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Expedition with micro- and macro-fungi: New perspectives to bridge the gaps*

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ABSTRACT

Fungi are the most fascinating group of organisms distributed widely in different ecosystems. Strategic geographic location of the Indian subcontinent is a major hub of fungal resources which offers ample scope for their exploration as well as application. My curiosity in mycology initiated journeying freshwater lotic habitats of the Western Ghats and west coast of India. It was soon ascertained that the freshwater hyphomycetes serve as model group facilitating assessment of basic concepts of detritus food chain and aquatic productivity. Second fascinating group attracted my attention was the marine fungi in various ecosystems of the west coast playing significant role in nutrient turnover. Third striking aspect of my interest was macrofungi of the Western Ghats and west coast. The basic function and ecosystem services of all these groups is breakdown and transformation of organic matter. The impacts of decomposition is highly valuable in production of precious metabolites, enrichment of organic matter and pull other groups of organisms to drive the energy flow initiated from detritus ecosystem. All these research areas are highly fascinating in the Indian subcontinent owing to diverse habitats, varied environment, wide range of substrates and numerous fungi. Progress towards basic or applied facets of fungal diversity, significance of metabolites and sustainable ecosystem functions demands collaborative endeavors. Specific strategies and schemes for prospective harness of fungal ecosystem services in the Indian subcontinent have been discussed in this commentary.

KEYWORDS: Aquatic fungi, diversity, decomposition, detritus food web, ecoregions, Indian Subcontinent, macrofungi, mangrove fungi, marine fungi, west coast, Western Ghats

INTRODUCTION

The Kingdom Mycota emerged as an independent eukaryotic line about 1 billion years ago (Lücking and Nelsen, 2018). Being devoid of photon trapping ability and gastrointestinal tract, fungi acquired outstanding capabilities to produce enzymes and metabolites. They are morphologically versatile from microscopic structures to giant fruit bodies. Usefulness of fungi in human nutrition, beverage and medicine archaeologically dates back to about 6,000 years (Willis, 2018). Although fungi are commonly viewed as plant and animal pathogens, they play a major role in nutrition, food processing, decomposition of organic matter, production of pharmaceuticals, generation of biofuels and serve as biopesticides or bioprotectants. The lifestyle of fungi is flexible, which is mainly dependent on the ecological niches and competent to perform their functions in terrestrial, aquatic, anaerobic, mutualistic and several extreme habitats. Fungi comprise versatile ability to develop network underneath the soil, process the organic matter, recycle or distribute nutrients, involve in growth promotion, antagonistic to disease causing organisms, offer stress tolerance and detoxify recalcitrant compounds (Suz *et al*., 2018).

Tremendous curiosity has been developed to explore the fungi after Rio convention on biodiversity in 1992, which has become a worldwide priority to understand the ecosystem structures and functions. The global estimate of fungi has become a black box, which needs inventiveness to provide evidence and statistics. The debate on fungal resource although ranges from 0.5 to 9.9 million based on morphological and molecular basis (Cannon, 1997; May, 2000; Blackwell, 2011), rationally accepted estimate is 2.2-3.8 million (Hawksworth and Lücking, 2017), which is more than six-fold of angiosperms (Willis and McElwain, 2013). However, molecular methods of fungal community gave a clue of existence of up to 5.1 million species (median of 0.5-9.9 million) (O'Brien *et al*., 2005). Fungal association with palms in Queensland was 1:26, while fungal association with palms in Australia and Brunei Darussalam was 1:33 (Fröhlich and Hyde, 1999) indicating regional difference in fungal estimation depending on the specific flora. The debate on fungal estimate will continue as and when additional evidences emerge. Currently documented fungi is only 7% (144,000) with the highest members documented in *Ascomycota* (90,000) followed by *Basidiomycota* (50,000) and *Microsporidia* (1,250), with addition at the existing rate of 2,000 per annum (Cannon *et al*., 2018; Niskanen *et al*.,

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2018) (**Box 1**). About 2,000 new fungi have been discovered during 2017, wherein the Asian Continent added the highest number (35%), followed by Europe (25%) and Australia (14%) (Niskanen *et al*., 2018). Up to 180 new mycorrhizal fungi were established in Australia, Europe and India. The current statistics broadened our knowledge on the whole genome sequence of about 1,500 species, which is more than those of plants and animals put together. It is evident that up to 90% of plant species on land co-exist mutualistically with fungi as mycorrhizas, which have a history of 400 million years. Among the mycorrhizas, the orchid mycorrhizal fungi were the highest (25,000) followed by ectomycorrhizal fungi (20,000) (Suz *et al*., 2018). This appraisal presents significance of filamentous aquatic fungi (freshwater and marine) and macrofungi with emphasis on the potential of the Indian Subcontinent to fill the knowledge gaps.

Box 1. Estimate of described eight fungal phyla (Total: ~144,140) (Source: Cannon *et al*., 2018)

Ascomycota	~90,000
Basidiomycota	~50,000
Microsporidia	~1,250
Chytridiomycota	~980
Zoophagomycota	~900
Mucoromycota	~760
Blastocladiomycota	~220
Cryptomycota	~30

FRESHWATER FUNGI

Freshwater fungi are phylogenetically diverse assemblage of *Ascomycota*, *Chytridiomycota*, *Cryptomycota* and *Zygomycota* distributed in different habitats worldwide (Jones *et al*., 2011; Raja *et al*., 2018). The lifestyle of freshwater fungi widely differs (e.g. saprobic, planktonic, endophytic, pathogenic and parasitic) and dependent on the ecological niche. Being integral component of aquatic food web, broad ecological functions of freshwater fungi are breakdown of coarse particulate organic matter (COPM) and drive the energy to higher trophic levels. They have also adapted to overcome the impact of one way transport of propagules, overgrazing by the shredders, dominance of other organisms living in the same niche, seasonal periodicity of detritus input and intermittent wet and dry regimes. Diversity of substrates in the lotic habitats supports their perpetuation as well as stability of population. The live (e.g. roots and macrophytes) as well as dead (e.g. leaf litter, flowers, twigs and logs) substrates are colonized by the freshwater fungi.

The life styles of these fungi have been fine tuned based on the longevity of the substrates in lotic ecosystem. Investigations pertain to freshwater fungi which could be divided into three major segments: i) diversity, distribution and phylogenetic studies based on morphological and molecular approaches; ii) studies on the ecology and ecosystem services; iii) production of secondary metabolites. Two dimensions of the aquatic detritus food web include decomposition of CPOM (horizontal) and energy flow (vertical) to the higher trophic levels (**Fig. 1**). The extent of energy flow depends on the nature of detritus, abiotic factors and biotic features of the aquatic habitat. Fungal decomposers have the main role in processing the detritus to transform into fungal biomass and products of decomposition. Depending on the fungal processing of detritus, the detritivores (e.g. shredders) facilitate or hasten the transformation of CPOM into several components. Aquatic fungi and detritivores together drive the energy to higher trophic levels and several products of decomposition serve as source of energy in aquatic habitats.

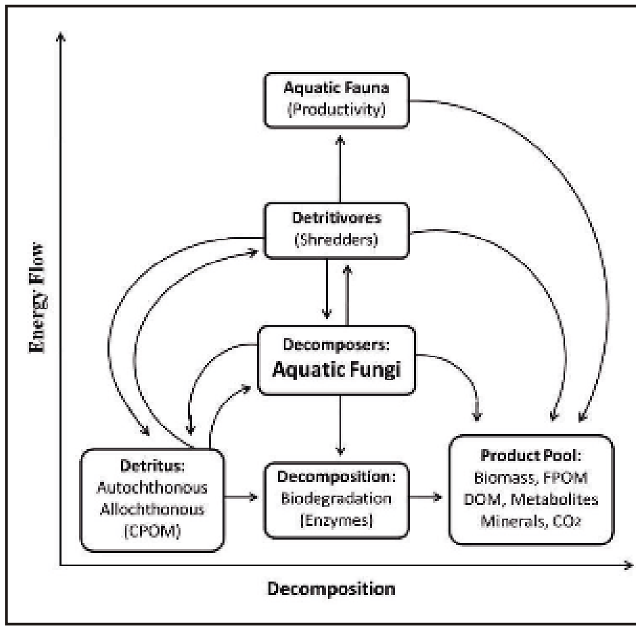

Fig. 1. Features of fungal driven detritus food web in lotic habitats (CPOM, coarse particulate organic matter; FPOM, fine particulate organic matter; DOM, dissolved organic matter).

Freshwaters are hit by as many as seven disturbances among the 10 worst perturbations in the world leading to the highest loss of species (Wall *et al*., 2001; Malmqvist and Rundle, 2002; Rockström *et al*., 2009). The human interference which has major influence on species loss in freshwaters include alteration of riparian habitats, extensive water extraction, loading pollutants and invasion of alien species. However, aquatic filamentous fungi have expanded their territory beyond their usual habitats (see Chauvet *et al*., 2016). The **Box 2** records some of the terrestrial and semi-aquatic habitats where aquatic fungi persist. Specific adaptations to such unusual (or stressed) habitats need to be investigated and such habitats are of special interest to follow up transformation of anamorphs into teleomorphs.

Hyphomycetous Fungi: Freshwater hyphomycetous fungi (or Ingoldian fungi) are characterized by production of morphologically distinct conidia especially multiradiate (staurosporus) and sigmoid (scolecosporus) (Ingold, 1975; Marvanová, 1997; Gulis *et al*., 2005). However, some of them also produce conidia of conventional shapes (spherical or

Box 2. Occurrence of aquatic hyphomycetes in selected niches outside the lotic habitats (Source: Sridhar, 2017a)

Terrestrial	Semi-aquatic
Forest floors	Stream slopes
Tree holes	Tree holes
Tree canopy	Stemflow
Crown humus	Throughfall
Live leaves/twigs/roots	Crown humus
Epiphytes	

oval or fusiform: e.g. *Dimorphospora, Tumularia* and *Vermispora*). The complex conidial shapes represent functional traits in aquatic habitats like floatation, impaction and sedimentation similar to plankton. Hyphomycetes have worldwide distribution and currently reported up to 300 species (95 genera) with preponderance in freshwaters of mid-latitudes (Wood-Eggenschwiler and Baerlocher, 1985; Gulis *et al*., 2005; Shearer *et al*., 2007; Raja *et al*., 2018; Seena *et al*., 2019).

The autochthonous and allochthonous detritus serve as major nutritional resource in aquatic habitats and several aquatic organisms compete to utilize such resources. Broad range of functions and survival strategies of hyphomycetes might have been evolved through natural selection especially adaptation to drastic variations of habitats (*r*-selection) or adaption to thrive for prolonged periods on stable organic substrates (*K*-selection) (Cooke and Rayner, 1984; Hawksworth and Mueller, 2005). Hyphomycetes, grow on fragile substrates like leaf litter, have to adapt *r*-selection (ruderal strategy) for rapid colonization, growth and reproduction owing to rapid loss of substrate. In order to compete for resource utilization, hyphomycetes follow boom-bust cycle or Baerlocher's effect (Sridhar, 2017b). The sequence of events like drift conidial adherence to detritus (arrival), conidial release from detritus (departure) and mycelial growth in detritus (biomass) happen with time lapse (Baerlocher, 2009). Conidial recruitment, release of conidia and fungal biomass accumulation on fragile substrate decreases owing to less hospitable status of substrate. Such events are dependent on nature of detritus, geographic conditions and human interference. Thus, evaluation of these variables serves as authentic strategy to assess the exponential decay pattern of detritus. To maintain the inoculum in the upstream, escape grazing from shredders and other adverse conditions, hyphomycetes have adapted several strategies: i) colonization on the stable organic substrates like wood (it may aid to produce teleomorphic state); ii) colonize live roots exposed in to water (as endophytes); iii) survive on the moist substrate in stream border or valley; iv) survival in intestine of aquatic fauna (e.g. crabs, fishes, prawns and tadpoles).

Ascomycetous Fungi: Similar to hyphomycetous fungi, ascomycetous fungi also colonize woody and herbaceous detritus in aquatic habitats (Wong *et al*., 1998; Shearer and Raja, 2017). Their reproductive structures mainly consist of flask or bowl shape. The ascospores have undergone modifications to develop sticky gelatinous sheaths as well as appendages as to float, adhere and colonize substrates in water. Recent report reveals that up to 675 species of ascomycetes have been reported in freshwaters worldwide (Shearer and Raja, 2017). Similar to aquatic hyphomycetous fungi, the diversity of ascomycete community differs along the latitudinal gradients with a clue that the highest diversity in the interface of temperate and tropical regions (Shearer *et al*., 2015; Raja *et al*., 2008, 2018).

Enzymes of aquatic ascomycetes (e.g. amylases, cellulases, peroxidases, pectinases and xylanases) aids in causing soft rot in woody debris in aquatic habitats, which is slower compared to fungal white rot or brown rot in terrestrial habitats (Savory, 1954). The extent of fungal decay of wood in aquatic habitats confined to a few millimeters owing to lack of oxygen in interior region (Shearer, 1992). However, ascomycetes could penetrate their hyphae into the deeper regions of wood to cause decomposition by translocation of molecular oxygen through their hyphae similar to fungal activity in deeper zones of anoxic sediments. Although hyphomycetous fungi growing on fragile leaf litter follow *r*-selection, those colonize stable woody litter have the opportunity to switch over to perfect state leading to adapt *K*-selection, which is advantageous to thrive under chaotic situations or disturbances (e.g. unusual niches, dryness, temperature stress, pollution and flood conditions) (Cooke and Ryaner, 1984; Chauvet *et al*., 2016).

Aeroaquatic Fungi: Aeroaquatic (or helicosporous) hyphomycetous fungi occur often in lotic habitats by building vegetative biomass underwater and production of conidia in air-water interface (helicospores). They are also inhabitants of moist forest litter, ponds and semi-aquatic habitats. As saprobes they grow on plant litter, wood, twigs and moist locations in and around aquatic bodies. *Helicoma*, *Helicomyces*, *Helicoön*, *Helicosporium*, *Spirosphaera* and related genera are characterized with two or three dimensional coiled spores as special adaption for flotation (Zhao *et al*., 2007). Helicosporous *Cirrenalia* and *Zalerion* exist in marine habitats. Other aeroaquatic and aeroaquatic-like fungi include *Candelabrum, Clathorsporium, Clathroconium, Clathrosphaerina, Helicodendron, Helicoubisia, Inesiosporium, Moorella, Pseudoclathrosphaerina, Spirosphaera, Strumella, Sympodioclathra, Trochophora,* and *Xenosproium*. Morphological characters are very important in classifying helicosporous hyphomycetes. Some of the important morphological features necessary for classification include habitat, substrate, conidial coiling pattern, hygroscopic/non-hygroscopic features of conidial filaments, colour/hyaline nature of conidial filaments, denticulate conidiogenous cells and pattern of conidiogenesis (Zhao *et al*., 2007). According to a recent literature, from the aquatic habitats up to 90 species (19 genera) of aeroaquatic fungi have been reported worldwide (Raja *et al*., 2018).

Studies in the Western Ghats and West **Coast:** The first report from India (Kambakkam Hills, north of Chennai, Tamil

Nadu) on the occurrence of four aquatic hyphomycetes in a streamlet was published by Ingold and Webster (1973). **Table 1** provides selected literature on aquatic fungi of the Western Ghats and west coast of India. Different aspects evaluated on freshwater fungi include diversity, distribution, endophytes, occurrence outside the usual habitat, decomposition, palatability to fish, enzymes, impact of pollutants and techniques followed. A few reviews, checklists and monographs consolidated the studies carried out in the Western Ghats and west coast of India. Most of the literature emphasized on the occurrence, diversity and distribution of aquatic hyphomycetes. Among several surveys carried in the Western Ghats and west coast, Sampaje stream in the Western Ghats at about 500 m asl (mid-altitude) possesses the highest number of aquatic hyphomycetes. Including studies outside the stream habitats (e.g. tree holes, stemflow and through fall) nearly 25% of globally known aquatic hyphomycetes have been recorded in a few samples during post-monsoon season. In any freshwater streams of the Western Ghats and west coast, single sample (e.g. water, foam and leaf litter) assessment provide at least 10% of globally known aquatic hyphomycetes. A few new genera and species of aquatic hyphomycetes have been described from the Western Ghats and west coast of India (e.g. *Kumbhamaya jalapriya, Synnematophora constricta, Trinacrium indica, Triscelophorus konajensis* and *Vermispora cauveriana*) (Sridhar, 2010; Borse *et al*., 2017). Diurnal periodicity of aquatic hyphomycete spores have been studied in the streams of the Western Ghat and west coast (Sridhar and Sudheep, 2010; Ghate and Sridhar, 2016d).

Many aquatic hyphomycetes have been reported as endophytes in riparian trees and ferns (Raviraja *et al*., 1996a) (**Table 1**). Similar to occurrence of more hyphomycetes in the mid-altitude of the Western Ghats (Raviraja *et al*., 1998a), endophytic fungi were also high in the mid-altitude region (Ghate and Sridhar, 2017b). Aquatic hyphomycetes have extended their niches within (sediments, aquatic roots and fish intestine) (Sridhar and Sudheep, 2011b; Sudheep and Sridhar, 2012; Ghate and Sridhar, 2015a) and outside their usual ecological niches (e.g. tree holes, stemflow, throughfall, bark, epiphytes and canopy) (Sridhar, 2009c; Chauvet *et al*., 2016). Aquatic and aeroaquatic hyphomycete spores were also found in the street runoff of urban habitats of a southwestern Indian city (Ghate and Sridhar, 2018). Besides aquatic hyphomycetes, several aeroaquatic hyphomycetes were also reported from the rainwater dripping from the tree species (Ghate and Sridhar, 2015c). Along with aquatic hyphomycetes, occurrence of aeroaquatic hyphomycetes, terrestrial hyphomycetes and aquatic ascomycetes have also been reported in leaf and woody substrates (e.g. Sridhar and Kaveriappa, 1989; Sridhar and Sudheep, 2011a; Sudheep and Sridhar, 2011, 2013a). Comparison of leaf litter decomposition in stream locations and tree holes in the west coast revealed involvement of several aquatic hyphomycetes with double the duration of half-life of decomposition in tree holes than stream locations (Sridhar *et al*., 2013).

Besides studying the colonization of aquatic hyphomycetes and allied group of fungi on leaf litter and woody litter in streams, a few studies are involved in assessing the pattern of decomposition (**Table 1**). Decomposition is the functional phase of aquatic fungi, which results in improvement of palatability, energy flow and probably facilitates the bioremediation process. Native and exotic tree leaves have been investigated to understand the pattern of decomposition in streams, rivers and dam sites (Raviraja *et al*., 1996b, 1998b; Sridhar *et al*., 2011a; Sudheep and Sridhar, 2013a). Studies on wood decomposition are relatively limited and these studies in addition follow the mass loss, changes in leaf chemistry as well as extracellular enzymes are assessed (Sridhar *et al*., 2011a; Sudheep and Sridhar, 2013b). Chandrashekar and Kaveriappa (1988, 1991, 1992) evaluated the capacity of production of extracellular enzymes by pure cultures of aquatic hyphomycetes.

Table 1. Selected literature on freshwater fungi of the Western Ghats and west coast of India.

Diversity and distribution	Subramanian and Bhat (1981), Sridhar & Kaveriappa (1984, 1989, 1992), Chandrashekar *et al*. (1986, 1990), Rajashekhar & Kaveriappa (1993, 2003), Raviraja *et al*. (1998a), Maddodi *et al*. (2009), Sridhar *et al*. (2010a, 2013), Sudheep & Sridhar (2011, 2012, 2013a, b), Ghate & Sridhar (2015a), Karun *et al*. (2016a)
Endophytes	Raviraja *et al*. (1996a), Ghate & Sridhar (2017b)
Outside the habitat	Sridhar & Kaveriappa (1987), Sridhar *et al*. (2006, 2013), Karamchand & Sridhar (2008), Sridhar & Karamchand (2009), Sridhar (2009c), Ghate & Sridhar (2015c, 2016b, 2018)
Decomposition	Raviraja *et al*. (1996b, 1998b), Sridhar *et al* (2011, 2013), Sudheep & Sridhar (2011, 2013a, b)
Palatability	Chandrashekar *et al*. (1989)
Enzymes	Chandrashekar & Kaveriappa (1988, 1991, 1992)
Pollution	Sridhar & Kaveriappa (1986), Chandrashekar & Kaveriappa (1989, 1994), Raviraja *et al*. (1998b), Raghu *et al*. (2001), Ghate & Sridhar (2018)
Technique	Chandrashekar *et al*. (1990), Sridhar & Sudheep (2011b), Sudheep & Sridhar (2012), Ghate & Sridhar (2015b)
Checklist	Patil & Borse (2015)
Review	Sridhar *et al*. (1992), Sridhar (2009a, c, 2010)
Book/Monograph	Borse *et al*. (2016, 2017)

Although there are no specific studies on the bioremediation of pollutants using aquatic fungi, some studies dealt with occurrence of aquatic hyphomycetes in polluted habitats and impact of pollutants on growth, sporulation and spore germination of aquatic hyphomycetes (**Table 1**). In addition, occurrence of aquatic fungal spores in urban runoff has been investigated recently (Ghate and Sridhar, 2018). A few new techniques have been developed to study the aquatic hyphomycetes (**Table 1**). Among them, indirect evaluation of fungi in aquatic sediments, fish intestine and spore trap using plant latex are interesting (Sridhar and Sudheep, 2011b; Sudheep and Sridhar, 2012; Ghate and Sridhar, 2015b). Reports on aquatic hyphomycetes on woody litter are limited, but applying bubble chamber incubation technique similar to the leaf litter revealed several aquatic hyphomycetes on woody litter from the Western Ghats and west coast (e.g. Sridhar *et al*., 2010a; Sudheep and Sridhar, 2011; 2013b). Available studies on the aquatic fungi in streams and rivers of the Western Ghats and west coast indicate that there are several major gaps in our knowledge on the aeroaquatic fungi, aquatic ascomycetes (including *Dothideomycetes*) and aquatic lichens. Recently, many freshwater lichens have been reported by Thüs *et al*. (2014) and no such reports from the freshwater habitats of the Western Ghats and west coast of India. Habitat destruction and pollution are the major threats for functioning of aquatic fungi. Aquatic fungi being the major link between detritus and aquatic fauna (e.g. crabs, fishes, prawns and tadpoles), rehabilitation tasks are of immense significance to harness their ecosystem services and valuable biomolecules.

MARINE FUNGI

Marine mycology embodies broad groups of fungi belonging to *Ascomycota*, *Basidiomycota*, *Blastocladiomycota*, *Chytridiomycota*, yeasts and fungus-like organisms. Pang *et al*. (2016) have broadened the definition of marine fungi to encompass those which could grow and or sporulate in marine habitats, develop mutualistic association with marine living beings in marine habitats and genetically adapted or metabolically dynamic in marine habitats. Marine fungi are accessible to a diverse substrata as well as niches (sand, soil and sediment; neritic, oceanic, deep sea and mangrove waters; dead algae, seagrass, mangrove vegetation and animal substrates; live algae, seagrass, mangrove vegetation and live animals). Similar to freshwater fungi, frequent question needs answer is on the estimation of marine fungi. Roughly the current known marine fungi are about 1,200 (10%) against the predicted estimate of 10,000-12,000 (Jones, 2011).

The functions and survival attributes of marine fungi depends on the substrata and the ecological niche (e.g. planktonic, saprophytic, mutualistic, pathogenic and parasitic). As an important component of marine food web, marine fungi mainly involve in decomposition and nutritional enrichment of organic matter to transfer energy to the higher trophic levels. They have several adaptations to lead planktonic life and strategies to prevail under adverse effect on their vegetative and reproductive phases. Marine fungi flourish on wood (drift, jammed and panels), algae (microalgae and macroalgae), sediment (coast, continental shelf and deep-sea) and rocks/corals (endolithic). Usually, the sea foam composed of spores of many marine and marine-derived fungi. The current research on marine fungi involves understanding: i) the diversity, distribution and phylogeny; ii) ecological consequences; iii) production of natural products of industrial and medicinal significance.

Diversity: Up to 943 ascomycetes have been reported in marine habitats (Jones *et al*., 2015). The members belonging to the orders *Eurotiales* and *Saccharomycetales* are known to have wide association with water, sand, sediment, plant and animal substrates. Similar to freshwater fungi, marine ascomycetes have appendaged ascospores for dispersal and to hold the substrates for growth (e.g. *Halosphariaceae* and *Lulworthiales*) (Jones, 1995; Campbell *et al*., 2005). *Lulworthiales* are obligate marine fungi associated with macroalgae and corals (Campbell *et al*., 2005). Although representation of basidiomycetous fungi is least in marine habitats, Jones *et al*. (2015) listed 21 filamentous and 75 basidiomycetous yeasts occurring in oceanic, mangrove and brackish water habitats. Up to 213 marine basidiomycetes and ascomycetous yeasts have been reported by Jones *et al*. (2015). Marine chytrids are also underestimated like marine basidiomycetes and reported 27 species (Jones *et al*., 2015). They are the most abundant group in the Arctic and sub-Arctic regions (Comeau *et al*., 2016) and also known as parasites on diatoms (Ohtsuka *et al*., 2016). Recent update on filamentous fungi included 300 species occurring in marine habitats (Jones *et al*., 2015). Studies on mangrove plant species yielded as many as 637 species of endophytic fungi (Sakayaroj *et al*., 2012b). Marine fungi are also composed of several pathogens on plants (mangrove and salt marsh), seaweeds, marine animals and diatoms.

Endophytic Fungi: Interest on ecological studies in different habitats of marine ecosystems resulted in documentation of a variety of marine fungi (Jones and Pang, 2012; Sakayaroj *et al*., 2012a). One such potential field of ecological interest is marine endophytic fungal studies. Endophytic fungi are generally known to confer fitness to establish in a specific niche by overcoming the negative impacts of abiotic and biotic stresses (e.g. resistance against herbivory, prevention of pathogen attack and drought tolerance). Some studies confined to mangrove ecosystems, coral reefs, islands and coastal sand dunes. Studies are available on endophytic fungal association with salt marshes, mangrove plants, mangrove associates, coastal sand dune plants, seaweeds and seagrass. However, many studies in marine habitats have documented endophytic fungi up to genus level indicating several new species. Endophytic fungal studies have not only added new fungi occurring in marine habitats, it has projected the potentiality of many marine-derived endophytic fungi in production of medicinally and industrially valuable bioactive compounds of bioprospect interest. Some marine endophytic fungi have bioremediation potential against stress as well as pollutants.

Food Web: Organic matter constitutes the major hub of transformation of energy into the marine food web. Input of CPOM to the ocean will be of autochthonous or allochthonous origin. The facets of organic matter breakdown by fungi in the marine ecosystem have been conceptualized in **Fig. 2**. The CPOM composed of stable (e.g. wood, root and animal remains) and fragile (e.g. leaf litter, seaweed and seagrass) material. The habitats that provide substantial input of CPOM include mangroves, salt marshes, coastal sand dunes, islands and coral reefs. The CPOM accumulates in sand, soil, sediment, intertidal, oceanic, continental shelf, pelagic and benthic habitats. Fungi being major components of life in marine habitats involve in degradation of organic matter leading to energy flow to the higher trophic levels. Decomposition of organic matter by fungi in marine habitats depends on the nature of CPOM and many abiotic factors. The fungal structure and function on CPOM leading to energy flow to the higher trophic segments via several products like fine particulate organic matter (FPOM), dissolved organic matter (DOM), metabolites, minerals and carbon dioxide (see Sridhar, 2012). During the transformation of organic matter by fungi, the physical as well as nutrient status of CPOM modifies leading to create habitats for colonization of other organisms. Besides, the fungal biomass accumulated in the

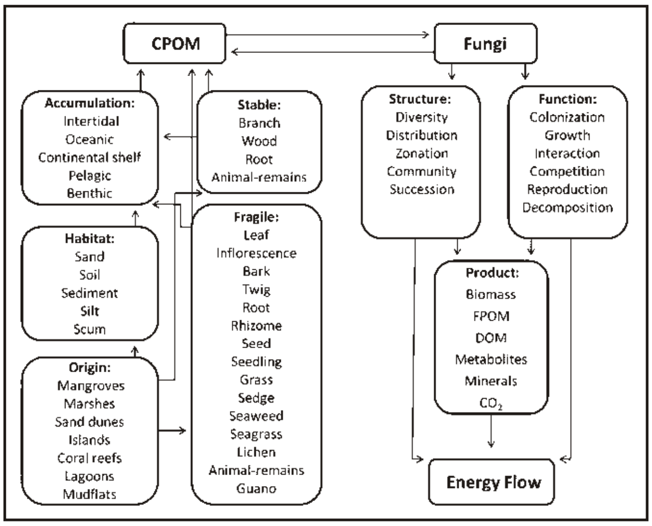

Fig. 2. Elements of fungal driven food web in marine habitats (CPOM, coarse particulate organic matter; FPOM, fine particulate organic matter; DOM, dissolved organic matter).

organic matter itself attractive to marine fauna. It is likely, several fungal keystone species and consortium of fungi involve in fine-tuning the CPOM transformation, which may also control the rates of turnover.

Petersen and Curtis (1980) performed a comparative study of energy budgets from subarctic, temperate and tropical areas (Greenland, North Sea and West Thailand). This study compares the incident solar energy, energy budgets of organic matter, phytoplankton, zooplankton, benthos and filter feeders. Such comparisons are not available for the decomposer food chain by fungal decomposers in spite of fungi serve as energy signatures especially in the detritus food chain. However, estimation of ergosterol helps up to some extent to understand the contributions to energy budgets by only filamentous fungi. Data are available on the decay coefficient and mass loss of wood, roots, leaf, sedge and seagrass in marine environments of different geographical locations (see Sridhar, 2012). In marine ecosystems, mangroves and coral reefs serve as productive regions of interest to study the interaction of fungi with biota and energy flow (Yap *et al*., 1994; Twilley, 1995). Information is available on the productivity of mangroves (e.g. carbon, nitrogen and phosphorus budget), global litter accumulation and annual range of litter production in mangroves (see Sridhar *et al*., 2012). Various animal populations depend on mangrove habitats for food and survival. Other than those inhabiting the floors (e.g. crabs, sea cucumbers and snails), birds, insects and bats are also important components of mangrove ecosystems in terms of detritus production. For example, the caterpillars of moth (*Hyblea purea*) are known to consume substantial leaf biomass of *Avicennia germinans* in the Caeté estuary in Brazil within a few weeks (Koch and Wolff, 2002). Such processing leads to accumulation of feces and leaf particles, which are the major energy source for transport. Similarly, bat and bird guano constitutes major organic matter input in many mangroves. In the Man-of-War Cay (Belize), shipworm borer (*Teredo bratschi*) activities are high especially on the stakes of mangroves owing to nutrient enrichment by guano deposition (ammonia, nitrate and phosphate) (Kohlmeyer *et al*., 1995). Such unusual situation in marine habitats may have different food web complexity and the dynamics of energy transfer by fungi needs further exploration.

Studies in the Arabian Sea: Occurrence of lignicolous filamentous marine fungi (12 ascomycetes and 6 mitosporic fungi) from India (Tamil Nadu coast) was the first report from India by Raghukumar (1973). Subsequently, studies on marine fungi continued in the east coast and west coast simultaneously. **Table 2** provides selected contributions on marine fungi from the west coast of India. Different facets of marine fungi studied include diversity, distribution and occurrence in deep-sea, endophytes, decomposition, enzymes and bioremediation. A few reviews, books and monographs consolidated the studies carried out in the west coast of India. Raghukumar (2017) contributed a book dealing with world marine fungi in the coast and oceanic regions, which consists of several studies carried out in India. Recently, Indian marine fungal database has been constructed by Kiran Ramachandra Ranadive and Neta Jagtap from Maharashtra (http://www.fungifromindia.com/fungiFromIndia/databases/IMFD/nextPage.php?id=references.php).

Similar to freshwater hyphomycetes, studies on the diversity and distribution of marine fungi in the west coast of India dominates other studies (**Table 2**). These studies include diversity of fungi in several marine habitats like coastal sand dunes, mangroves and small islands of the west coast. Several new species of marine fungi have been described from the west coast of India (Sridhar, 2013; Borse *et al*., 2017). Most commonly studied substrates to assess marine fungi are the woody litter, while some studies also assessed the animal remains in mangroves and beaches. The woody litter and animal substrates needs long-term incubation to assess the colonized marine fungi. Assessment of deep-sea for fungi is a new venture, which has expanded our knowledge on the diversity, occupation of extreme habitats and their

Table 2. Selected literature on marine fungi of the west coast of India.

Diversity and distribution	Prasannarai & Sridhar (1997, 2000-2001, 2001, 2003), Ananda *et al*. (1998), Prasannarai *et al*. (1999), Maria & Sridhar (2002, 2003a, 2004), Ananda & Sridhar (2004), Sridhar & Maria (2006), Karamchand *et al*. (2009), Jebaraj *et al*. (2010), Raghukumar *et al*. (2010), Khan & Manimohan (2011), Singh & Raghukumar (2014)
Deep-sea	Damare *et al*. (2006), Jebaraj *et al*. (2010), Singh & Raghukumar (2014)
Endophytes	Ananda & Sridhar (2002), Maria & Sridhar (2003b), Anita & Sridhar (2009), Anita *et al*. (2009), Shreelalitha & Sridhar (2015)
Decomposition	Maria *et al*. (2006), Ananda *et al*. (2008), Sridhar *et al*. (2010b)
Enzymes	Raghukumar *et al*. (1994, 1999, 2004, 2008), Damare *et al*. (2006),
Bioremediation	D'Souza-Teilo *et al*. (2006), Raghukumar *et al*. (2008), Verma *et al*. (2010)
Checklist	Borse *et al*. (2013)
Review	Sridhar (2009b, 2013), Sridhar *et al*. (2012), Singh & Raghukumar (2014)
Book/Monograph	Raveendran & Manimohan (2007), Borse *et al*. (2012, 2017), Raghukumar (2017)
Database	http://www.fungifromindia.com/fungiFromIndia/databases/IMFD/nextPage.php?id=references.php

biotechnological potential (Damare *et al*., 2006; Raghukumer *et al*., 2010). Small islands provide diverse intertidal and marine habitats suitable for colonization of fungi owing to their specific topography and vegetation, which are ideal to test several mycological hypotheses.

Studies on the endophytic fungi in the west coast mainly concentrated on mangrove vegetation (mangrove and mangrove associates), which provide a variety of substrates (leaves, bark and roots) and zonation for fungal colonization (canopy, tidal zones and roots in sediments). The endophytic fungi in mangrove vegetation composed of a mosaic of fungi (terrestrial, mangrove and marine) and some are also plant pathogens (e.g. Ananda and Sridhar, 2002). There are no studies on the fungi occurring in stemflow, throughfall and tree holes of mangrove tree species.

Several enzymes have been assessed from the marine fungi of the west coast (e.g. lignin modifying enzymes, xylanases and laccases) (**Table 1**). Many such enzymes besides biotechnological potential (paper, pulp and textile industries) they are useful in bioremediation (e.g. dye degradation and treatment of industrial effluents). Decomposition of organic matter in marine environment is crucial for energy flow to higher trophic levels. A few studies are available on the degradation of leaf litter, sedge and woody litter in the mangroves (e.g. Maria *et al*., 2006; Ananda *et al*., 2008; Sridhar *et al*., 2010b). These studies in addition to document the fungal diversity, recorded differences in the dynamics of mass loss, chemical changes and fungal colonization during the exposure period. Another study has evaluated the fungal association on the intertidal wood and introduced wood panels in a harbour of the southwest coast (Prasannarai *et al*., 1999). However, so far decomposition of seaweeds and seagrass has not been studied. Another area of immense importance is the study of diversity of marine lichen-forming fungi as reported by Hawksworth (2000).

Even though marine fungi are diverse in the west coast and Arabian Sea, their metabolites, biotechnological and bioremediation potential have been less explored. Some of the important areas attracted meagre attention are the studies on association of fungi with marine fauna, deep-sea mycology, endophytic association and decomposition of organic matter. Human interference in marine habitats resulted in increased plastic input to the mangroves, coast and ocean ecosystems. There is a wide scope to isolate and harness the power of plastic degrading fungi from the marine environments.

MACROFUNGI

Macrofungi constitute an important non-timber forest resource worldwide. They consists of mainly *Ascomycota* and *Basidiomycota*, in addition a few *Zygomycota* have also been recognized (Mueller *et al*., 2007). Their prime functions to stabilize ecosystem are crucial through decomposition of organic matter, turnover of nutrients, restoration of soil productivity and develop mutualistic association (Deighton, 2003; Schmit, 2005). The functional role of macrofungal communities investigated in forest ecosystems include association with woody materials, mutualistic relationship as ectomycorrhizas and decomposition as saprophytes (Winterhoff, 1992). The macrofungal communities in the forest ecosystem are mainly controlled by a number of climatic, abiotic factors and biotic factors (Kutszegi *et al*., 2015). Macrofungi are valuable source of nutrition, food supplements and medicine (Wani *et al.*, 2010; De Silva *et al*., 2013; Donnini *et al*., 2013). Even though nearly 1,000 species of ectomycorrhizal fungi are edible, a few species have been commercially harnessed (Hall and Zambonelli, 2012; Donnini *et al*., 2013). Macrofungi have attracted the attention of mycologists owing to their edibility, mutualistic association and production of bioactive metabolites (e.g. enzymes, toxins, metabolites, hallucinogens, pharmaceuticals and plant growth promoters).

Diversity: Based on the flowering plant species/macrofungus ratio, Mueller *et al*. (2007) estimated global macrofungi ranging from 53,000 to 110,000, which is close to the macrofungal estimate by Hawksworth (2001). However, Rossman (1994) and Hawksworth (2019) are of the opinion that 10% of all fungi exists (2.2-3.8 million) as macrofungi, which is ranging between 220,000 and 380,000. The major input on macrofungal research comes from the European and North American continents (Kutszegi *et al*., 2015). According to Mueller *et al*. (2007), about 35,000 species are unknown based on the published and unpublished species lists worldwide (North America; Mexico, central America and Caribbean; tropical South America; temperate South America; Antarctica; Temperate Asia; Africa; Europe; museums; botanical garden of Oslo; tropical Asia; Hawaii; Australia; New Zealand; New Caledonia; New Guinea). Certainly, the known and unknown number of macrofungi further shoot up as several regions of the world are unexplored or underexplored. The diversity of macrofungi in a given region depends on the availability of different substrates (**Box 3**) as well as suitable ecological conditions.

Mutualistic Association: Up to 90% of plant species are in association with mycorrhizal fungi (Suz *et al*., 2018). The ectomycorrhizae (EM) is one of the principal groups among macrofungi which engage in root colonization of tree species worldwide. Three important groups of fungi composed of EM fungi are *Ascomycota*, *Basidiomycota* and *Mucoromycota*. The EM fungi are well known to develop external mantle in root surroundings, on penetration of hyphae develop the Hartig net in the cortex and epidermal intercellular spaces (Smith and Read, 2008). The main tasks of EM fungi are to augment more surface for absorption, acquisition of nutrients

Box 3. Diverse substrates support the macrofungi

Soil:	Humus, lateritic, sandy, loamy, termite mound, anthill and compost
Root:	Below ground and exposed
Wood:	Coarse, medium, fine and bark
Leaf litter:	Petiole, midrib, veins and lamina
Dung:	Monogastic and polygastric
Insect:	Adult, larva, dead, carapace and nest

and develop resistance against pathogens in the rhizosphere (Agerer, 2006). Such association with host plant species facilitates the mycorrhizal fungi to absorb organic compounds as well as energy sources (Bonfante and Genre, 2008). According to an estimate, 20,000 to 25,000 EM fungi are associated with 6,000 tree species (Rinaldi *et al*., 2008; Tedersoo *et al*., 2010). The major studies have been performed on EM fungi in the temperate and subarctic ecosystems (Smith and Read, 2008). A largest number of EM fungi have been reported from the Holarctic regions compared to Austral and tropical regions (Tedersoo *et al*., 2010). There is a postulation that EM fungi are Gondwanan origin and they are not capable to disperse from the endemic tree species as well as owing to their host-specificity.

Mutualistic association between fungi with termites is confined to Africa and Asia. It is highly fascinating and such association results in degradation and enrichment of plant materials required for termites. In Africa and Asia up to 330 species belonged to the subfamily *Macrotermitinae* involved in cultivation of termitomycetes (Müller *et al*., 2005). About 40 species of *Termitomyces* are known to symbiotically associate with termites (Kirk *et al*., 2001). Termitomycetes are represented by tiny *Termitomyces microcarpus* (2 cm pileus) to giant *T. titanicus* (1 m pileus) (Tibuhwa *et al*., 2010). Termitomycetes serve as alternative source of human nutrition against plant and animal source. In addition, they are also known for their antioxidant properties and production of extracellular enzymes (serve as additives in food, bread leavening, silage processing and clarification of fruit juices) (Ghorai *et al*., 2009). Termites are also in association with the ruminant dung, which result in tripartite relationship among termites, ruminants and termitomycetes (Karun and Sridhar, 2013).

Unlike lignocellulosic materials, which are relatively poor in nutritional quality will be enriched by the herbivores yielding enriched dung, thus attracted by a variety of detritivores like beetles and millipedes. Other than ruminant dung, there seems to be meager or no studies pertaining to the macrofungal relationship with dung or dung-like resources (e.g. non-ruminant dung, bird guano, bat guano, worm casts and insect droppings). Similar to ecology of termites and termitomycetes, further insights are necessary to comprehend the positive and or negative relationship of macrofungi (other than *Cordyceps* and allied species) with insects. For example, 34 species of the attine genus *Apterostigma* are known to cultivate the coral fungi or clavarioid fungi belonging to *Pterulaceae* (Mehdiabadi and Schultz, 2010).

Studies in the Western Ghats and West Coast: Several studies pertaining to the diversity, distribution, taxonomy, ecology, nutritional and bioactive potential of macrofungi have been undertaken in the Western Ghats and west coast of India (**Table 3**). More emphasis has been laid on the diversity, distribution and taxonomy of macrofungi. Several books and monographs facilitate identification of macrofungi in the Western Ghats and west coast of India. However, consolidated information is available through a few reviews. Checklists are available only for *Agaricales* and *Aphyllophorales* (Ranadive *et al*., 2011; Farook *et al*., 2013; Ranadive and Jagtap, 2016). Ranadive *et al*. (2015) have developed a database for wood rotting *Aphyllophorales*.

A few studies have been carried out exclusively on the ectomycorrhizal fungi (**Table 3**). So far, about 150 species belonging to 34 genera of ectomycorrhizal fungi (with known host tree species) associated with native and exotic tree species have been reported from the Western Ghats. Eight host trees belonging to the family *Dipterocarpaceae* harboured up to 80% of ectomycorrhizal fungi reported. The tree species *Vateria indica* harboured the highest number of ectomycorrhizal fungi followed by two *Hopea* spp. and *Diospyros malabarica*. The most dominant genus was *Inocybe*, followed by the genera *Russula* and *Amanita*. A recent study on the impact of fire (moderate) in scrub jungles has diminished ectomycorrhizal fungi from 54% to 15% (Greeshma *et al*., 2016). Interestingly, many ectomycorrhizal fungi are also edible and or medicinal, thus their ecosystem services are manifold. Several typical ectomycorrhizal fungi have been reported without connecting or identifying the host tree species. Evaluation of host-fungus relationship of ectomycorrhizal fungi in the Western Ghats and west coast is very crucial to make progress in sylviculture, polyculture and agroforestry.

Studies on the nutritional properties of wild mushrooms have attracted attention recently (**Table 3**). About 51 species (in 23 genera) have been reported as edible exclusively based on the ethnic knowledge of tribals in the Western Ghats (Karun and Sridhar, 2017). Although several *Amanita* are poisonous, one of the *Amanita* species found in the scrub jungles of west coast form ectomycorrhizal association with several tree species and is reported to be ethnically edible in tender stage

Table 3. Selected literature on macrofungi of the Western Ghats and west coast of India.

Diversity and distribution (see also: Ectomycorrhizae below)	Manimohan *et al*. (1988, 1995, 2004, 2006, 2007), Manimohan & Leelavathy (1988, 1989a, b), Bhavanidevi (1995), Natarajan (1995), Vrinda *et al*. (1997a, b,c, 1998, 2000, 2003), Thomas *et al*. (2001, 2002), Thomas & Manimohan (2003), Natarajan *et al*. (2005a), Pradeep & Vrinda (2005, 2007), Brown *et al*. (2006), Leelavathy *et al*. (2006), Swapna *et al*. (2008), Deepa *et al*. (2009), Kumar & Manimohan (2009a, b), Bhosale *et al*. (2010), Ranadive *et al*. (2011), Karun & Sridhar (2013, 2014a, b, 2015, 2016, 2017), Pradeep *et al*. (2013, 2016), Karun *et al*. (2014, 2018a), Mohanan (2014), Senthilarasu (2014), Borkar *et al*. (2015), Ghate & Sridhar (2016a, c), Greeshma *et al*. (2016), Senthilarasu & Kumaresan (2016), De Souza & Kamat (2017), Dattaraj *et al*. (2018), Jagadish *et al*. (2019).
Ectomycorrhizae	Natarajan & Raman (1983), Natarajan *et al*. (2005b), Mohan (2008), Pradeep & Vrinda (2010), Mohanan (2014)
Nutrition	Johnsy *et al*. (2011), Sudheep & Sridhar (2014), Ravikrishnan *et al*. (2015), Ghate & Sridhar (2017a, 2019), Greeshma *et al*. (2018a), Karun *et al*. (2018b), Pavithra *et al*. (2018)
Bioactive properties	Puthusseri *et al*. (2010), Pavithra *et al*. (2016), Karun *et al*. (2016b, 2017), Ghate & Sridhar (2017a), De Souza *et al*. (2018), Greeshma *et al*. (2018b)
Checklist	Natarajan *et al*. (2005c), Ranadive *et al*. (2011), Farook *et al*. (2013), Ranadive & Jagtap (2016)
Review	Riviere *et al*. (2007), Thiribhuvanamala *et al*. (2011), Ranadive (2013), Ranadive *et al*. (2013), Sridhar (2018)
Book/Monograph	Sathe & Daniel (1980), Sathe & Deshande (1980), Leelavathy & Ganesh (2000), Mohanan (2011), Aravindakshan & Manimohan (2015), Hakimi *et al*. (2013), Latha & Manimohan (2017)
Database	Ranadive *et al*. (2015)

(Greeshma *et al*., 2018a). Similarly, ectomycorrhizal *Astraeus hygrometricus* and *A. odoratus* found in the foothill of the Western Ghats and the west coast are also known for its nutritional and medicinal potential (Pavithra *et al*., 2015, 2018). Termitomycetes are highly preferred edible mushrooms in the Western Ghats as well as west coast. The Western Ghats represent 50% of the species of *Termitomyces* recorded worldwide (40 spp.) (Karun and Sridhar, 2013). Major inventory on termitomycetes was prepared in Goa (35 spp.) followed by Kerala (15 spp.), Karnataka (9 spp.), Maharashtra and Tamil Nadu (2-3 spp.) (see De Souza and Kamat, 2017). *Termitomyces microcarpus* is widely distributed in the Western Ghats. Some termitomycetes of the Western Ghats and west coast (*Termitomyces clypeatus, T. globulus, T. umkowaan*) possess low lipid, high protein, high fibre and many essential amino acids to cater the needs of human nutrition and health (Sudheep and Sridhar, 2014; Karun *et al*., 2018b; Ghate and Sridhar, 2019).

Studies on the bioactive potential of a few wild macrofungi from the Western Ghats and west coast have been carried out (**Table 3**). In addition to nutritional potential, several macrofungi of the Western Ghats and west coast are also known for their pharmaceutical potential (e.g. *Amanita* sp., *Astraeus hygrometricus*, *Lentinus squarrosulus* and *Termitomyces clypeatus*). These mushrooms with nutraceutical potential possess many bioactive components (phenolics, flavonoids, vitamin C, β-carotene, phytic acid, lycopene and trypsin inhibition activity) and showed potent antioxidant properties (Pavithra *et al*., 2016; Ghate and Sridhar, 2017a; Greeshma *et al*., 2018b). Bioactive components and antioxidant potential of four macrofungi of the Western Ghats showed their ability to combat the cardiovascular diseases (Karun *et al*., 2017). It is interesting to note that the elephant dung-inhabiting fungi of the Western Ghats are known for their hallucinogenic potential (Manimohan *et al*., 2007; Karun and Sridhar, 2015). Recently, sulphur rich melanin pigment has been purified and characterized from the edible mushroom *Termitomyces albuminosus* occurring in Goa region (De Souza *et al*., 2018).

There are several gaps in our knowledge on macrofungi of the Western Ghats and west coast of India. There is ample scope to evaluate the macrofungal association with different habitats and with different tree species. Ethnic knowledge is valuable in identifying edible and poisonous macrofungi. The basis of ethnic identification of edible mushrooms rests on the host tree species supporting the growth of a specific mushroom. Recently, several *Cordyceps* and allied species have been reported from the Western Ghats and west coast of India (see Dattaraj *et al*., 2018). There is a wide scope to protect habitats supporting the growth of *Cordyceps* in the Western Ghats and west coast of India to harness their biomedical potential.

THE INDIAN SUBCONTINENT

The Indian Subcontinent (66º-98ºE, 8º-36ºN) as seventh largest country in the world possesses an area of 3.3 m k^2 with 100 m ha of mountains, 30 m ha of arid zones and 8,000 km coastline (Singh and Chaturvedi, 2017). The geographic and climatic diversity ranged from tropical to arctic with mountains, plains and wetlands as major ecosystems. It encompasses 24.2% forest cover (17,500 angiosperms), inland waters (rivers: 14 major and 44 medium rivers with several tributaries; natural lakes: 0.72 m ha; reservoirs: 3.15 m ha; seasonal shallow waters: 1.5 m ha), coastal wetlands (mangroves, estuaries and coast: 8 m ha) and coral reefs (2,400 km^2).

Being one of the 12 megabiodiversity and megagene centers, the Indian Subcontinent possesses 10 biogeographic zones, 25 biogeographic provinces and more than 400 biomes. The trend of increased biological diversity towards the equator has been ascertained repeatedly, which is highly applicable to the Indian Subcontinent owing to its strategic geographic and climatic position. Increased latitudinal gradient of diversity is owing to high resource availability to consumers resulting in coexistence of a large number of species (Frank *et al*., 2018). **Fig. 3** shows 10 biogeographic zones of the Indian Subcontinent with their area in per cent. Although the area of Western Ghats (4%) and Himalayas (5.6-6.4%), which is substantially lower than other geographic zones (e.g. Deccan peninsula, 42%; and semi-arid zone, 46.6%), these are the hotspots of biodiversity due to the existence of endemic and endangered species. **Table 4** provides different ecoregions of 10 biogeographic zones. Interestingly, although the Nicobar Island is tiny, it is one of the hotspots of biodiversity of the Indian Subcontinent. Each of the ecoregions represents uniqueness in aquatic, soil, forest, grassland, mountains and desert ecosystems. The biogeographic classification has not encompassed many ocean resources especially coral reefs and deep sea ecosystems in the boundary of the Indian Subcontinent. Considering the geographical setup, climatic conditions, variety of ecoregions and ecosystems, it is not surprising that the Indian Subcontinent consists of diverse mycota.

ENDEAVORS

Investigations on fungi and allied organisms represent a major way forward of progress in mycology of the Indian Subcontinent. Existing climatic and geographic zones in India provide shelter for almost all types of fungal groups. According to an estimate, based on the association of fungi with vascular plants in India at the ratio of 1:6 yields about 96,000 fungi, however 28% of them are invented

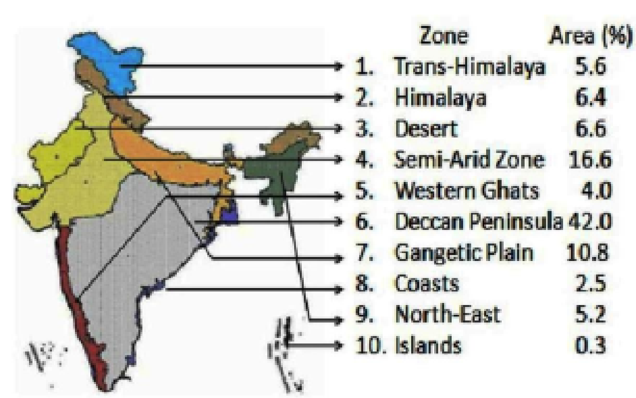

Fig. 3. Ten biogeographic zones of the India Subcontinent.

Table 4. Ecoregions of 10 biogeographic zones of the Indian Subcontinent (see Figure 4 for details of geographic boundaries; *, hotspots of biodiversity).

	Biogeographic zone	Ecoregion
1	*Trans-Himalaya	a) Ladakh Mountains b) Tibetan Plateau c) Sikkim
2	*Himalaya	a) North-West Himalaya b) West Himalaya c) Central Himalaya d) East Himalaya
3	Desert	a) Thar b) Katchchh
4	Semi-arid Zone	a) Punjab Plain b) Gujarat Rajputana
5	*Western Ghats	a) Konkan Region b) Malabar Region
6	Deccan Peninsula	a) Central Highlands b) Chotta Nagpur c) Eastern Highlands d) Central Plateau e) Deccan South
7	Gangetic Plain	a) Upper Gangetic b) Lower Gangetic
8	Coasts	a) West Coast b) East Coast
9	North-East Zone	a) Brahmaputra Valley b) North-East Hills
10	Islands	a) Andaman b) *Nicobar c) Lakshadweep

(Manoharachary *et al*., 2005; Hawksworth, 2019) suggests the wide gap in our knowledge on the Indian mycota. The vascular plants exist in climatic and geographic conditions of India (tropical, sub-tropical and Himalayan arctic weather), the plant/fungus ratio 1:6 may be an underestimate and warrants reassessment. **Box 4** lists some of the mycologically underexplored or neglected ecosystems, food webs and substrates. Attention to explore such gray areas will expand our knowledge on the role of fungi in the ecosystem functions and ecosystem services.

Box 4. Some of the neglected ecosystems, food webs and substrates

Ecosystem	Food web	Substrate
Aero-aquatic	Freshwater	Weeds
Intermittently aquatic	Marine	Insects
Thermal springs	Islands	Humus
Sand dunes	Marshes	Compost
Tree canopy	Mangroves	Dung
Termite mounds	Detritus	Recalcitrants
Anthills		
Nest		
Caves		

The most important challenge in ecological investigations is to establish the connection between the biological diversity with ecosystem functions (Cardinale *et al*., 2000). In the recent past, several global collaborations have been initiated to explore the fungal resources, diversity, distribution, phylogeny, ecology and ecosystem services. Such partnerships or networks are not prominent in the Indian situation, which tends to bridge the gaps in our knowledge on the significance of mycota. **Fig. 4** provides major divisions of mycological investigations undertaken or needs further emphasis in India.

Each division or subdivision needs collaborative efforts to acquire comprehensive knowledge on fungal resources and

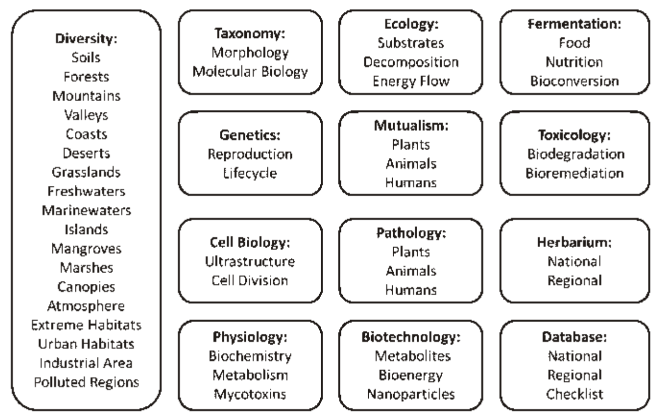

Fig. 4. Segments of mycological research in the Indian Subcontinent.

their significance. Ethnic knowledge (tribal or traditional) has been largely ignored pertain to edible, poisonous and medicinal mushrooms. Strategies followed by the tribals (nutrition, medicine and toxicity) are important to understand the value of mushrooms and future studies need to evaluate the authenticity. Nonetheless, part of the share should be set out to tribal upliftment from the benefit derived by the ethnic knowledge.

CONCLUDING REMARKS

One of the most important challenges of the 21st millennium is the assessment of global biodiversity for sustainable exploitation and conservation for future benefits. Similar to plants and animals, understanding the fungal resource and functions are crucial to link or broadcast their diversity with ecosystem services. Evaluation of fungal resources or their roles could be achieved by different approaches such as ecosystem-based or niche-based (e.g. forests, aquatic habitats, soils, islands and coasts), host-based (e.g. trees, crops, weeds and animal species) and substrate-based (e.g. leaf litter, woody litter, dung, soil, humus, compost and insect). Considering the importance of fungi in the ecosystem services, strategies of conservation could be implemented, which may differ from region to region. Collaborative efforts will also pave way to open new doors in mycology of the

Indian Subcontinent. Being diverse in climatic, geographic and ecological conditions, collaborative ventures on mycology in the Indian Subcontinent itself will be highly rewarding by offering more or less global replica of diversity and role of mycota. On comparison of studies on freshwater fungi, marine fungi and macrofungi in the Western Ghats and west coast, the major emphasis has been laid on the assessment of diversity, phylogeny and distribution. In view of exploiting these diverse fungi especially for their metabolites, enzymes and bioremediation potential, it is obvious to have a strong collaboration and network. Besides, the collaborative effort of scientific networks will facilitate to bridge the gaps by precise comparisons (e.g. Himalayas vs. Western Ghats; east coast vs. west coast; Arabian Sea vs. Bay of Bengal; islands of west vs. islands of east; lateritic scrub jungles of western vs. eastern region). Recent advances especially in fungal taxonomy and phylogeny in India resulted in addition of many new species of fungi to the global list (Willis, 2018). Similarly, advances in fungal biotechnology, nanotechnology, pharmaceuticals and metabolomics are also in progressive phase. Attention need to be addressed seriously on the enrichment of repositories, databases and sequences of fungi for future developments. As focused on culture-dependent fungi, culture-independent fungi could also be exposed by molecular tools. The conventionally practiced morphological perspectives with the recent advances in molecular approaches demand further mycological progress in India by working hand in hand with microscopes and PCR machines.

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