Five Decades of Research on the Freshwater Hyphomycetes in India 17

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Abstract

Aquatic hyphomycetes, an important mitosporic fungal community, are involved in organic matter processing and energy flow in the lotic ecosystems worldwide. They have been studied widely in the past century and present on their morphology, taxonomy, phylogeny, anamorph-teleomorph connections, distribution, ecology, physiology, metabolites, and role in the food web. Owing to the community structure, the fascinating field of aquatic hyphomycetology attracted the attention of scientists throughout the world. The Indian subcontinent is of special significance owing to its unique geographical setup (tropical, subtropical, and temperate climatic conditions) with innumerable number of water bodies. The first report on aquatic hyphomycetes in India was in the year 1953 without the acquaintance that they are natives of lotic habitats. The real study in India was initiated five decades ago in a stream located in the northern region of Tamil Nadu followed by various studies on morphology, taxonomy, diversity, distribution, ecology, and detritus breakdown. Major studies have been carried out from the lotic habitats of Western Ghats and Himalayas. The current scenario in the Indian subcontinent reveals the growth of literature on aquatic hyphomycetes pertaining to basic aspects followed by their ecology, while applications are being initiated. This review encompasses historical perspectives, literature resource, habitats, methods of evaluation, diversity, distribution, ecology, and human interference with future perspectives.

Keywords

Ingoldian fungi · Diversity · Distribution · Ecology · Evaluation · Human interference

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17.1 Introduction

Mycological investigations in aquatic habitats received less attention compared to the terrestrial habitats (Bärlocher and Boddy 2016). Major fungal phyla represented in the freshwaters include Ascomycota, Basidiomycota, Chytridiomycota, Zygomycota, and stramenopiles or heterokonts. They are capable of perpetuating in different aquatic niches such as detritus, sediments, biofilms, and live plant tissues (Shearer et al. 2007). They have adapted many trophic strategies mainly saprophytism, parasitism, and mutualism for their survival and dissemination (Jobard et al. 2010). Aquatic hyphomycetes are polyphyletic fungi known for the production of two major conidial shapes with interesting conidial ontogeny (staurosporus, multiradiate; scolecosporus, sigmoid); they are also designated as "freshwater hyphomycetes" or "Ingoldian fungi." Initial studies on aquatic hyphomycetes came from the aquatic habitats of temperate regions mainly North America and Europe (Bärlocher 1992a). Later, it was realized that they have wide geographic distribution (Ingold 1975). Despite their occurrence in different climatic and geographical conditions, the evolutionary forces faced by them in lotic habitats seem to be consistent (e.g., flow of water, availability of substrate, and physico-chemical factors).

Goh and Hyde (1996) proposed four subgroups among freshwater hyphomycetes: (a) Ingoldian fungi—grow on plant detritus in tree-lined lotic bodies and well-aerated lakes; (b) aeroaquatic fungi—normally grow in stagnant waters (ponds and puddles) or in slow-flowing streams that provide semiaquatic conditions; (c) terrestrial aquatic fungi—conidial fungi that live in rain drops on plant parts (leaf surface and trunk surface); and d) submerged aquatic fungi—heterogeneous fungi occurring on submerged decaying plant debris. A recent global assessment reveals occurrence of 335 morphospecies of aquatic hyphomycetes on a wide range of substrates (Duarte et al. 2016). Among geographic regions, Europe is the most studied continent followed by North America, South America, and Asia. However, less attention has been received by the African continent as well as polar regions. Among the 15 geographic regions examined, up to 50% goal of survey has been fulfilled by North America, temperate Europe, and tropics (western and eastern), and this shows the lacuna in our knowledge. Surprisingly, wide geographic regions share similar climatic conditions that possess high similarity in aquatic hyphomycete populations (Wood-Eggenschwiler and Bärlocher 1985; Duarte et al. 2016). Geographically, aquatic hyphomycete community has been influenced by narrow spatial scale (3–100 km) (Pascoal et al. 2005; Duarte et al. 2016). Thus, there is a wide scope for extensive inventory of aquatic hyphomycetes from various geographic locations.

The Indian subcontinent owing to its strategic geographic location offers a variety of climatic conditions (tropical, subtropical, and temperate) and ecosystems (plains, mountains, valleys, forests, coasts, semiarid regions, desert, and marine zones) with numerous water bodies (Sridhar 2020). The main geographic regions that drew attention of researchers to study aquatic hyphomycetes were the Western Ghats and Western Himalayas (the major hot spots of biodiversity). Although the earliest report on aquatic hyphomycetes was available in India during the mid-twentieth century (Bhattacharya and Baruah 1953), the study was initiated by Ingold and Webster (1973). Various facets of studies in the Indian subcontinent include morphology, description, diversity, distribution, colonization, periodicity, ecology, mutualism, decomposition, physiology, and impact of pollution. The purpose of this review is to consolidate investigations carried out on aquatic hyphomycetes in the Indian subcontinent for the last five decades and to draw the attention of future researchers towards the fascinating field aquatic hyphomycetology with environmental, agricultural, and industrial relevance.

17.2 Historical Perspectives

17.2.1 Background

Studies on aquatic hyphomycetes were initiated more than a century ago (Bärlocher 1992a). They had drawn the attention of mycologists during the late eighteenth century (Saccardo 1880; Hartig 1880; de Wildeman 1893, 1894, 1895). *Heliscus lugdunensis* was the first fungus with clove-shaped conidia described by Saccardo (1880) on the pine bark found in Lyon (France) as well as in Northern Italy. It was followed by description of parasitic fungus *Cercospora acerina* on maple seedlings by Hartig (1880). Further advances were made by de Wildeman (1893, 1894, 1895) by the addition of three tetraradiate (*Tetracladium* spp.) and one sigmoid conidia of aquatic hyphomycetes associated with algae, leaves of willow, and a macrophyte (*Hippuris vulgaris*) in aquatic and semiaquatic habitats. Rostrop (1894) found *Tetracladium maxilliforme* (as *Titaea maxilliformis*) from the stems of red clover (*Trifolium pratense*). There was some confusion in the early twentieth century on the identification of *Tetracladium marchalianum* as an algal member (of the genera *Asterothrix* and *Cerasteria*) based on the drawings by de Wildeman (1893) (Huber-Pestalozzi 1925). Subsequently, it has been resolved that the spores of *T. marchalianum* belonged to a fungus (Lowe 1927; Karling 1935). Investigations on aquatic hyphomycetes were continued by Kegel (1906) by the discovery of *Varicosporium elodeae* on dead shoots of a perennial macrophyte (*Elodea canadensis*). This study was followed by the description of *Tetracladium setigerum* (as *Tridentaria setigera*) that appeared on the leaves of a flowering plant (*Angelica sylvestris*) and *Casaresia sphagnorum* on peat moss (*Sphagnum*) (Fragoso 1920).

After about two decades, Ingold (1942) found out the exact habitat of aquatic hyphomycetes based on his elegant observations on scum samples collected from an alder-lined stream in England. He further confirmed the growth of mycelia, conidiophores, and conidia of aquatic hyphomycetes by submerging decaying leaves of alder and willow in shallow water for 2 days. Further, he also established the pure cultures, and the culture strips on incubation in distilled water that produced huge crop of conidia. Ingold (1975) in his monograph very well illustrated the conidial ontogeny of multiradiate and sigmoid conidia of several aquatic hyphomycetes. Ingold has interpreted three important functions of unusual configuration of conidia of aquatic hyphomycetes: (a) reduces sedimentation rate of conidia leading to successful dispersal, (b) tips of conidia adhere to the substrate firmly, and (c) complicated spore shape prevents conidial ingestion by aquatic fauna. Further studies took a different shape owing to the fundamental discovery by Ingold (1942); it was led by a zoologist H.B.N. Hynes (1963) to discover starlike structures of conidia of aquatic hyphomycetes in the gut content of stonefly larvae (Plecoptera). That was the beginning to understand the importance of aquatic hyphomycetes in the aquatic food web owing to their intermediary role between leaf detritus and leaf-shredding macroinvertebrates (Hynes 1963; Kaushik and Hynes 1971). Subsequently, Bärlocher (1981) demonstrated survival of conidia of aquatic hyphomycetes through gut passage of an amphipod crustacean (*Gammarus pulex*).

Webster (1959) proved experimentally the concepts of Ingold (1942) about the significance of conidial shape. Further, Webster and his associates studied the ecology of aquatic hyphomycete in greater detail (see Bärlocher 1992b). They established the planktonic role of conidia of aquatic hyphomycetes in dispersal, anchorage, and resistance against downward stream flow. Many scientists studied the dynamics and seasonal occurrence of aquatic hyphomycetes on autumn-shed deciduous leaves, twigs, and conifer needles (Arnold 1970; Triska 1970; Newton 1971; Bärlocher and Kendrick 1974; Bärlocher et al. 1978; Bärlocher 1982). Earlier studies were on the degradation of plant polymers (Tubaki 1957; Thornton 1963; Nilsson 1964) which were thoroughly investigated by Suberkropp and Klug (1980). Ever since the discovery of aquatic hyphomycetes by Ingold (1942), many investigators studied the biodiversity and geographical distribution throughout the world (Wood-Eggenschwiler and Bärlocher 1981; Webster 1987; Sridhar et al. 1992; Shearer et al. 2007; Bärlocher and Marvanová 2010; Duarte et al. 2012, 2015; Fiuza et al. 2017; Moro et al. 2018; Seena et al. 2019). Further advances took place on ecological services (Shearer 1992; Bärlocher 2005; Pascoal and Cássio 2008; Bärlocher and Sridhar 2014) and human interference (Sridhar and Raviraja 2001; Krauss et al. 2008; Schlosser et al. 2008; Canhoto et al. 2015) on aquatic hyphomycetes. Similar to taxonomy, diversity, and ecological studies, several traditional, biochemical, and molecular methods have been developed to study the aquatic hyphomycetes and their role more precisely (Gessner et al. 2003; Graça et al. 2005; Descals 2008; Suberkropp 2008; Bärlocher 2010; Ghate and Sridhar 2015b). Thus this group of fungi, being an important community in the lotic aquatic ecosystem, drew the attention of mycologists, ecologists, limnologists, biochemists, botanists, and zoologists.

17.2.2 Indian Scenario

Attention of the Indian mycologists was drawn towards the study of aquatic hyphomycetes after a decade of Ingold (1942) breakthrough. The first aquatic hyphomycete recorded was *Varicosporium elodeae* on submerged leaves by Bhattacharya and Baruah (1953) in Assam (northeast India). Later, Subramanian and Lodha (1964) described *Speiropsis hyalospora* occurring on horse dung in Uttar

Pradesh. *Articulospora tetracladia* as dark powdery colonies were found on decaying bamboo culms (*Bambusa* sp.) in Pune, Maharashtra (Patil and Rao 1972). Two years later, from a freshwater stream passing through scrubs at Kambakkam hills (80 km north of Chennai, Tamil Nadu), Ingold and Webster (1973) found additional conidia of four aquatic hyphomycetes (*Condylospora spumigena, Ingoldiella hamata, Lunulospora curvula,* and *Triscelophorus monosporus*) based on the assessment of submerged leaf litter, scum, and foam samples. This study was followed by reports of 5 and 12 species of aquatic hyphomycetes from Maharashtra (Thakur 1977; Patil and Kapadnis 1979). Further, Saikia and Sarbhoy (1980) described *Flabellospora octacladia* occurring on the stem of *Citrus aurantifolia* from Assam. Similar to Tamil Nadu, Ingold (1973) reported *Ingoldiella hamata* in foam samples in Andhra Pradesh followed by some more aquatic hyphomycetes that were reported from Andhra Pradesh (Rao and Manoharachary 1980; Manoharachary and Murthy 1981). The major massive report up to 30 species of aquatic hyphomycetes (in 23 genera) comes from Subramanian and Bhat (1981) based on the assessment of foam samples collected from 12 altitudinal lotic locations of the Western Ghats. This study was supported by another report of about 23 species of aquatic hyphomycetes from the River Payaswini in the Western Ghats based on leaf litter, foam, and water analysis (Sridhar and Kaveriappa 1982). A review by Sridhar et al. (1992) consolidated the studies on aquatic hyphomycetes focused on distribution (78 species in 45 genera) in 32 aquatic/semiaquatic habitats with regional differences, substrates, survival outside the streams, and additional studies carried out from different ecological regions of the Indian subcontinent.

Besides the diversity and distribution (in water, leaf litter, and foam), further studies on aquatic hyphomycetes have been continued on different ecological aspects including the occurrence on woody litter (Sridhar et al. 2010; Sudheep and Sridhar 2011), association with sediments (Sudheep and Sridhar 2012; Ghate and Sridhar 2015a; Karun et al. 2016), occurrence in estuarine habitats (Sridhar and Kaveriappa 1988), seasonal fluctuations (Sridhar and Kaveriappa 1984; Mer and Sati 1989; Chandrashekar et al. 1990), diurnal periodicity (Sridhar and Sudheep 2010; Ghate and Sridhar 2016), occurrence outside the streams (Sridhar 2009c; Chauvet et al. 2016), leaf litter decomposition (Raviraja et al. 1996b; Sudheep and Sridhar 2013a; Sridhar et al. 2013), palatability of leaf litter (Chandrashekar et al. 1989; Sridhar and Sudheep 2011a), mutualistic association (Raviraja et al. 1996a; Pathak and Sati 2017; Ghate and Sridhar 2017), production of lignocellulosic enzymes (Chandrashekar and Kaveriappa 1988), antimicrobial activity (Sridhar 2012; Singh and Sati 2019), nutritional requirements (Sati and Belwal 2005; Sati and Bisht 2005), phosphate solubilization (Sati and Pant 2018), plant growth enhancement (Sati and Arya 2010a, b), impact of human interference (Raviraja et al. 1998a; Chandrashekar and Kaveriappa 1989), and trapping conidia on latex-smeared slides (Ghate and Sridhar 2015b).

17.2.3 First Attempts

Several studies have been initiated in India from the mid-twentieth century. Box 17.1 highlights different facets on aquatic hyphomycetes initiated for the first time from 1953 onwards. Interestingly, similar to the global scenario, in the Indian subcontinent two reports on aquatic hyphomycetes initially came mainly from the terrestrial habitats (e.g., Subramanian and Lodha 1964; Patil and Rao 1972). The first authentic study was carried out in a stream in Tamil Nadu by the two British scientists Cecil T. Ingold and John Webster (1973) during their visit to C.V. Subramanian's laboratory in Madras University. Again the first taxonomic description of *Flabellospora octacladia* comes from the terrestrial habitat of Assam (Saikia and Sarbhoy 1980). With excellent illustrations, Subramanian and Bhat (1981) published a voluminous report from the Western Ghats, which stimulated several workers in the field. It is almost equivalent to the monograph published by Ingold (1975) based on his expeditions in different parts of the world. Aquatic hyphomycete-colonized leaf litter becomes a nutrient source. Rao and Manoharachary (1982) demonstrated the preference of conditioned leaf discs to juvenile fish and prawns against unconditioned leaf discs. The first seasonal dynamics comes from a coastal stream of southwest of Karnataka (Sridhar and Kaveriappa 1984). Laboratory in vitro studies by Sridhar and Kaveriappa (1986) demonstrated the impact of pesticides on aquatic hyphomycetes. Production of extracellular enzymes by aquatic hyphomycetes has been studied by Chandrashekar and Kaveriappa (1988). Chandrashekar et al. (1991) studied the occurrence of aquatic hyphomycetes in a thermal sulfur spring for the first time. Besides occurrence of aquatic hyphomycetes in water, scum, foam, and plant detritus in streams, their unnoticed ecological niche as endophytes in riparian roots extended into streams was demonstrated by Raviraja et al. (1996a). The important function of aquatic hyphomycetes is the breakdown of dead leaf litter; it was studied in the Western Ghats and southwest Karnataka by Raviraja et al. (1996b). Although aquatic hyphomycetes prefer unpolluted streams, they also continue leaf litter decomposition in polluted habitats too; it has been demonstrated by Raviraja et al. (1998a). The first genus of aquatic hyphomycete *Synnematophora* sp. growing on the mango leaf litter was reported from the Sampaje stream in the Western Ghats by Sridhar and Kaveriappa (2002). The growth response of aquatic hyphomycetes on different nutrients in vitro was studied by Sati and Bisht (2005). The first study of occurrence in tree canopy comes from the Southwest Karnataka (Sridhar et al. 2006). The first diurnal fluctuation of aquatic hyphomycete conidia in streams of the Western Ghats and west coast was studied by Sridhar and Sudheep (2010). Besides the basic function of aquatic hyphomycetes in energy flow, they also promote plant growth; this was demonstrated using endophytic hyphomycetes by Sati and Arya (2010a). Aquatic hyphomycetes also possess antimicrobial activity against bacteria and fungi (Sati and Arya 2010b; Arya and Sati 2011). Occurrence of aquatic hyphomycetes in sediments had been assessed by Sudheep and Sridhar (2012). Based on the growth of aquatic hyphomycetes on latex (Sridhar and Kaveriappa 1987a), Ghate and Sridhar (2015b) designed a conidial trap technique in streams on latex-smeared slides. To support the plant growth promotion, Singh and Sati (2017) demonstrated the ability of phosphate solubilization by endophytic aquatic hyphomycetes.

Box 17.1: Studies Carried Out on Aquatic Hyphomycetes for the First Time in India

- Report of *Varicosporium elodeae* in Assam (Bhattacharya and Baruh 1953)
- Investigation in freshwater stream of Tamil Nadu (Ingold and Webster 1973)
- Description of *Flabellospora octacladia* in Assam (Saikia and Sarbhoy 1980)
- Major report in foam samples of Western Ghats (Subramanian and Bhat 1981)
- Palatability to fish and prawn (Rao and Manoharachary 1982)
- Seasonal study in southwest coast (Sridhar and Kaveriappa 1984)
- Impact of agrochemicals (Sridhar and Kaveriappa 1986)
- Enzymes (Chandrashekar and Kaveriappa 1988)
- Thermal sulfur spring in Western Ghats (Chandrashekar et al. 1991)
- Endophytes in riparian roots in Western Ghats (Raviraja et al. 1996a)
- Leaf litter breakdown in Western Ghats and south west coast (Raviraja et al. 1996b)
- Leaf litter breakdown in polluted river stretch in Western Ghats (Raviraja et al. 1998a)
- Report of genus *Synnematophora* in Western Ghats (Sridhar and Kaveriappa 2002)
- Growth response to nutrients (Sati and Bisht 2005)
- Report in tree canopy of south west coast (Sridhar et al. 2006)
- Colonization on woody litter in Western Ghats (Sridhar et al. 2010)
- Diurnal periodicity in Western Ghats and south west coast (Sridhar and Sudheep 2010)
- Report on plant growth promotion (Sati and Arya 2010a)
- Antifungal activity (Sati and Arya 2010b)
- Antibacterial activity (Arya and Sati 2011)
- Occurrence in hyporheic zones of Western Ghats (Sudheep and Sridhar 2012)
- Conidial trap technique on latex smear in southwest coast (Ghate and Sridhar 2015b)
- Phosphate solubilization (Singh and Sati 2017)

17.3 Literature Source

17.3.1 Reviews and Articles

Indian mycologists have invested their efforts on various aspects of aquatic hyphomycetes from different ecoregions of the Indian subcontinent. Table 17.1 provides a broad outline of selected topics studied. Overviews on aquatic hyphomycetes consolidated the studies carried out mainly from the Western Ghats and Himalayas. Major emphasis was to understand the diversity and distribution based on the assessment of water filtration, incubation of submerged leaf litter, and foam scanning. Besides screening submerged leaf litter, some studies evaluated submerged wood samples in streams and rivers (e.g., Sridhar et al. 2010, 2011a; Sridhar and Sudheep 2011b; Sudheep and Sridhar 2011, 2013b). Recently a new aquatic hyphomycete *Bactrodesmium aquaticum* has been described from the submerged woody debris (Borse et al. 2019a). Some studies have tried to understand the pattern of colonization of aquatic hyphomycetes through baiting specific leaf litter in streams of the west coast and Western Ghats (Sridhar and Kaveriappa 1989b; Sudheep and Sridhar 2013a). Sati and Tiwari (1992a) studied colonization pattern on the chir pine (*Pinus roxburghii*) needle litter in freshwater streams of Kumaun, Himalayas. In addition, two other studies evaluated the association of aquatic hyphomycetes in stream sediments (Sudheep and Sridhar 2012; Ghate and Sridhar 2015a).

Ecological studies on aquatic hyphomycetes in India include seasonal and diurnal periodicity, thermal sulfur springs in the Western Ghats, and stream sediments in relation to water qualities. Seasonal periodicity of aquatic hyphomycetes has been studied mainly from the Western Ghats and Himalayas (Sati and Pant 2006; Sati and Belwal 2009; Sridhar and Kaveriappa 1984, 1989a). Diurnal periodicity of conidia in streams has been studied in the Western Ghats as well as the southwest coast (Sridhar and Sudheep 2010; Ghate and Sridhar 2016). Occurrence and functions of aquatic hyphomycetes depend on the organic matter as well as the water quality (Rajashekhar and Kaveriappa 2003; Sati and Arya 2009). Besides organic debris (leaf and woody litter), several aquatic hyphomycetes have a mutualistic association as endophytes mainly in the riparian roots extended into the streams (Ghate and Sridhar 2017; Sati et al. 2009b). Besides stream environment, aquatic hyphomycetes occur outside the stream habitats (terrestrial litter, tree holes, stemflow, and throughfall) (Sridhar 2009c).

Organic matter decomposition is one of the major functions of aquatic hyphomycetes in the lotic ecosystem. Some investigations have been carried out on the leaf and woody litter in the streams of the Western Ghats and west coast (Raviraja et al. 1998a; Sridhar et al. 2011a; Sudheep and Sridhar 2013a, b). Decomposition of leaf litter in streams by aquatic hyphomycetes improves the nutritional quality (e.g., proteins and lipids), which attracts the stream fauna, and they prefer the colonized than fresh litter (Chandrashekar et al. 1989; Sridhar and Sudheep 2011a). However, the growth of aquatic hyphomycetes in the streams as well as on the medium depends on the nature of carbon and nitrogen sources (Chandrashekar and

Table 17.1 Selected literature dealing with aquatic hyphomycetes in India (see Table 17.3 for new species reported from India)

	Feature	References
Overviews	Western Ghats and Himalayas	Sridhar et al. (1992), Sati et al. (2002), Belwal and Sati (2006), Ramesh and Vijaykumar (2006), Sridhar (2009a, 2010, 2017, 2019), Arya and Sati (2012)
Diversity and distribution	Water, leaf litter, woody litter, and foam	Subramanian and Bhat (1981), Sridhar and Kaveriappa (1982, 1989a, 1992), Rajashekhar and Kaveriappa (2003), Belwal et al. (2006), Sati and Pant (2006), Maddodi et al. (2009), Sridhar et al. (2010, 2011a), Sudheep and Sridhar (2011), Sridhar and Sudheep (2011b), Sudheep and Sridhar (2013b), Sati et al. (2014), Chaudhari et al. (2016), Nemede et al. (2016), Pant and Sati (2018), Pant et al. (2019), Prashar et al. (2019)
Colonization	Leaf litter colonization	Sridhar and Kaveriappa (1989b), Sati and Tiwari (1992a, 2006), Sati and Pant (2006), Sudheep and Sridhar (2013a)
	Wood litter colonization	Sridhar et al. (2010), Sudheep and Sridhar (2011, 2013b)
	Sediments	Sudheep and Sridhar (2012), Ghate and Sridhar (2015a)
Ecology	Seasonal periodicity	Sridhar and Kaveriappa (1984, 1989a, 1989b), Chandrashekar et al. (1990), Sati and Pant (2006), Sati and Tiwari (2006), Sati and Belwal (2009), Sudheep and Sridhar (2013a, 2013b), Sreekala and Bhat (2016)
	Diurnal periodicity	Sridhar and Sudheep (2010), Ghate and Sridhar (2016)
	Thermal sulfur spring	Chandrashekar et al. (1991), Rajashekhar and Kaveriappa (1996)
	Sediments	Sudheep and Sridhar (2012), Karun et al. (2016)
	Water quality	Rajashekhar and Kaveriappa (2003), Sati and Arya (2009)
Mutualistic association	Endophytes (live roots of trees, grass, and ferns)	Raviraja et al. (1996a), Sati and Belwal (2005), Sati et al. (2009b), Ghate and Sridhar (2017), Sati and Pathak (2017), Pant and Sati (2018), Pant et al. (2019)
Occurrence outside the streams	Terrestrial leaf litter	Sridhar and Kaveriappa (1987b)
	Stemflow and throughfall	Sridhar and Karamchand (2009), Ghate and Sridhar (2015c)
	Tree holes	Karamchand and Sridhar (2008), Sridhar et al. (2013)
Decomposition	Leaf and woody litter	Raviraja et al. (1996b, 1998a), Sridhar et al. (2011a, 2011b, 2013), Sudheep and Sridhar (2013a, 2013b)

(continued)

Table 17.1 (continued)

	Feature	References
Animal preference	Prawns and fish	Rao and Manoharachary 1982; Chandrashekar et al. (1989), Sridhar and Sudheep (2011a)
Nutrition and physiology	Carbon and nitrogen sources	Chandrashekar and Kaveriappa (1988, 1991), Sati and Bisht (2005, 2006)
	Temperature, light, and pH	Rajashekhar and Kaveriappa (1996, 2000), Sati et al. (2012)
Human interference	Organic pollution	Raviraja et al. (1998a)
	Heavy metals	Raghu et al. (2001)
	Pesticides	Sridhar and Kaveriappa (1986), Chandrashekar and Kaveriappa (1989)
Techniques	Conidial count and conidial trap	Sati and Belwal (2009); Ghate and Sridhar (2015b)
Applications	Enzymes	Chandrashekar and Kaveriappa (1988, 1991)
	Antimicrobial activity	Arya and Sati (2011, 2012), Sati and Singh (2014), Singh and Sati (2019)
	Phosphate solubilization and plant growth promotion	Sati and Arya (2010a)Singh and Sati (2017), Sati and Pant (2018)
	Biomonitors/bioindicators	Raviraja et al. (1998b), Dubey (2016)

Kaveriappa 1988, 1991; Sati and Bisht 2005, 2006). Besides nutrient sources, aquatic hyphomycetes are also influenced by the impact of temperature, light, and pH (Rajashekhar and Kaveriappa 2000; Sati et al. 2012).

Human interference is one of the major impacts on the aquatic ecosystems. Studies have been carried out on the impact of organic pollution, heavy metals, and pesticides in Indian lotic habitats (Raviraja et al. 1998a; Raghu et al. 2001; Chandrashekar and Kaveriappa 1989). Some of the organic matter leads to decline in aquatic hyphomycetes in Indian lotic bodies between 50% and 83% (Sridhar and Raviraja 2001). For assessment of diversity, colonization, and functions of aquatic hyphomycetes, various methods are necessary. Those methods could be adapted from other microbial studies or should be designed specifically depending on the needs (spore production, spore count, spore impaction, and extent of colonization) (Descals 2005; Sati and Belwal 2009; Ghate and Sridhar 2015b). The knowledge gained by any basic research needs to be carried forward towards applications. Likewise, some studies have been performed in India on aquatic hyphomycetes (cellulolytic enzymes, antimicrobial activity, and biomonitoring) (Chandrashekar and Kaveriappa 1991; Raviraja et al. 1998b; Sati and Singh 2014; Sati and Arya 2010b). Interestingly, some aquatic hyphomycetes showed phosphate solubilization ability, which is important in plant nutrition and helpful in growth promotion (Sati and Pant 2018; Singh and Sati 2019). The most fascinating application comes from a study of plant growth promotion of root endophytic aquatic hyphomycetes studied by Sati and Arya (2010a). Two test host plants on inoculation of three endophytic fungi did not show any disease symptoms. Among the endophytes, two species showed significant impact on growth and biomass of test plants studied. Nevertheless, aquatic hyphomycetes are important biomonitors of water quality of streams and rivers; similarly some of them are good candidates of bioindicators (Raviraja et al. 1998b; Dubey 2016).

17.3.2 Books and Theses

Substantial literature availability leads to publication of books and promotes further studies. Table 17.2 provides titles of books and theses published from India. All the authors of books belong to the academic institutions rather than private organizations. However, the content of six books partially deals with aquatic hyphomycetes. Studies dealt with aquatic hyphomycetes in the books include description, diversity, distribution, physiology, ecology, and checklists.

Nearly 35 theses have dealt with aquatic hyphomycetes either partially (20) or completely (15). The highest number of theses came from the North Maharashtra University, Jalgaon, Maharashtra (15), followed by the Mangalore University, Karnataka (9), and Kumaun University, Nainital, Uttarakhand (7). Major studies have been undertaken in the Western Ghats (23) compared to Himalayan region (7). Different aspects dealt in the theses included diversity, distribution, ecology, decomposition, endophytes, physiology, techniques, and enzymes (Fig. 17.1). Diversity and distribution of aquatic hyphomycetes have attracted more attention (47%) followed by ecology (25%) and rest of the aspects fall below 10%. Some of the theses have interesting topics like enzymes (Chandrashekar 1988), biochemical aspects (Chandrashekar 1988; Raviraja 1996; Maddodi 2002; Sudheep 2011), occurrence outside the streams (Sridhar 1984; Karamchand 2008), antimicrobial activities (Arya 2009; Singh 2014), endophytes (Singh 2014; Ghate 2016; Pant 2020), and plant growth promotion (Singh 2014).

17.4 Methods of Examination

Inventory of aquatic hyphomycetes needs specific methods of evaluation. A list of classical, biochemical, and molecular techniques has been given in the review by Sridhar et al. (2020). Some of the techniques have been followed by the researchers in India. Routine inventory needs assessment of stream water by filtration through Millipore filters, collection of submerged organic matter (leaf and woody litter) and incubation of sections (in shallow damp chamber or distilled water) in the laboratory (for a few weeks), or bubble chamber incubation with forced aeration using aquarium aerators (up to 48 h) followed by filtration through Millipore filters (porosity, 5 or 8μm). To get an overall idea of aquatic hyphomycete community, randomly collected leaf litter on incubation in distilled water in the laboratory for 4–5 days and collect the incubated water in beakers to induce foam on addition of a small quantity of detergent (e.g., sodium lauryl sulfate) followed by aeration to assess the accumulated conidia (Chandrashekar et al. 1986). Several aquatic hyphomycetes

Table 17.2 Titles of books and theses on aquatic hyphomycetes from India (arranged year-wise)

Book	Content	References
Recent Mycological Researches	Partial	Sati (2006)
Frontiers in Fungal Ecology, Diversity and Metabolites	Partial	Sridhar (2009b)
Microbes - Diversity and Biotechnology	Partial	Sati and Belwal (2012)
Freshwater Higher Fungi of India	Partial	Borse et al. (2016)
Freshwater and Marine Fungi of India	Partial	Borse et al. (2017)
Common Zoosporic and Water-Borne Conidial Fungi	Partial	Manoharachary and Kunwar (2018)
Thesis		
Aquatic Fungi of Maharashtra	Partial	Kapadnis (1980)
Studies on Water-Borne Fungi of Dakshina Kannada and Kodagu Regions	Complete	Sridhar (1984)
Some Aspects of Water-Borne Fungi and Their Enzymes	Complete	Chandrashekar (1988)
Taxonomy and Species Composition of Hyphomycetes in Forested Streams and Their Colonization Pattern on Tree Leaves in Nainital, Central Himalaya	Complete	Tiwari (1992)
Studies on Water-Borne Hyphomycetes of Some of the Rivers in Karnataka with Special Reference to Cauvery and Kali Rivers	Complete	Rajashekhar (1994)
Studies on Water Borne Fungi of Uttara Kannada Region	Partial	Vijayakumar (1995)
Ecological and Biochemical Studies on Aquatic Hyphomycetes of Western Ghats and West Coast of India	Complete	Raviraja (1996)
Studies on Water-Borne Conidial Fungi in the Running Fresh Water Bodies of Kumaun Himalaya	Complete	Belwal (2002)
Studies on Diversity, Ecology and Biology of Aquatic Fungi of Some Freshwater Streams of Western Ghats Forests in Goa state, India	Complete	Sreekala (2002)
Role of Aquatic Hyphomycetes in the Streams and Rivers of the Western Ghats, Karnataka - Ecological and Biochemical Studies	Complete	Maddodi (2002)
Studies on Root Endophytic Fungi Including VAM on Riparian Forest Plants	Partial	Pargain (2005)
Response Pattern of Aquatic Hyphomycetes Along Physicochemical Gradients	Complete	Bisht (2006)
Studies on Freshwater Filamentous Fungi of Western Ghats and West Coast of India	Partial	Karamchand (2008)
Studies on Aquatic Fungi from Dhule District	Partial	Patil (2008a)
Studies on Non-Zoosporic Fungi from Jalgaon District	Partial	Patil (2008b)
Studies on Aquatic Fungi from Satpura Range in Dhule District	Partial	Pawara (2008)
Diversity of Water-Borne Conidial Fungi and their Antimicrobial Activities in Kumaun Himalaya	Complete	Arya (2009)
Biodiversity of Salt Water Fungi from Lonar Lake and Freshwater Fungi from Buldhana District	Partial	Patil (2010)

(continued)

Table 17.2 (continued)

Book	Content	References
Diversity, Ecology and Bioprospecting of Fungi of Kaiga Environs of the Western Ghats	Complete	Sudheep (2011)
Studies on Aquatic Fungi from Melghat Wildlife Sanctuary, Amravati District	Partial	Nemede (2012)
Macrofungi and Aquatic Hyphomycetes of the Western Ghats and West Coast of India	Partial	Karun (2014)
Diversity of Aquatic Fungi in Shimoga District of Karnataka	Complete	Raju (2014)
Bio-Prospecting of Root Endophytic Aquatic Fungi as Plant Growth Promoters and Antimicrobial Potential	Complete	Singh (2014)
Effect of Environmental Factors on Diversity of Aquatic Fungi in Chikmagalur District, Karnataka	Complete	Suresha (2014)
Studies on Aquatic Fungi from Dang District, Gujarat	Partial	Ahire (2016)
Biodiversity of Aquatic Fungi from Ahmednagar District, Maharashtra	Partial	Borade (2016)
Studies on Macrofungi and Aquatic Fungi of Selected Wetlands of the Southwest India	Partial	Ghate (2016)
Studies on Aquatic Fungi from Nandurbar District	Partial	Wagh (2016)
Biodiversity of Aquatic Fungi from Thane District, Maharashtra	Partial	Gosavi (2017)
Biodiversity of Aquatic Fungi from Pune District, Maharashtra	Partial	Jagdale (2018)
Biodiversity of Aquatic Fungi from Khandwa District, Madhya Pradesh	Partial	Patil (2018a)
Biodiversity of Aquatic Fungi from Tapi District, Gujarat	Partial	Patil (2018b)
Studies in Aquatic Fungal Biodiversity from Maharashtra	partial	Sindhe (2018)
Biodiversity of Aquatic Fungi from Pachmarhi Biosphere Reserve, Madhya Pradesh	Partial	Chaudhari (2020)
Evaluation of Himalayan Root Endophytic Aquatic Hyphomycetes for Bioactivity and Phosphate Solubilization	Complete	Pant (2020)

also sporulate on damp incubation in the laboratory (Sridhar et al. 2020). Accumulated foam could be collected from the streams fixed in formalin-acetic-alcohol and examination in the laboratory will also facilitate to follow the aquatic hyphomycete community. Quantitative estimation of conidia has been attempted by Sati and Belwal (2009).

Similar to the study of leaf litter, woody litter was also studied by damp incubation and bubble chamber incubation (Sridhar et al. 2010; Sridhar and Sudheep 2011b). Using damp chamber incubation of woody litter (bark and cambium) collected from 12 high-altitude streams of the Western Ghats, 30 species of aquatic hyphomycetes were recorded (bark 20 spp.; cambium 18 spp.). Naturally submerged soft and hard woody litter (diam 1.5 cm; length 3 cm) were divided into nine vertical sections by Sridhar and Sudheep (2011b). Similar sections were simultaneously

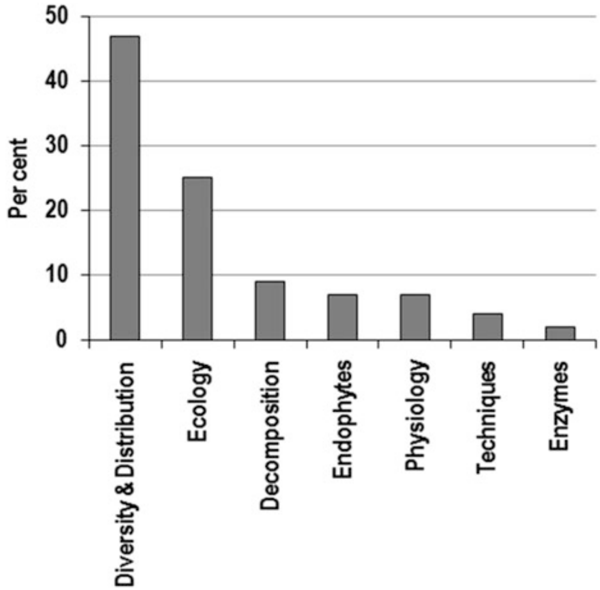

Fig. 17.1 Different aspects studied on aquatic hyphomycetes in India

assessed by damp chamber incubation (4 months) as well as bubble chamber incubation (72 h). Ten and 26 species of aquatic hyphomycetes were found in hardwood and softwood, respectively. In addition, Sridhar and Sudheep (2011b) mapped the occurrence of aquatic hyphomycetes in different sections of soft- and hardwoods. A single submerged leaf (e.g., banyan) or a woody litter may support up to 10–25 species of aquatic hyphomycetes, which could be detected conventionally. However, no attempts have been made so far in India to assess the phylogeny of aquatic hyphomycetes in water, foam, and detritus using molecular techniques although such attempts have been made for the last two decades elsewhere (Box 17.2).

Box 17.2: Studies Carried Out on the Molecular Phylogeny of Aquatic Hyphomycetes (Source: 2002–2012 – Duarte et al. 2013)

- 2002 – Sequencing 18s rDNA of 5 *Tetracladium* spp.
- 2003 – Anamorph-teleomorph connection by sequencing 18s rDNA
- 2005 – Sequencing 18S rDNA partial sequences of 22 new species
- 2006 – Partial sequencing of 28s rDNA of 8 species
- 2006 – Sequencing of l8S and 28S rDNA partial sequencing ITS of 11 species
- 2006 – ITS sequencing to establish endophytic and aquatic phases of *Dwayaangam*
- 2009 – Sequencing 28S rDNA partial sequences of 22 species

(continued)

Box 17.2 (continued)

- 2010 – Sequencing partial ITS for single conidia
- 2010 – Selection of best barcode COX1, ITS and DI/D2 of the genus *Tetracladium*
- 2012 – ITS barcodes for intraspecies diversity of *Articulospora tetracladia*
- 2014 – New DNA barcodes (Duarte et al. 2014)
- 2014 – ITS phylogenetic analysis of 18 species of *Campylospora* (Marvanovà and Laichmanovà 2014)
- 2015 – 454 Pyrosequencing (Duarte et al. 2015)
- 2016 – Metabarcoding to assess diversity in coarse and fine particulate organic matter (Wurzbacher et al. 2016)
- 2018 – LSU and ITS sequence data of *Nawawia* and *Neonawawia* (Yang et al. 2018)
- 2020 – Multigene (15 genes) analysis of ITS phylogeny of *Tricladiaceae* (Johnston and Baschien 2020)

A new conidial trapping technique has been designed by Ghate and Sridhar (2015b). On baiting six latex-smeared slides with plain slides as control in a stream of southwest coast up to 18 h, slides smeared with banyan (*Ficus benghalensis*) ranked first in trapping conidia of different species of aquatic hyphomycetes. Banyan latex-smeared slides showed the highest diversity of aquatic hyphomycetes followed by the latex of *Plumeria rubra*. The simplicity and novelty of this technique are that the slides with latex smears could be easily transported to different locations in slide boxes, and could be exposed to flowing water for various periods (e.g., 1–4 h). In the intervals, one could collect leaf litter, woody litter, and foam samples for comparison. After different periods of exposure of slides, water on latex smear is drained, stained with aniline blue in lactophenol, fixed with the cover glass, and easily transferred into slide boxes for conidial assessment in the laboratory.

Sudheep and Sridhar (2012) emphasized the assessment of aquatic hyphomycete population in sediments using baiting technique. The defined amount of sediment (fine particulate matter) could be inoculated to pre-weighed sterile leaf discs to allow aquatic hyphomycetes to colonize on shaking (150 rpm) for 2 weeks. After retrieving the incubated leaf discs, they should be incubated again for 48 h in sterile distilled water in bubble chambers to generate conidia. This indirect method provides information on those aquatic hyphomycete conidia or mycelia in the sediment samples. Assessment of dry mass of sediments and leaf discs in parallel samples facilitates to roughly guess the fungal biomass in sediments. This technique was also followed by Ghate and Sridhar (2015a) to assess aquatic hyphomycetes in an intermittent stream in southwest India.

Morphological observations are the fundamental aspect for identification of fungi. Aquatic hyphomycetes produce two major types of conidia: staurosporus (branched) and scolecosporus (sigmoid). However, some conidia have conventional cylindrical or oval shapes, while aeroaquatic fungi produce helicosporous spores (coiled in different dimensions). Such shapes of the conidia facilitate dispersal in water, attachment to the organic substrate, and prevention of consumption by aquatic fauna. In addition to conidial morphology, conidial developmental stages (ontogeny) are also helpful in authentic identification. Although conidial ontogeny is simple in some scolecosporus species, it is a bit complex in staurosporus species (Sridhar and Kaveriappa 1987c, 1989d). A sample of sigmoid, helicosporous, multiradiate, and oval shaped conidia reported from the Western Ghats is shown in Fig. 17.2.

17.5 New Species from India

Up to 17 new species and 1 new genus have been described from different parts of India (Table 17.3). Description of ten new species and one genus came from the Western Ghats, while five new species were found in Himalayas. The rest two species were one each from the Cauvery river in Karnataka and Purna River in Gujarat. The first two species (*Flabellospora octacladia* and *Chaetospermum indicum*) were described from Assam and Maharashtra, respectively (Saikia and Sarbhoy 1980; Talde 1981). After a gap of 5 years, *Triscelophorus konajensis* was reported from the southwest coast of Karnataka (Sridhar and Kaveriappa 1987d). After 4 years, three more species were described from the Western Ghats and Himalayas (1991–1993). Eight years later, additional five species were described from the school of D.J. Bhat, Goa University (2001–2002). It was followed by description of a new synnematous genus *Synnematophora* on the mango leaves (*Mangifera indica*) in Payaswini river of the Western Ghats (Sridhar and Kaveriappa 2002). Seven years later, a root endophytic fungus *Tetracladium nainitalense* was described by Sati et al. (2009a) from Nainital in Himalayas. After a decade, from Nainital Sati and Pant et al. (2019) described a new *Catenomycopsis vinayaka*. From Maharashtra and Gujarat two and one species were described by B.D. Borse and his school, respectively (Borse et al. 2019a, b). Three species were described from the terrestrial habitats (*Flabellospora octacladia, Phalangispora bharathensis,* and *Speiropsis rogergoosensis*). However, *F. octacladia* and *P. bharathensis* were later found in the foam samples of Amalibari stream and Panzara river (Maharashtra), respectively (Patil et al. 2014). The sporodochial fungus *P. bharathensis* was recorded again on the fallen leaves of mango (*Mangifera indica*) in Tamhini Ghats of Maharashtra and included additional characteristics (Rajeshkumar 2014). Two new species *Tetracladium nainitalense* and *Kumbhamaya jalapriya* were described as aquatic root endophytes; the former was found with roots of *Eupatorium odenophorum* and *Colocasia* sp. in Nainital, while the latter with roots of *Hopea ponga* in Goa.

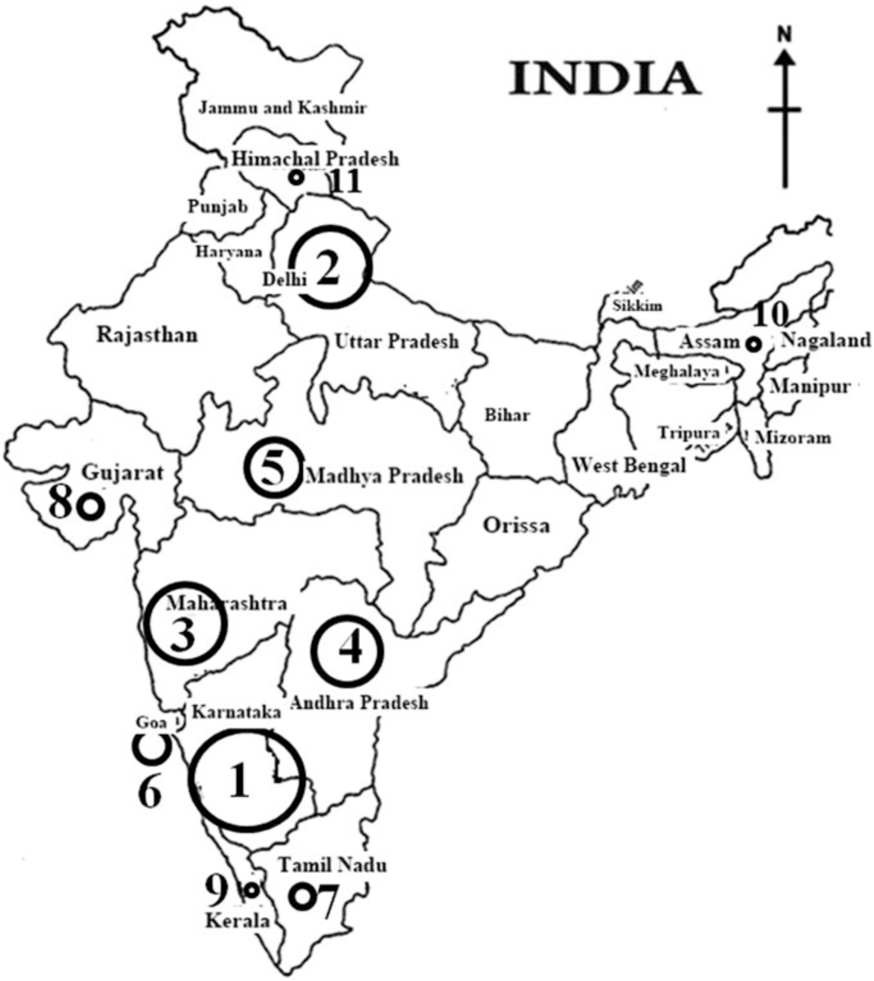

Fig. 17.2 Extent of literature resource on aquatic hyphomycetes in different parts of India

17.6 Habitats, Diversity, and Distribution

17.6.1 Habitats

The Western Ghats and Himalayas are the two ecoregions that attracted the attention of researchers to carry out studies on aquatic hyphomycetes. These two mega diverse habitats being major hot spots of biodiversity provide innumerable aquatic ecosystems and niches for diverse species of aquatic hyphomycetes. Most of the

Table 17.3 Freshwater hyphomycetes and allied species described from India (arranged year-wise) [*, new genus]

	Substrate	Location	References
Flabellospora octacladia Saikia & A.K. Sarbhoy	On stems of *Citrus aurantifolia*	Tinsukia, Assam	Saikia and Sarbhoy (1980)
Chaetospermum indicum Talde	Submerged stem of *Fimbristylis quinquangularis*	Purna and Dudhana rivers, Maharashtra	Talde (1981)
Triscelophorus konajensis K.R. Sridhar & Kaver.	Submerged leaves of *Ficus benghalensis*	Mangalore, Karnataka	Sridhar and Kaveriappa (1987d)
Vermispora cauveriana Rajash., Bhat & Kaver.	Submerged leaves of *Ficus religiosa*	Srirangapatna, Karnataka	Rajashekhar et al. (1991)
Tricladium indicum Sati & N. Tiwari	Submerged conifer needles of *Pinus roxburghii*	Niglat, Uttarakhand	Sati and Tiwari (1992b)
Pestalotia submersa Sati & N. Tiwari	Submerged leaves and needles of *Pinus roxburghii*	Niglat, Uttarakhand	Sati and Tiwari (1993)
Trinacrium indica Lekha, S.K. Nair & Bhat	Submerged leaves of *Coffea arabica*	Somwarpet, Karnataka	Soosamma et al. (2001)
Dendrospora yessemreddea S.K. Nair & D.J. Bhat	Freshwater foam	Bondla Wildlife Sanctuary, Goa	Sreekala and Bhat (2002)
Kumbhamaya jalapriya S.K. Nair & Bhat	Submerged live roots of *Hopea ponga*	Mollem Wildlife Sanctuary, Goa	Sreekala Nair and Bhat (2002)
Phalangispora bharathensis T.S.K. Prasad & Bhat	Fallen decaying *Holigarna arnottiana* leaves	Cotigao Wildlife Sanctuary, Goa	Prasad and Bhat (2002a)
Speiropsis rogergoosensis T.S.K. Prasad & Bhat	Dead leaves of *Artocarpus hirsutus* on soil	Kumara Parvatha, Karnataka	Prasad and Bhat (2002b)
**Synnematophora constricta* K.R. Sridhar & Kaver.	Submerged leaves of *Mangifera indica*	Payaswini river, Karnataka	Sridhar and Kaveriappa (2002)
Tetracladium nainitalense Sati & P. Arya	Root endophyte in *Eupatorium odenophorum* and *Colocasia* sp.	Nainital, Uttarakhand	Sati et al. (2009a)
Bactrodesmium aquaticum B.D. Borse, N.S. Pawar & S.Y. Patil	Submerged herbaceous and woody debris	Nakana Dam, Maharashtra	Borse et al. (2019a)
Setosynnema limnetica B.D. Borse & N.S. Pawar	Submerged leaves	Tapti river, Maharashtra	Borse et al. (2019b)
Tripospermum limneticum S.Y. Patil, N.S. Pawar & B.D. Borse	Submerged leaves of *Eucalyptus* sp. and *Polygonum glabrum*	Purna River, Gujarat	Patil et al. (2019)
Catenomycopsis vinayaka Sati & Pant	Root endophyte in *Eupatorium adenophyllum*	Nainital, Uttarakhand	Sati and Pant (2019)

studies come from the streamlets, streams, waterfalls, rivers, and rarely dams at different altitudinal ranges of the Western Ghats and Himalayas (see Tables 17.1 and 17.3). Interestingly, two thermal sulfur springs harbored aquatic hyphomycetes in the Western Ghats (Chandrashekar et al. 1991; Rajashekhar and Kaveriappa 1996). Recently, Chaudhari et al. (2016) listed occurrence of up to 45 species (in 29 genera) of aquatic hyphomycetes from Madhya Pradesh based on water, foam, plant detritus, stem flow, and live roots. Six species appeared to be endophytic in roots, while ten species were found in stem flow of tree species.

Including water samples, various substrates screened were leaf litter, woody litter, conifer needles, foam, scum, sediments, and damp terrestrial litter. In addition, the live roots of riparian trees or vegetation also supported aquatic hyphomycetes as endophytes in the Western Ghats and Himalayas (Raviraja et al. 1996a; Sati and Belwal 2005). Recently, studies have been carried out on the occurrence of aquatic hyphomycetes outside the streams: terrestrial leaf litter, stemflow, throughfall, decaying epiphytes (ferns), tree holes (dendrotelmata), and crown humus in the Western Ghats and southwest coast (Sridhar and Kaveriappa 1987b; Sridhar 2009c) (see more details in Table 17.1). These observations justify early reports on the occurrence of typical aquatic hyphomycetes in different substrates in terrestrial habitats in India and elsewhere. A recent study also revealed occurrence of 31 species of aquatic and aeroaquatic hyphomycetes on damp leaf litter of ten tree species during southwest monsoon in the scrubland of southwest Karnataka (Sridhar et al. 2020). However, the extent of occurrence is low in terrestrial habitats as compared to aquatic habitats, and their functions in terrestrial habitats appear to be different than aquatic habitats.

17.6.2 Richness and Diversity

Majority of studies in the Indian habitats concentrated on the species richness. In addition, it is necessary to provide the frequency of occurrence, conidial output, and substrate preference if any. Such approaches improve our knowledge to provide diversity, evenness, rarefaction indices (expected number of species), core-group fungi, keystone species, cryptic species, and so on. Minimum water quality parameters provide additional value to the study undertaken on aquatic hyphomycetes. Molecular approaches will direct us on colonized fungi in the substrates; these are usually missed by conventional methods of study. Such approaches emphasize seasonal fluctuations, succession, decomposition, mass loss of organic matter, food web, and pattern of energy flow.

Diversity of aquatic hyphomycetes is higher in the streams of the Western Ghats compared to the foothill, coastal region, and plains (Sridhar and Kaveriappa 1984, 1989a; Chandrashekar et al. 1990; Rajashekhar and Kaveriappa 2003; Sati and Tiwari 2006; Sati and Pant 2006; Maddodi et al. 2009; Sudheep and Sridhar 2013a). The diversity in the Western Ghat streams could be comparable to the streams of Himalayas based on the studies by S.C. Sati and coworkers (Sati and Tiwari 2006; Sati and Pant 2006). They concluded that the dense riparian vegetation and abundance of substrate in Himalayas are responsible for high diversity of aquatic hyphomycetes. Mountain streams in the Western Ghats showed lower species richness (10 spp.) compared to the mid-altitude streams (20 spp.); gradual decrease was seen towards foothill streams (14 spp.) and coastal streams (12.5 spp.) (Sridhar and Kaveriappa 1989c; Raviraja et al. 1998b). Decrease in the species richness towards foothill and coastal region has been predicted due to the impact of reduced forest area as well as changes in water quality by human interference (e.g., agricultural chemicals and sewage input). This view has been further supported by Rajashekhar and Kaveriappa (2003) with strong correlation between the vegetation and aquatic hyphomycetes. In addition, besides temperature, other water parameters due to human interference have negative impact on the richness and diversity of aquatic hyphomycetes. Sreekala and Bhat (2016) have also evaluated the seasonal variation in species richness and diversity in three streams of the wildlife sanctuaries of Goa (123–280 m asl), and concluded that species density is dependent on rainfall, riparian vegetation, and substrate availability. Such precise comparisons could not be given for other ecoregions in India owing to lack of such studies.

In addition to assessing water, foam, and leaf litter, some studies have examined submerged woody litter in streams or rivers of the Western Ghats (Sridhar et al. 2010; Sudheep and Sridhar 2011, 2013b). Woody litter from 12 high-altitude streams of the Western Ghats yielded 30 aquatic hyphomycetes with higher species in the bark (20 spp.) than cambium (18 spp.) (Sridhar et al. 2010). Assessment of 350 woody litter naturally deposited in Kali river and Kadra Dam in the Western Ghats on bubble chamber incubation yielded 15 and 11 spp., respectively (Sudheep and Sridhar 2011). On immersion of two woody litter (*Anacardium occidentale* and *Terminalia paniculata*) in Kaiga stream and Kadra Dam in the Western Ghats, *T. paniculata* yielded 17 and 16 spp. of aquatic hyphomycetes in the stream and dam, respectively, whereas *A. occidentale* yielded 17 and 14 spp., respectively (Sudheep and Sridhar 2013b).

Similar to leaf litter and woody litter, live roots of riparian trees were also assessed for the occurrence of aquatic hyphomycetes (Raviraja et al. 1996a; Sati et al. 2009b; Sati and Arya 2010a; Ghate and Sridhar 2017). In the Western Ghats, about 22 species of aquatic hyphomycetes were endophytic in riparian roots (Raviraja et al. 1996a; Ghate and Sridhar 2017), while 29 species were endophytic in the Himalayan region (Sati and Pathak 2017). The diversity of aquatic hyphomycetes in the mid-altitude stream was higher than high-altitude stream, which is similar to the diversity found in water, foam, and detritus (Raviraja et al. 1998b; Ghate and Sridhar 2017). Chaudhari et al. (2016) claimed that there are six species of root endophytic aquatic hyphomycetes in Madhya Pradesh. This indicates that the riparian roots constitute an excellent ecological niche of aquatic hyphomycetes for their survival as well as perpetuation.

Patil and Borse (2015) in their checklist of aquatic mitosporic fungi in India conducted investigations on different substrates. Considering some additional reports on the occurrence of aquatic hyphomycetes on woody litter (Sridhar et al. 2010, 2011b; Sridhar and Sudheep 2011b; Sudheep and Sridhar 2011, 2013b), submerged leaf litter stands first in the number of species colonized followed by woody litter, foam samples, water samples, and roots.

17.6.3 Distribution

Based on the extent of literature in the Indian subcontinent, Karnataka state stands first (37%) in the Western Ghats followed by Uttarakhand (21%) in Himalayas, Maharashtra (20%) in the Western Ghats, Andhra Pradesh (9%), Madhya Pradesh (5%), Goa (3%) in the Western Ghats, Gujarat (2%), Tamil Nadu (2%), Kerala (1%) in the Western Ghats, and Assam and Himachal Pradesh (<1%) in Himalayas (Fig. 17.3). Patil and Borse (2015) in their checklist classified distribution of freshwater mitosporic fungi in different states of India. The pattern of distribution is almost similar to the extent of reports presented above. The recent checklist by Borse et al. (2017) in the Indian subcontinent represents about 191 species of aquatic hyphomycetes (in 66 genera). Considering a recent report by Duarte et al. (2016), global occurrence is 335 morphospecies; thus India represents up to 57% of aquatic hyphomycetes. This is not surprising because the Indian subcontinent represents tropical, subtropical, and temperate climatic conditions. Further, it provides immense scope for studies in water bodies owing to ten biogeographic zones (trans-Himalayas, Himalayas, desert, semiarid zone, Western Ghats, Deccan Peninsula, Gangetic Plain, coasts, north-east zone, and islands) (Singh and Chaturvedi 2017). However, the vast ecoregions of the Indian subcontinent have not been inventoried for aquatic hyphomycetes (see Fig. 17.3). Although Goh and Hyde (1996) classified aquatic mitosporic fungi into four different groups, the actual aquatic hyphomycetes consisting of staurosporus (multiradiate), scolecosporus

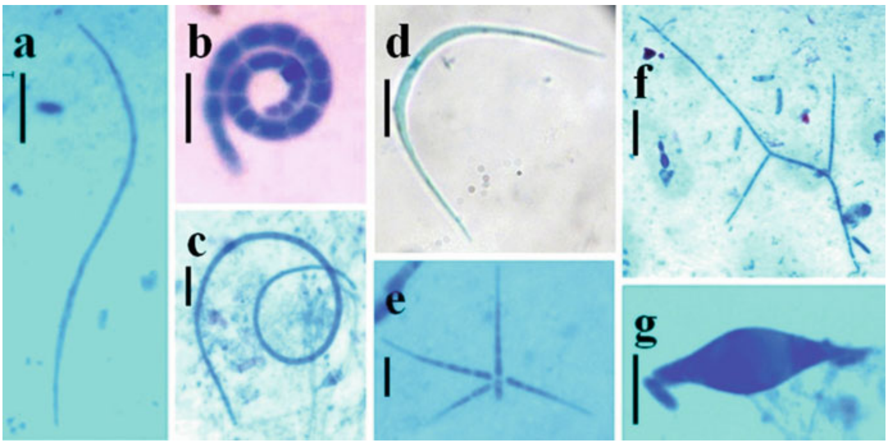

Fig. 17.3 Different conidia of aquatic hyphomycetes in the streams of Western Ghats: (**a**) *Anguillospora longissima*, (**b**) *Helicoma* sp., (**c**) *Helicosporium* sp., (**d**) *Lunulospora curvula*, (**e**) *Triscelophorus acuminatus*, (**f**) *Tricladium* sp., and (**g**) *Tumularia aquatica* (scale bar, 20μm)

(sigmoid), helicosporous (coiled), and conventional cylindrical and oval/spherical conidial shapes depict their adaptation to flowing waters. It will be convenient to consider typical aquatic hyphomycetes with the above spore features rather than including all those found in aquatic habitats. Other fungi found in aquatic bodies will be transients/immigrants or transferred through colonized substrate or accumulated in foam by terrestrial runoff leading to overlap with true aquatic hyphomycetes. Another advantage of such restrictions leads to focused attention and progress in future on aquatic hyphomycetes more precisely. It is not surprising that several aquatic hyphomycetes are found in tree canopies and terrestrial damp litter due to continuous wet conditions for a long period (4–6 months) especially in the Western Ghats. Shearer et al. (2007) rightly pointed out that "it is highly likely that species from aquatic habitats in the tropics also occur in the tropical rainforest habitat due to the very moist conditions."

17.7 Ecological Perspectives

Aquatic hyphomycetes are dependent mainly on the detritus material available from the riparian vegetation and transfer of coarse particulate organic matter from the terrestrial runoff. Their phenology coincides with the phenology of surrounding vegetation, rainfall, and physicochemical features of aquatic habitats. Further, their activity depends on the chemistry of the detritus material as well as the presence of consumer population. Availability of stagnant refuge and heterogeneous nature of stream bottom are the most important requirements. Depending on these factors, aquatic hyphomycetes show seasonality, succession, and decomposition of organic matter. Keystone, core-group, and cryptic nature of aquatic hyphomycetes in a given lotic body also depend on various factors. Under unfavorable situations, aquatic hyphomycetes need to face stressful conditions for survival and perpetuation.

17.7.1 Seasonal Studies

Two-year seasonal study of aquatic hyphomycetes in streams (coastal, foothill of the Western Ghats and mid-altitude of the Western Ghats) revealed increase in species richness and conidia during the post-monsoon season (September–December) followed by monsoon and summer seasons (Sridhar and Kaveriappa 1989a). Baiting five leaf litters in a southwest coastal stream also revealed similar seasonal fluctuation in a number of species (Sridhar and Kaveriappa 1989b). Such fluctuations are coinciding with increased rainfall and decreased water temperature. Further studies in the Western Ghats also showed similar results (Chandrashekar et al. 1990; Sudheep and Sridhar 2013a). On the contrary, in the two Himalayan streams near Nainital, species richness was higher during rainy and autumn seasons (July–September/October) than summer season (Sati and Tiwari 2006). Owing to decline in water temperature during winter in Himalayan streams, the species richness reduced substantially. In the Western Ghats, *Campylospora chaetocladia,* *C. filiformis, Flagellospora curvula, F. penicillioides, Lunulospora curvula, Phalangispora constricta, Synnematophora constricta, Triscelophorus acuminatus, T. monosporus,* and *T. konajensis* were the most frequent core-group species (Sridhar and Kaveriappa 1989a; Chandrashekar et al. 1990). In Himalayan streams, *Alatospora acumulata, Anguillospora longissima, Clavariopsis aquatica, Lunulospora curvula, L. cymbiformis, Tetrachaetum elegans, Triscelophorus acuminatus,* and *T. monosporus* were the core-group fungi (Sati and Tiwari 2006; Sati and Pant 2006). Among the core-group fungi, *L. curvula, T. acuminatus,* and *T. monosporus* were common to the Western Ghats and Himalayas. Based on the assessment of aquatic hyphomycetes in three streams in Goa, Sreekala and Bhat (2016) concluded that the best season to recover aquatic hyphomycetes is the monsoon season.

17.7.2 Diurnal Studies

As the post-monsoon season in the Western Ghats and southwest coast of India is the more productive season for aquatic hyphomycetes, Sridhar and Sudheep (2010) studied the diurnal periodicity of drift conidia at 3-h intervals. Two peaks of drift conidia were observed during 9 am and 9 pm in both streams. Higher species richness and diversity were seen during the day in Western Ghats stream, while it was during the night in the coastal stream. The top five species in this study simulate similar to the seasonal studies. Another diurnal study on banyan latex-smeared slides (*Ficus benghalensis*) in the Western Ghats and coastal streams was done at 3-h intervals during the post-monsoon season (Ghate and Sridhar 2016). Among the drift conidia (water samples), control slides (without latex smear), and experimental slides (with latex smear), the latter method showed higher conidial trapping efficiency with higher conidial richness, species richness, and diversity. The peak richness and diversity were seen during 12 am to 3 am in the Western Ghats stream, while 3 am to 6 am in the coastal stream. As seen in the first diurnal study (Sridhar and Sudheep 2010), the top five species coincide with annual studies. There was no bias in the entrapment of staurosporus and scolecosporus conidia on latex smears. Latex entrapment method serves as a method of choice in assessing aquatic hyphomycetes in streams (Ghate and Sridhar 2016).

17.7.3 Decomposition

Litter decomposition is one of the basic ecosystem services in the aquatic ecosystems and many life activities are connected directly or indirectly with this function (Bärlocher et al. 2020). Decomposition of four-leaf litters *Acacia auriculiformis*, banyan (*Ficus benghalensis*), cashew (*Anacardium occidentale*), and *Eucalyptus globulus* up to 16 weeks in two streams of the Western Ghats in relation to leaf and water chemistry was studied by Raviraja et al. 1996b). The highest conidial production was seen in banyan leaf litter. Raviraja et al. (1998a) further studied the decomposition of banyan and eucalypt leaf litter in an organically polluted stretch of Netravati river in the Western Ghats in relation to leaf and water chemistry. Relatively lower species richness and diversity of aquatic hyphomycetes were seen compared to other pristine streams in the Western Ghats. Decomposition of immersed leaf litters of teak (*Tectona grandis*) and Marwa (*Terminalia paniculata*) in two sites of the Kali river (reference site and impoverished site) up to 20 weeks yielded 24 species of aquatic hyphomycetes (Sridhar et al. 2011b).

A study on the decomposition of woody litters of teak and cashew wood (*Anacardium occidentale*) in Kaiga stream and Kadra Dam in the Western Ghats for 12 months showed higher diversity of aquatic hyphomycetes in stream than dam site (Sudheep and Sridhar 2013b). Aquatic hyphomycetes overcome the loss of their mycelial biomass or conidia by unidirectional flow of water in streams and rivers by colonizing the long-lasting substrates like woody debris and live roots of riparian vegetation. In addition, conidial survival in the intestine of fishes facilitates replenishment to the upper reaches. Moreover, many aquatic hyphomycetes survive in semiaquatic habitats of forest floor litter and in canopy (leaves, twigs, humus, stemflow, and throughfall) that facilitates their input into the nearby lotic bodies.

17.7.4 Physiology

A few studies have concentrated on the nutrition and physiology of aquatic hyphomycetes. Rajashekhar and Kaveriappa (2000) studied the impact of temperature and light on aquatic hyphomycetes. On exposure of nine species to different temperature ranges (5–35 °C), maximum growth was attained between 20 and 30 °C. *Vermispora cauveriana* showed the highest growth, while it was lowest in *Tetracladium setigerum*. On exposure to continuous dark, normal light-dark conditions and continuous light, sporulation of 6, 16, and 17 species, respectively, indicted the promotion of sporulation by light. Sati et al. (2012) studied the effect of temperature, pH, and light on the growth of aquatic hyphomycetes. For five aquatic hyphomycetes, optimum temperature is in the range of 20–25 °C for growth; optimum pH was in the range of 6.5–8.5. White as well as red light sources were favorable for growth, while blue light and darkness were inhibitory.

Chandrashekar et al. (1991) worked on the physiology of aquatic hyphomycetes using the water samples from a sulfur thermal spring in the Western Ghats (Bendre Thirtha). On incubation of coffee leaves naturally colonized in a Western Ghats stream in spring water at different temperatures (16 °C, 22 °C, 28 °C, 34 °C, and 40 °C), a gradual decrease in sporulating species was seen, i.e., 10, 8, 9, 1, and 0, respectively. The sulfide content (0.1–3.1 mg/L) did not affect the sporulation of aquatic hyphomycetes. In another study in a different sulfur thermal spring (Panekal) in the Western Ghats, Rajashekhar and Kaveriappa (1996) showed that sulfide concentration at 4 mg/L inhibited the colony growth of five aquatic hyphomycetes. Incubation of aquatic hyphomycetes colonized leaves in spring water at different temperatures (15, 20, 25, and 30 °C), and sporulating species were 0, 7, 7, and 2 spp., respectively, and in control, 9, 21, 19, and 7 spp., respectively, while only one species sporulated at 35 °C and no sporulation at 40 °C. In the spring, synergistic effect of temperature and sulfide was seen.

Glucose and sucrose were the suitable carbon sources among eight carbon sources tested on four aquatic hyphomycetes, while fructose served as a good carbon source for two species and starch supported the growth of three species (Sati and Bisht 2006). The ammonium ions were the most preferred nitrogen source for four aquatic hyphomycetes followed by nitrates (Sati and Bisht 2005). Cystine served as a good source of nitrogen to all species studied, while asparagine was preferred by two species and proline was preferred by two species.

17.8 Ecosystem Services and Applications

Although some key information is available on aquatic hyphomycetes in India, it is necessary to link them towards ecosystem functions. One of the major ecosystem services of aquatic hyphomycetes is the breakdown of coarse particulate organic matter (CPOM) into fine particulate organic matter (FPOM) and dissolved organic matter (DOM) (Suberkropp and Klug 1980). Being highly adapted to the lotic ecosystems, they serve as intermediaries between detritus and aquatic fauna (e.g., macroinvertebrates and vertebrates). To augment such transformation, they must have evolved to produce strong extracellular enzymes for degradation of lignocellulosic biomass (lignocelluloses, cellulose, hemicellulose, and pectin) and other plant polymers.

17.8.1 Enzymes

A few studies have been carried out to follow the capability of aquatic hyphomycetes to produce extracellular enzymes in India (e.g., Chandrashekar and Kaveriappa 1988, 1991). *Ingoldiella hamata* and *Phalangispora constricta* showed pyrocatechol oxidase activity, while amylase activity by *Triscelophorus acuminatus* (Chandrashekar and Kaveriappa 1988). *Lunulospora curvula* possesses high cellulase and amylase activities, while *P. constricta* had triacyl glycerol-hydrolyzing lipase activity. Among the carbon sources, carboxymethyl cellulose and ammonium sulfate are the excellent carbon and nitrogen sources to stimulate cellulase production in 12-day-old cultures of *L. curvula* as well as *Flagellospora penicillioides* under the optimal pH (5.2) with temperature (28 °C) (Chandrashekar and Kaveriappa 1991). The highest amylase production was achieved in *L. curvula* and *P. constricta* in a medium containing starch and ammonium sulfate with optimum pH (5.3) and temperature (28 °C) (Chandrashekar and Kaveriappa 1992). Starch and ammonium sulfate were the best sources of carbon and nitrogen for the production of amylase by *L. curvula* and *P. constricta* at pH (5.2) and temperature optima (28 °C), while amylase production in both species was reduced in the presence of glucose and sucrose.

17.8.2 Food Web

On the onset of enzymes, aquatic hyphomycetes enrich the detritus which is palatable to aquatic fauna (as shredders). Enzymes of aquatic hyphomycetes also serve their functions in the intestine of aquatic fauna. In addition to enzymes and proteins, ergosterol, the filamentous fungal sterol, has been identified as an important signature compound to assess the fungal activity. Besides, ergosterol is essential in the metamorphosis of arboreal insects (those that lay eggs in aquatic habitats as part of life cycle) and palatability to crustaceans and fish (Rao and Manoharachary 1982; Chandrashekar et al. 1989; Sridhar and Sudheep 2011a). Two approaches pertain to the interactions of aquatic hyphomycetes with detritus shredders that have been proposed by Bäerlocher (1992): (a) enrichment of quality litter by fungi into easily digestible state and (b) fungal enzymes continue to function in the gut of detritus shredders. To support these hypotheses, the juvenile fish and prawns preferred leaf discs colonized by aquatic hyphomycetes against control leaf discs (Rao and Manoharachary 1982). In another study, rubber leaf litter (*Hevea brasiliensis*) enriched by aquatic hyphomycetes was preferred against the control leaf litter by the fish (*Oreochromis mossambicus*) in a laboratory mesocosm study owing to enhancement of nutritional quality (Chandrashekar et al. 1989). The sequence of preference of rubber leaves colonized was by *Lunulospora curvula, Flagellospora penicillioides, Wiesneriomyces laurinus, Helicosporium* sp., *Triscelophorus acuminatus, Ingoldiella hamata,* and *Phalangispora constricta*. Sridhar and Sudheep (2011a) have demonstrated the occurrence of conidia of aquatic hyphomycetes in the feces of three fishes occurring in the Western Ghats (*Aplocheilus lineatus, Puntius filamentosus,* and *Rasbora daniconius*). They also showed the viability of aquatic hyphomycete spores using baiting technique as described for sediments (see Sect. 17.4).

17.8.3 Endophytes

Generally endophytic fungi are resourceful owing to their versatile properties (e.g., antimicrobial activity and metabolites). Nearly 40 species of aquatic hyphomycetes are known as endophytes in Indian waters (e.g., Ghate and Sridhar 2017; Sati and Pathak 2017). Endophytic *Anguillospora longissima* showed antibacterial activity against Gram-positive and Gram-negative bacteria (e.g., *Agrobacterium tumefaciens, Bacillus subtilis, Erwinia chrysanthemum, Escherichia coli,* and *Xanthomonas pseudomonas*) (Sati and Singh 2014). Same endophytes were antagonistic against plant pathogens like *Colletotrichum falcatum*, *Fusarium oxysporum*, *Pyricularia oryzae*, and *Tilletia indica* (Singh and Sati 2019).

Endophytic aquatic hyphomycetes are of agricultural significance owing to their excellent phosphate solubilization ability and plant growth enhancement. Endophytic fungi, *Anguillospora longissima*, and *Cylindrocarpon aquaticum* were potent phosphate solubilizers (Singh and Sati 2017). Among them, *A. longissima* was more potent than *C. aquaticum* with phosphate solubilization index 1.23 and 1.19, respectively. Another endophytic fungus *Tetracladium setigerum* served as a potent phosphate solubilizer with phosphate solubilization index 1.3–1.5 on 7-day incubation in Pikovskaya's (PVK) agar medium with the highest phosphate solubilization (3.5 mg/L) in PVK broth after 21 days of incubation (Sati and Pant 2018). Among the endophytic *Heliscus lugdunensis*, *Tetrachaetum elegans*, and *Tetracladium nainitalense*, the first two showed growth promotion of two test plants (*Hibiscus esculentus* and *Solanum melongena*) through increased fresh weight, dry weight, length of shoots, and length of roots, while the latter had no such impacts (Sati and Arya 2010a). Further, inoculation of former two species did not show any disease symptoms in the host plants indicating their growth promotion traits under natural conditions.

17.8.4 Environmental Monitoring

Another important environmental application of aquatic hyphomycetes is the use of individual species, community, and their functions (e.g., conidial output, leaf mass loss, and ergosterol content) as indication of pristine or perturbation of lotic habitats. On an average, 20–25 species could be recorded in a moderate stream in India in one sampling. If the number of species falls below 10, there seems to be some factor responsible for decreased species richness (e.g., Raviraja et al. 1998a; Raghu et al. 2001). Water chemistry will depict the perturbations like pH, salinity, oxygen concentration, and biochemical oxygen demand. Organic pollution severely hampers the diversity as well as their conidial output (Raviraja et al. 1998a). Identification of pollution-tolerant and -sensitive indicator species will also help assessing the impact of pollution. For example, *Lunulospora curvula* and *Triscelophorus monosporus* were tolerant to heavy metal pollution in a stream near iron-ore mine (Raghu et al. 2001). Precise monitoring of risks of pollution in aquatic habitats could also be monitored by switching immersed leaf litter between unpolluted and polluted streams. Similarly, the lotic habitats could be classified as pristine, moderately polluted, and severely polluted based on species richness, diversity, conidial output, and mass loss of plant litter.

17.9 Human Interference

17.9.1 Deforestation and Urbanization

Freshwater biodiversity is hit by five major human interferences such as flow modification, habitat degradation, overexploitation, pollution, and invasion of exotic species (Dudgeon et al. 2006). The most important threat is channeling by removal of obstructions for agricultural or recreational purpose. Such interference reduces retention of detritus, which in turn destroys the potential ecological niches of aquatic hyphomycetes. Urbanization, deforestation, and removal of riparian vegetation lead to change in the course of the streams, which hampers the critical ecological functions of aquatic hyphomycetes. The richness and diversity of riparian vegetation have been correlated to the increased species richness and diversity of aquatic hyphomycetes (Raviraja et al. 1998b; Rajashekhar and Kaveriappa 2003). Other human interference includes input of agricultural chemicals (e.g., pesticides and heavy metals), sewage, industrial wastes, and so on. In some regions, natural or artificial forest fires have additional threats to functions of aquatic hyphomycetes. Interestingly, urban runoff of southwest coastal city (Mangalore) possesses 35 species of aquatic and aeroaquatic hyphomycetes indicating their survival and role in urban habitats (Ghate and Sridhar 2018).

17.9.2 Pollution

Among ten major threats on earth, as many as seven hit the freshwaters (Rockström et al. 2009). Organic pollution, heavy metals, and pesticides are known to impoverish the stream fungi (Raviraja et al. 1998a; Sridhar and Raviraja 2001; Raghu et al. 2001). Organically polluted stretch of Netravati river in the Western Ghats resulted in 83% decline of aquatic hyphomycetes (Raviraja et al. 1998a). In Sitabhumi river, adjacent to Kudremukh iron-ore mine in the Western Ghats, heavy metal pollution reduced the diversity (6 spp.) as well as spore output (<1/mg leaf mass) of aquatic hyphomycetes (Raghu et al. 2001). However, a few species tolerated the extent of heavy metal pollution (e.g., *Lunulospora curvula* and *Triscelophorus monosporus*).

Growth of *Flagellospora penicillioides, Lunulospora curvula,* and *Phalangispora constricta* was not influenced by herbicides and fungicides up to 5 mg/L (Chandrashekar and Kaveriappa 1989). Organochlorine insecticides did not influence the growth at <10 mg/L, while inhibition of sporulation was seen between 5 and 10 mg/L (Sridhar and Kaveriappa 1986). In laboratory experiments incubation of aquatic hyphomycetes colonized leaf litter with Bordeaux mixture and benzene hexachloride inhibited sporulation of many species at 5–10 mg/L (*Campylospora chaetocladia, C. filicladia, Flabellospora verticillata, Flagellospora curvula, F. penicillioides, Lunulospora curvula, L. cymbiformis, Triscelophorus acuminatus, T. konajensis,* and *Wiesneriomyces laurinus*) (Sridhar and Kaveriappa 1986). Similarly, herbicides (Paraquat and 2,4-dichlorophenoxy butyric acid) and fungicides (Dihane M-45 and Captafol) have no growth inhibition up to 5 mg/L (*F. penicillioides* and *L. curvula*) (Chandrashekar and Kaveriappa 1989). Some of the pesticides (Bavistin, Captafol, 2,4-DB Fernoxone, Malathion, Mancozeb, Paraquat, Thodan, and Tridemorph) did not inhibit sporulation ability of aquatic hyphomycetes up to 5 mg/L, while conidial germination was inhibited at the same concentration (Chandrashekar and Kaveriappa 1994). Thus, the reproductive phase and germination of conidia seem to be more sensitive to herbicides/pesticides compared to vegetative phase and help in the recovery of activities of aquatic hyphomycetes on dilution of pollutants. Function of some valuable species of aquatic hyphomycetes (as keystone and core-group species) in the lotic ecosystem may be severely affected by human interference and elimination of such species will lead to severe impoverishment (retarded decomposition and energy flow) of lotic habitats.

17.10 Future Perspectives and Conclusions

Considering aquatic hyphomycetes as an important mycota in lotic ecosystems, several challenges could be projected in view of environmental protection and safety. Beyond doubt the aquatic hyphomycetes serve as a model community to assess ecological services (food web and energy flow), perturbations or risk assessment (reduction in diversity and detritus breakdown), and restoration (rehabilitation and reinstatement) of lotic habitats. This could be achieved by monitoring structural (richness and diversity) and functional (palatability, enzyme/metabolites/growth factors) attributes of aquatic hyphomycetes. Assessment of leaf litter breakdown as a simple and cost-effective approach helps to evaluate structural (pattern) as well as functional (processes) phases of aquatic hyphomycetes in lotic ecosystem. Besides species richness and diversity approaches, systematics, anamorph-teleomorph connections, interaction with detritus shredders, energy flow, and stream productivity are other potential aspects of interest.

Based on the investigations carried out in the Western Ghats, mid-altitude streams possess the highest diversity of aquatic hyphomycetes. For example, Sampaje stream (~500 m asl) consists of about 90% of aquatic hyphomycetes (up to 80 spp.) reported from the whole Western Ghats region. As compared to the global richness (335 spp.), nearly 25% of species occur in a single location of the Western Ghats. Designation of such important lotic habitats in the rest of the Western Ghats, Himalayas, and other important ecoregions in India helps to impose conservation measures.

It is possible to classify the research carried out on aquatic hyphomycetes in India into three phases: phase 1—morphology, diversity, and distribution; phase 2—ecological studies; and phase 3—applications. Studies on phases 1 and 2 have been fulfilled to some extent, while phase 3 has been initiated. In application front, production of enzymes, secondary metabolites, growth factors, antimicrobial potential, medicinal potential, importance in agriculture, and inland fisheries are some of the aspects worth exploring to attract the funding agencies. Gaps in our knowledge in different aspects like richness, diversity, ecology, phylogeny, culture collections, new methods, molecular approaches, and applied aspects could be accomplished by well-designed national networks.

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