Upper Siang and Upper Subansiri (https://zeenews.india.com/news/eco-news/caterpillar-fungus-on-radar-of-international-smugglers_671336.html). In China, it is distributed from the southernmost site in Yulong Naxi Autonomous County in northwestern Yunnan Province to the northernmost site in the Qilian Mountains in Qilian County [75], Diqing Tibetan, Shangri-La (formerly known as Zhongdian), Lijiang counties [76] and in most counties in northwestern Yunnan [77–79]. Recognizing it's ecological and economical importance, it was nominated as the national fungus or flagship fungus of China [80] and since 1999 has been listed in AppendixII of the National Protection Law for Wild Plants of China [81]. Since 2020, it is listed as a vulnerable species (V) after the IUCN Red List of Threatened Species [82]. It's availability and connectivity with the people residing in FHL needs to examine in future studies, especially in those high altitude protected areas in Myanmar bordering China. Likewise, there are certain mushrooms of proven high economic value such as Matsutake which is crucial to local livelihoods and to the provincial tax base [83].

4.4. *Fungi in ecosystem services on the verge of climate change*

Biodiversity is a basis for all ecosystem services [84]. The continued loss of biodiversity and accelerating rates of environment and global change have threatened the well-functioning and provisioning of ecosystems [85]. It is well-established that a higher diversity of fungi increases the productivity of trees and also directly influences "food supply" and "biochemicals, natural medicines, and pharmaceuticals" [10]. Fungi are associated with many important ecosystem services (Table 3). Ecologically, they have an important role as decomposers, waste decomposition and recycling of essential nutrients in soil [1]. Mycorrhizal association is one of the most important mutualistic relationship between plants and fungi facilitating essential exchange and communication of nutrient and minerals (Pérez-Moreno et al., 2021).

With an average increase in temperature of 1.5 °C above pre-industrial levels, 8% of plants, 4% of vertebrates and 6% of insects will lose over half of their climatically determined geographic range. These figures will increase to 16% of plants, 8% of vertebrates and, 18% of insects for global warming of 2 °C [86]. Fungi are also negatively affected by climate change, large scale environmental degradation including pollution, habitat loss and deforestation [87].

The Far Eastern Himalayas are one of the most fragile environments on Earth and, a rich repository of biodiversity. Climate changes is increasing the risk of extinction of ecosystems which would greatly hinder their contribution of naturally resourced goods and services on which local and downstream communities rely [28,40,47,88–90]. The Hindu Kush Himalayan Assessment [91], has highlighted the importance of the mountain ecosystem for attaining Sustainable Development Goal (SDG) 15 # Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. As indicated by Ref. [92], further exploration in the fields of mycology, silviculture, landscape management and climate change will clarify the scenarios and opportunities that even exist in FHL. Similarly, risks associated with biodiversity-related factors, such as forest fires, extreme weather events, and the spread of invasive species, pests and diseases (including soil borne fungal diseases), would also be lower at 1.5 °C than at 2 °C of warming, supporting a greater persistence of ecosystem services [86]. Fungi has also been also studied as a proven indicator of climate warming and air pollution [93].

4.5. *Regional fungal assessment and databases: an urgent need*

Biological systems are structured hierarchically from the molecular to the ecosystem level, where entities such as individuals, populations, species, communities and ecosystems are heterogeneous [24]. With an increasingly connected world, some taxonomic databases dedicated to fungi have been developed such as Index Fungorum (http://www.indexfungorum.org/) and MycoBank (https://www.mycobank.org/) are the major ones. Furthermore, soil fungal communities in terrestrial environments are also publicly accessible on the GlobalFungal database containing over 2 billion unique sequence variants of the fungal nuclear ribosomal internal transcribed spacers ITS1 and ITS12, covering more than 57,184 samples contained in 515 original studies (GlobalFungi, https://globalfungi.com/accessed on July 24, 2022). Irrespective of their higher number of distributions, very sparse and rather fragmentary scientific publications dealing with systematic review/assessment of fungi at local, regional and global levels have been produced [7–14,54,94]. Even large scale assessments reports on biodiversity and ecosystem services produced by the IPBES (https://ipbes.net/assessing-knowledge) and the regional Hindu Kush Himalaya (HKH) Assessment - the first comprehensive assessment of the HKH region including FHL [91] are either silent on fungi or have only sparse information of well-known species like *Ophiocordyceps sinensis* and fail to cover global status and trends [95]. Since the Rio Convention on Biological Diversity in 1992, the conservation of biological diversity has become a central point of interest and conservation initiatives and have advanced a holistic ecosystem-based approach [10,96]. This lack of a comprehensive understanding of fungal diversity requires further exploration, reviews/assessments and robust ecological approach. Such inventories and assessments also need to take into account both the positive and negative impacts (notably allergic/poisoning reactions) of fungal species in order to maximize the provision of ecosystem services.

5. Conclusion

We show that available benchmark literature demonstrate early evidence for the availability, uses and prospects of fungi in FHL and surrounding areas. Significant limitations include a lack of literature available from the core FHL area, an imbalanced representation of fungi among the three countries studied, and a lack of quantitative data for meta-analysis especially on species richness and abundance. Nevertheless, this review was an opportunity to raise awareness on the research gap that exists for such underrepresented taxonomic groups in this biodiverse species rich landscape. Globally and across all organismal groups including fungi, species are on the verge of extinction with land-use change followed by direct exploitation and climate change and acting synergistically [97]. Beyond the landscape scale, these data are also crucial as a supplement to the knowledge of fungi for elucidating ecosystem services, overcome the knowledge gap and to set further research protocols and priorities linking the global, regional and national commitments. For the FHL, we recommend, wider inventorying of fungi in the landscape and linking it with applied knowledge around how fungi are a key component of natural ecosystems and how they support provision of wide range of ecosystem services (e.g., maintenance of soil fertility by decomposing organic matter, facilitation of uptake of water and nutrients through mycorrhizal association, enhancement of carbon sequestration in soil). Importantly, how they relate to socio-cultural, traditional knowledge and practices and economic context of communities in the landscape; as well we how they become part of national and international legislation and policy for biodiversity conservation, climate actions, and sustainable development.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2022.e12756.

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