RESEARCH ARTICLE

Exploration of Mangroves Associated Microbes for Bioactive Metabolites

Sushmita Paul*, Fatima Siddiqua, Kumananda Tayung

DOI: 10.18811/ijpen.v9i03.03

Abstract

Mangroves are woody plants found growing at transition zones between land and sea in tropic and sub-tropical regions. They are highly adapted morphologically and physiologically to survive in extreme environments. Mangroves are found worldwide in their distribution, with 110 species that belong to 20 different families. In India, mangrove forests are mostly found on the Andaman and Nicobar Islands and the West and East Coast. Mangroves have enormous ecological, commercial and biological significance. They are also regarded as hotspots for microbes because of their rich microbial diversity. Various types of microorganisms like bacteria, fungi, microalgae and macroalgae are abundant in mangrove ecosystems. More recently, fungal endophytes associated with mangroves have added to their microbial diversity. Many mangrove plants are used as ethno-medicine in traditional health care. Mangroves are also used as antimicrobial and antiviral agents. Fungal endophytes -colonizing medicinal plants are reported to produce important bioactive metabolites. These endophytes are believed to produce same and more biologically active metabolites as compared to their respective hosts. Many fungal endophytes isolated from mangrove species have produced some important biological active metabolites like triterpenes, indole triterpenes, isocoumarin and marinamide. Therefore, the study of fungal endophytes associated with medicinal mangroves may give rise to important endophytic strains that might produce novel and new bioactive metabolites of pharmaceutical, industrial and agricultural importance. Due to the alarming rate of depletion of mangrove genetic resources across the world, it is highly needed to explore fungal endophytes associated with mangroves for the inventorisation of new metabolites.

Keywords: Bioactive metabolites, Fungal endophytes, Microbial diversity, Mangroves.

International Journal of Plant and Environment (2023); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

Mangroves are a group of woody plants growing at the transition zones between sea and land in sub-tropical and tropical latitudes. They are well adapted to their habitat's extreme tides and high salinity conditions. They are also accustomed to strong winds, anaerobic muddy soils and extreme high temperatures (Kathiresan and Bingham, 2001). They are a highly developed group of plants that can rapidly adapt to morphological and physiological adaptations. They exist in those extreme environments and have devised mechanisms to pick up water despite having osmotic potential. Some plants easily absorb salts and eliminate them through special glands located within the leaves. Some others transmit salts that enter the mature leaves and get stored in bark or wood. Several others are extremely conservative in their water use as the salinity of the water increases. A total of 20 families with 110 recognized species of mangrove plants are known to date.

Mangroves are distributed among 112 countries and territories, compromising an overall boundary of about 181,000 km2, dominating approximately 1/4th of the world's coastline. In terms of productivity as well as sustained tertiary yields, mangroves are the second most important marine ecosystem after coral reefs. The great Indian peninsula also covers about 7000 km^2 of mangroves, out of which 70% exist on the east coast, 18% exist in the islands of Andaman and Nicobar, and only about 12% exist on the west coast (Krishnamurthy *et al.*, 1987). Orissa locating in the eastern part of Indian peninsula has rich forests of mangroves specifically located in the costal belt of estuarine regions of the rivers namely Brahmani, Jambu, Baitarani, Devi, Mahanadi, Burabalanga, etc. A remote sensing survey was conducted in 1984 and according to its report the mangrove forest has spread over 214.58 km^2 in the state of Orissa (Samal and Patnaik, 1989). Mangroves have enormous ecological value such as providing stability and protection to coastlines, supporting the coastal fisheries and improving the coastal waters. They also add economic value by providing good yields of commercial forest goods. Among the entire ecosystems on earth, mangrove forests are the most efficient and productive because they produce a large amount of organic carbon, which is more than the requirements of the entire ecosystem. The mangrove forests play a significant role in the carbon cycle of the plant. Many investigations suggest that the extracts obtained from both mangroves and mangrove-dependent species possess proven suppressive and eradicative activities against animal, human and plant pathogens. Above all, mangrove ecosystems support rich microbial diversity and may be considered microbial hotspots mostly dominated by mangrove fungi. Recent discoveries on mangroves established the fact that mangrove plants harbor some special fungi

Department of Botany, Gauhati University, Guwahati, India.

***Corresponding author:** Sushmita Paul, Department of Botany, Gauhati University, Guwahati, India, Email: sushmitapaul62@gmail.com

How to cite this article: Paul, S., Siddiqua, F., Tayung, K. (2023). Exploration of Mangroves Associated Microbes for Bioactive Metabolites. International Journal of Plant and Environment. 9(3), 202-209.

Submitted: 07/07/2023 **Accepted:** 21/08/2023 **Published:** 28/09/2023

known as fungal endophytes. Fungal endophytes invade the internal tissues of plants and establish themselves there, without inducing any symptoms of disease or any visible injury to the host (Bills, 1996). In recent years, mangrove fungi have been observed to produce several novel bioactive substances of agricultural, pharmaceutical and industrial importance. Several fungal endophytes are reported from mangrove species (Ananda and Sridhar, 2002; Suryanarayan and Kumaresan, 1998) and most of these fungal endophytes are able to produce various potent bioactive molecules with multifold applications (Li *et al.*, 2007; Xu *et al.,* 2006; Huang *et al.,* 2007; Liu *et al.,* 2006). Therefore, this review spotlights the diverse groups of microbes and endophytes associated with the mangrove forests that serve as reservoirs of potent bioactive metabolites.

Bioprospecting Need of the Hour

Drug-resistant strains of fungi, bacteria, viruses and parasites are rapidly increasing because of improper handling and overuse of antibiotics (Daleyi, 2002). Examples of such drug-resistant strains are the microorganisms belonging to genera- *Staphylococcus, Pseudomonas* and *Streptococcus* (Chitnis *et al*.., 2000). Some strains are highly resistant to antibiotics such as cephalosporins, beta-lactams and methicillin, which target peptidoglycan synthesis. Some strains show resistance against neomycin and streptomycin which target the bacterial ribosome. In the USA, strains of bacteria causing tuberculosis (TB) are reported to be resistant to drug treatment. Mutations in the genome of microorganisms and the incorporation of foreign genomic material like plasmids into them are the main causes of their developing resistance to antibiotics. This event is a matter of great concern for the medical community, as the pathogens are swiftly becoming resistant to a plethora of antibiotics. The continuous evolution of resistant microorganisms towards antibiotics can be a natural or artificially mediated process. The antibiotics are extremely misused and are carelessly handled which is responsible for developing drug-resistant bacteria. The antimicrobial agents are used not only in the agricultural industries but also in farming as well as for clinical purposes. For example, 10,200 tons of antibiotics were used in the USA in 1996, out of which about 50% were used in manufacturing growth promoters and veterinary medicine (Swartz, 2000). The introduction of new human diseases like - severe acute respiratory syndrome and AIDS calls for new drug discoveries and their development to combat them. Diseases like AIDS need drugs that specifically target them and the new therapies also demand specific drugs for treating ancillary infections caused by a weak immune system. Several immunocompromised patients (e.g., organ transplant and cancer patients) are also in need of new novel drugs that are at high risk for opportunistic pathogens like *Cryptococcus* spp., *Aspergillus* spp. and *Candida* spp. which may not be major problem in general. More drugs are urgently required to effectively treat nematode and parasitic protozoan infections namely leishmaniasis, trypanomiasis, malaria, and filariasis. Malaria is more efficient at claiming lives every year than any other infectious agent with, except for *Mycobacterium tuberculosis* and the AIDS virus. In the agricultural industry and poultry, several *Enterococcus* strains are resistant to antibiotics like tetracycline, macrolides and penicillin. Various antibiotics used as clinical agents have been obtained from soil microorganisms. Extensive screening of these microbes from diverse habitats revealed low metabolic diversity obtaining same compound repeatedly. Therefore, the search of novel bioactive compounds in recent years has been directed to those microbes that are unexplored and can survive in extreme environments. These microbes have produced diversified metabolites that have generated bioprospecting for biotechnological applications. Fungal endophytes colonizing mangroves are less explored and occur in extreme environments, thus providing an opportunity for the isolation of new and potent endophytic strains that may generate novel metabolites for use in pharmaceutical, industrial and agricultural applications.

Microbial Diversity in Mangroves Ecosystem

The microbial diversity of mangrove ecosystem deserves greater attention. The diversity of microbes encloses the degree of variability among different types of microorganisms (fungi, bacteria, viruses and many others) in the natural world or as altered by human interference. Microbes are useful for balancing the earth's function. The diversity of microbes constitutes an infinite source of novel compounds for innovative biotechnology. In fact, microbial diversity is the biggest unexplored reservoir of the biodiversity present on earth. Recent estimates revealed that until recent times only approx. 5% of the total fungal species and 0.1% of bacterial species were currently known (Lange, 1996). Therefore, even after studying a lot of microbes, there are still plethoras of microbes that remain unexplored in the environment because many of them are overlooked or unable to culture in laboratory conditions. Thus, exploring and studying the microbial diversity in diverse habitats give an opportunity to discover new and potent microbes that might have medical, industrial and agricultural importance. Mangrove ecosystems provide a special environment for holding a diversified class of microbes. Numerous other life forms are reported, namely bacteria, cyanobacteria, fungi, algae, microalgae, and fungus like protozoa and microalgae.

Bacteria

Several diversified bacterial communities fill up these unique ecological niches that provide a beneficial role in recycling nutrients and controlling the chemical surroundings of the mangrove ecosystem. The primary group of decomposers that take part in the decomposition of anaerobic mangrove debris are sulfate-reducing bacteria such as *Desulfotomaculu, Desulfococcus, Desulfosarcina* and *Desulfovibrio* (Chandrika *et al.*, 1990). This group of bacteria greatly controls the changes of phosphorus, iron and sulfur and largely contributes to their existing environment's vegetation and soil patterns (Sherman *et al.*, 1998). In some particular seasons methanogenic bacteria become abundant in the grounds of mangrove ecosystems where the species of *Avicennia* dominate all the other species (Mohanraju and Natarajan, 1992; Ramamurthy *et al.*, 1990). N_2-fixing *Azotobacter* is abundant in habitats of the mangrove of Pichavaram, South India (Ravikumar, 1995) and this nitrogen-fixation bacterium serves to be an efficient biofertilizer. The halotolerant bacterial strains of N_2-fixing *Rhizobium* derived from nodules present in roots of *Sesbania* and *Derris scandens* sp. living in the Sundarbans' mangrove swamps (Sengupta and Choudhuri, 1990). It is observed that in several mangrove habitats present within some mining areas, iron-reducing bacteria are common (Panchanadikar, 1993). They also play other useful roles in the mangrove ecosystem and thus, serve as an important component. Some of them live mutually with other living organisms, for instance, rod-shaped bacteria are quite commonly present inside the detritivores (hindguts) of mangrove forests (Harris, 1993) and the branch-shaped sulfur-oxidizing bacteria are present as endosymbionts inside the members of the Lucinacea family. Different bacterial populations have shown distinctive spatial distribution patterns. They are also evidenced to present epiphytically on mangrove surfaces; however, various species prefer to occupy different portions of tree. Cyanobacteria isolated from mangroves are also reported where they establish any sub-merged surfaces, including aerial roots, sediments, trunks, roots and branches (Sheridan, 1991).

Fungi

Mangroves are home to a large group of fungi known as mangroves fungi. They play vital ecological roles in decomposing organic matter and provide protein-rich detritus that serve as food to fishes in the mangroves ecosystem. Hyde (1990a) has listed about 120 species of mangrove fungi from 29 mangrove forests around the globe. These include 31 deuteromycetes, 87 ascomycetes and about 2 basidiomycetes. In the Indian peninsular, workers have reported many mangroves fungi from different ecosystems. From the mangrove samples obtained from the Andaman and Nicobar Islands, about 63 species belonging to higher fungi was reported by (Chinnaraj, 1993a). Similar samples were collected from the Islands of Lakshadweep, yielding 32 species and from mangrove samples obtained from the Maldives, around 39 species belonging to higher fungal group were found in (Chinnaraj, 1993b). According to Ravikumar and Vittal (1996), around 48 fungal species are involved in the decomposing debris of *Rhizophora* located in Pichavaram, South India. Numerous fungal species live directly on mangroves; however, not well known. About 10 fungal species were isolated from the surfaces of leaves of 7 mangrove species was reported during their investigation by Sivakumar and Kathiresan (1990). The dominant phylloplane fungi reported were *Penicillium, Rhizopus nigricans*, *Alternaria alternata*, and *Aspergillus* spp. Marine oomycetes also present in mangrove communities. According to the investigation report of Tan and Pek (1997), around five of the *Halophytophthora* species collected from Singapore mangroves. A total number of two new parasitic species (*Cladosporium marinum* and *Pestalotiopsis agallochae*) derived from the leaves of *Excoecaria agallocha* and *Avicennia marina* (Pal and Purkayastha, 1992b). A great number of fungal species colonize the subsurface of the mangrove roots. Sengupta and Choudhuri (1994) also reported VA-mycorrhiza-like fungi and *Rhizoctonia* from mangrove communities in the Sunderbans. About 30 species of such lignicolous fungi (wood-decay fungi) have been reported in Malaysian mangroves (Tan and Leong, 1992). The most abundantly present lignicolous fungi are *Phoma* sp., *Lignincola laevis*, *Eutypa* sp., *Kallichroma tethys*, *Lulworthia* sp., *Halosarpheia retorquens*, *Marinosphaera mangrovei* and *Julelia avicenniae*. In recent years, fungal endophytes have been associated with mangroves isolated from different mangrove species. Ananda and Sridhar (2002) have studied endophytic fungi from four mangroves species of west coast of India where they found *Mycocentrospora acerina* and *Triscelophorus acuminatus* as endophytes. Similarly, Suryanarayanan and Kumaresan (1998) studied endophytic fungi from four halophytes from an estuarine mangrove forest. They isolated 36 endophytic fungal species, including sterile forms with some dominant genera like *Colletotrichum*, *Phomopsis*, *Phyllosticta* and *Sporormiella*.

Micro and Macroalgae

The communities of benthic microalgae and phytoplankton greatly improve the functioning of the mangrove environments. Although the contributions of phytoplankton to the productivity in localized mangrove areas may be much less, they serve as an important component of that environment. Lee (1990) reported that benthic macroalgae and phytoplankton altogether provides less than 10% of total net primary production in the mangroves of Hong Kong. According to Robertson and Bladder (1992), microalgae contribute much less to the productivity of mangrove systems but provide strong support to higher trophic levels. Despite being low in productivity, mangrove's phytoplankton communities are quite striking and diversified. The studies of Phytoplankton of West Bengal, India reported 46 number of different species of phytoplanktons, namely, Bacillariophyceae and Dinophyceae, Cyanophyceae (Santra *et al.*, 1991). *Chaetoceros*, *Pleurosigma*, *Rhizosolenia*, *Ceratium, Biddulphia* and *Protoperidinium* were the dominant genera growing yearly. According to Kannan and Vasantha (1992) about 82 phytoplankton species (15% dinoflagellates; 72% diatoms) appear in the mangroves in Pichavaram of South India. A few of the diatoms like *Nitzschia closterium*, *Thalassiothrix frauenfeldii, Thalassionema nitzschioides* and *Pleurosigma* sp. are most abundant. Algal diversity is quite high in mangrove environments. Studies on rich algal diversity in mangrove ecosystems have carried out in various parts of the world. According to the new records of algal surveys a great many number of species like *Stictosiphonia kelanensis* collected from Atlantic mangroves, *Caloglossa angustalata* (Rhodophyta), *Boodleopsis carolinensis* (Chlorophyta), *Bostrychia pinnata* and *Bostrychia simpliciuscula* collected from Singapore and *Caloglossa stipitata, C. ogasawaraensis*, *C* and *Bostrychia pinnata* collected from a place named Peru, *Caloglossa ogasawaraensis* and *B. pinnata* collected from the Atlantic coast, United States of America and *B. calliptera* from a place named the Central Gulf of Mexico (West, 1991a, 1991b) and *C. lepricuriil*, *C stipatata*, *B. moritziana*, *B. radicans, Catenella caespitosa* and *B. pinnata* collected from Guatemala (Pedroche *et al.*, 1995). The algae derived from mangrove habitats have potent commercial values. For instance, a red alga called *Gracilaria changii* derived from mangrove's of Malaysian habitats is a great source of agar with content range of 12 to 25% (of its dried weights) (Phang *et al.*, 1996). Some are consumable food resources like *Catenella impudica, Caloglossa lepriurii* and *Monostroma oxyspermum*. According to Ananda Rao (1998), *Caulerpa* sp. possesses important biological active substance that can serve as potent pharmaceutical compound.

Table 1: Selected ethno pharmaceuticals from mangrove forests (Uthoff, 1996).

Mangroves species	*Part used*	*Preparation*	*Treatment*
Rhizophora mucronata	bark	infusion	diarrhoea, dysentery
Ceriops decandra	bark	infusion	diarrhoea, dysentery
Bruguiera parviflora	heartwood	extracts	constipation
Rhizophora mucronata	root cortex	extract	insect repellent
Avicennia spp.	Barks	extract	skin parasites
Clerodendron inerme	leaves	bark	skin parasites
Acanthus ilicifolius	bark, root	bath	skin diseases, allergies
Avicennia spp.	Resin	---	tumors and ulcers
Ceriops tagal	bark	extract	wound cleaning
Thespesia populnea	fruits and leaves	ointment	scabies
Xylocarpus moluccensis	seeds	extract	wound cleansing
Avicennia officinalis	roots, heartwood	extract	stimulant and tonics
Avicennia alba	resin	---	contraceptive
Hibiscus tiliaceus	blossoms	infusion	infection in ear canals
Bruguiera gymnorrhiza	fruits	sap	eye diseases
Clerodendron inerme	roots	extract	hepatitis, chills
Bruguiera parviflora	heartwood	extracts	stomatitis
Cerbera manghas	fruits	sap	rheumatism
Ceriops tagal	barks	---	bruise/ hemorrhage
Excoecaria agallocha	leaves	---	epilepsy
Rhizophora mucronata	bark	infusion	leprosy
Acanthus lilicifolius	leaves	ointment	rheumatism

Mangroves and Fungal Endophytes

Mangroves or mangrove forests are coastal wetland located at the transition zones of deltas, estuaries, creeks, lagoons, backwaters, mudflats and marshes located in subtropical and tropical latitudes Mangrove forests produce a satisfactory quantity of detritus like woody debris, inflorescence and leaf litter and thus, comprises an ideal environment for several detritus dependent fauna and microbes. The water's productivity of mangrove depends upon the extension of the cover of mangrove canopy which supplies nitrogen, carbon and phosphorous. Mangrove forests provide habitat to many species, as wave buffers or as the nursery grounds, saving seagrass beds and colonies of coral polys referred as coral reefs from the process of sedimentation and man-made events. However, the economic significance of the mangroves forest is that it provides the life-supporting system for those indigenous populations surviving on the edges of the mangroves forests. These indigenous communities depend on mangrove forests for their basic requirement like providing fuel, building material for houses, boats and fishing equipment, foodstuff like fish, mussels, crustaceans, leaf vegetables, honey, vinegar, sugar, raw resource material for household utensils and clothing, tanning agents, alcoholic drinks and traditional medicinal remedies. Therefore, the mangroves ecosystem allows a degree of subsistence living and the chance to extract market products as a source of income. However, the extremely valuable products of mangroves forest are the medicinal property of several mangroves' species, which are widely used in traditional healthcare practices.

Mangroves as Potential Medicinal Uses

Plants sculpted the system of traditional medicine that has existed for thousands of years. About 2600 B.C, the first record of traditional medicine was reported from Mesopotamia and the substances used mainly were oils obtained from *Papaver somniferum* (opium poppy), *Cedrus* species (cedar), *Glycyrrhiza glabra* (licorice), *Cupressus sempevirens* (cypress) and *Commiphora* species (myrrh) which are still used to this day for the treatment of several ailments. The Report of World Health Organization (WHO) suggests that approx. 80% of the world's human population from developing countries depends mainly on traditional medicines for their primary health care. The natural products obtained from plants helped the health care section. Historically, corporate drug discovery depends on indigenous knowledge that is profitably deliberated to modern science through ethnobotany. Half of the modern prescribed medicines are of plant's origin and continue to be an ideal source of effective therapeutic compounds (Cragg and Newman, 1999). Various substances available in mangrove woods are mainly used as ethno-pharmaceuticals in traditional medicines (Uthoff, 1996). Several species of mangroves are used as ethno medicines for treatment of several diseases (Table 1). Pounded or pulverized, as extracts, infusions, juices, baths and inhalers, tree bark, roots, leaves, seed resin and heartwood of individual mangrove species are generally used as remedies especially for treating wounds along with their anti-inflammatory, homeostatic, wound-cleansing and antiseptic properties and

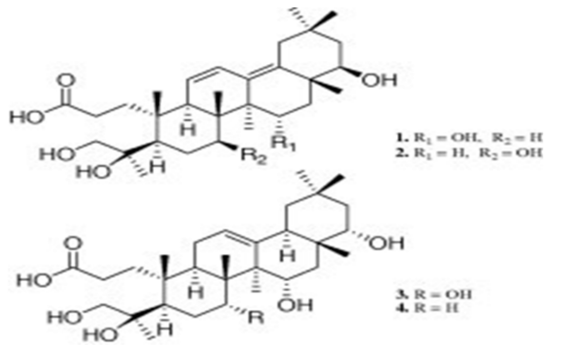

Fig. 1: structure of A-seco-oleane-type triterpenes (Li *et al*., 2008)

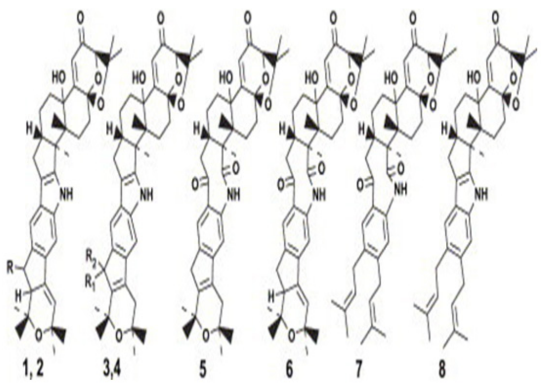

Fig. 2: structure of Indole triterpenes (Xu *et al*., 2007)

also against chronic illnesses. Occasionally leaves (*Excoecaria agallocha*) along with seeds (*Xylocarpus granatum*) are taken directly. Most of the ligneous plants occurring in the mangroves can be classified with certainty as medicinal plants. However, many of these medicinal properties of the mangroves have not been evaluated for pharmaceutical analysis. Moreover, organic extract of mangroves species like, *Aglaia cucullata*, *Aegiceras corniculatum*, *Cynometra iripa* and *Aegialitis rotundifolia* exhibit species-specific activity in resisting the growth and development of six virulent bacterial strains that are highly infectious to fish i.e., *Pseudomonas fluorescens, Vibrio alginolyticus*, *Edwardsiella tarda*, *Aeromonas hydrophila* and *P. aeruginosa* (Choudhury *et al.,* 2005). Fijian *Rhizophora* (red mangroves) has been widely used as primary traditional treatment for the common cold and related symptoms. The extract of *Rhizophora* also reported to have antimicrobial and antiviral compounds (Premanathan *et al.,* 1999; Hernandez *et al.,* 1978). Recently, Premanathan *et al.* (1999) reported that A polysaccharide from the leaf of *R. apiculata* (designated as RAP) provide resistance against SIV or HIV-2 or HIV-1 strains in numerous cell cultures and assay systems.

Fungal Endophytes

Fungal endophytes are quite important group of plant symbionts however; a vast number of them remained unexplored and unstudied. They are the group of fungi living within healthy plant tissue asymptomatically or systematically with no visible injuries to the host (Caroll, 1988; Bills, 1996). More research are conducted on fungal endophytes compared to bacterial endophytes and their diversity among various plant groups is considerably huge. The first reported fungal endophyte was derived from grasses (*Lolium temulentum* L.) and trees (*Picea canadiensis)*. Since then, many studies clear the presence of fungal endophytes in bark, xylem, stem, twigs and leaves of every plant species investigated so far (Petrini 1986; Redlin and Carris, 1996). Fungal endophytes are studied in ferns, grasses, trees, and shrubs, showing that even individual species of plant harbor numerous fungal species (Fisher and Petrini, 1990). It is believed hypothetically that about 1.5 million species of fungi are present on earth; about 70,000 (5%) of the total are studied and 1.43 million (95%) remain unstudied. This number would be expected to be much larger if fungal endophytes are taken into consideration. Despite their spectacular abundance of diversity in the woody plants, their interaction with the host plants captures less recognition than that of the grass endophytes (Saikkonen *et al.,* 1998). Some studies on the relative abundance, colonization and species composition of the endophytes of tropical plants have indicated their continuous presence in numerous shrubs and trees (Tejesvi *et al*., 2005; Raviraja, 2005). Endophytes in tropical forests may contribute to some extent to fungal diversity and shape the dynamics of plant communities (Hawksworth, 2001). Among millions of plants species on the planet, only a few of them and their endophytic microflora are studied so far (Strobel, 2002). Therefore, the opportunity of finding new and important endophytic microbes within the myriad of the world's plant is great. Many works are carried out regarding the vital roles of endophytes obtained from the host plants that indicated their ability to stimulate growth, disease resistance, withstand adverse environmental conditions, and recycle nutrients (Sturz and Nowak, 2000). They are also identified as an ideal source of biologically active metabolites (Strobel and Daisy, 2003; Tan and Zou, 2001) of limitless importance. At present, fungal endophytes are thoroughly studied from medicinal plants because of the facts that these plants harbor some potent microbes that imitate the chemistry of their host plants and produce the same natural bioactive products or its derivatives that are more active natured and effective than those of their host. Strobel and Daisy (2003) reported that plants surviving and growing specific to some location with distinct environmental condition also having distinct ethnomedicinal uses. Some important endemic locations should be studied as they expect to harbor novel endophytic microbes producing prominent metabolites with diverse applications. In recent years, numerous fungal endophytes were reported from medicinal plants and these endophytes were evident to produce many important bioactive metabolites of agricultural, industrial and pharmaceutical importance. There are certain advantages in studying the associated fungal endophytes of medicinal plants:

- The associated fungal endophytes may produce the same bioactive molecules as the host plant. Moreover extraction of bioactive compounds from plants origin is a rather difficult and complicated procedure compared to that of microbial origin.
- If microbial origin of bioactive substance would be available it would eliminate the need to harvest, extract and amount of the substance from the plants as the compound would conceivably be produce by fermentation and price of the drug would be highly reduced.

- Exploitation of rare and endanger medicinal plants would be reduced and gene pool of those plants could be conserved, as microbial sources of the drug obtained from those plants would be available.
- A biotechnological approach could be made on the microbes. The microbes could be manipulated and molecular studies can be done. Attempts could be made to enhance the activity and production of the metabolites by genetic engineering techniques.

Many species of mangrove forests are used as ethno medicines for the treatment of various diseases. Some of the species of mangroves are also reported to have antimicrobial and antiviral properties. However, evaluation for bioactive metabolites of the fungal endophytes in association with these mangroves is still under-explored. Therefore, studying fungal endophytes of some medicinal mangroves' might leads to the discovery of some interesting endophytic strain that may produce important and novel bioactive metabolites useful for the mankind.

Some Bioactive Metabolites from Mangrove Endophytes

Several fungal endophytes established within mangroves have been isolated and reported. Some of these endophytes have been shown to produce important bioactive metabolites. Suryanarayanan *et al*., (1998) have studied fungal endophytes from the leaves of *Rhizophora mucronata* and *Rhizophora apiculata* during different seasons. They reported that the leaves were colonized by fungal endophytes like *Sporormiella minima, Acremonium* sp. and (MG90) sterile fungus. Similarly, Ananda and Sridhar (2002) studied endophytic fungi from four mangrove species of west coast of India where they found *Mycocentrospora acerina* and *Triscelophorus acuminatus* as endophytes. An endophytic fungus, identified as *Phomopsis* sp. derived from a plant of mangrove i.e., *Hibiscus tiliaceus* yield four active biological compound named as 3,4-*seco*-olean-11,13-dien-4,7β,22β,24-tetraol-3-oic acid (1), 3,4-*seco*-olean-13-en-4,7,15,22,24-pentaol-3-oic acid(2), 3,4-*seco*-olean-11, 13-dien-4,15α, 22β, 24-tetraol-3oic acid (3), and 3,4-*seco*-olean-13-en-4,15,22,24-tetraol-3-oicacid (4)(Li et al, 2008) (Fig. 1).

Another endophytic fungus, named as *Penicillium* sp. (strainHK10459) was isolated from a mangrove species, *Aegiceras corniculatum* and eight new bioactive compounds of indole triterpenes identified as shearinines D–K (1–8), paspaline (9), shearinine A (10) and paspalitrem A (11) (Xu *et al.,* 2007) (Fig. 2) was derived from the fungal endophyte. These compounds have biological activity as well as blocking activities on the large-conductance of calcium-activated potassium channels.

Another interesting metabolite obtained from a fungal endophyte are the finding of two cyclic peptides from *Castaniopsis fissa*, a mangroves species of South China Sea (Yin *et al.,* 2005) (Fig. 3). Two cyclotetrapeptides, one (1) and two (2), derived and their chemical structures were made clearly visible by analyzing the spectroscopic data and chiral HPLC experiments. 1 is a new compound, while 2 was a known one.

Several other fungal endophytes those were isolated from different mangroves species produced novel metabolites with promising biological activity. A fungal endophyte derived from a mangrove located in the sea coast of South China that yield

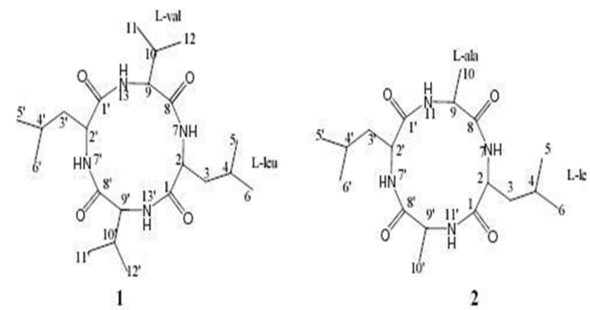

Fig. 3: Structure of compounds 1 & 2 (Cyclic peptide) Yin *et al*., 2005

a new isocoumarin compound characterized as 3,4 dihydro-6-methoxy-8-hydroxy 3,4,5 trimethylisocoumarin seven carboxylic acid methyl esters. This compound had cytotoxic properties against the Hep-G2 and Hep-2 cells (Huang *et al.,* 2007). From the mangrove of the same Seacoast, two endophytic fungi are isolated that are able to produce a biological active compound designated as Marinamide (Feng and Yongcheng, 2006). Similarly, a fungal endophyte, identified as *Xylaria* sp.2508 isolated from a species of mangrove, produced another biologically active compound named Xyloketals. Besides fungal endophytes, other microorganisms like bacteria, yeast, and actinomycetes may also closely associate with the mangroves and might produce important bioactive metabolites. However, limited investigations have been performed in this regard. For example, streptomyces, an endophytic bacteria isolated from a mangroves plant i.e., *Aegiceras comiculatum*, yielded active metabolites named cyclopentenone derivatives. Such discoveries reinforced that fungal endophytes harboring within the tissues of mangroves could be new source of important and potent bioactive metabolites. Further, these endophytes also produce new and interesting compounds, which could be even more useful as lead to other compounds.

Conclusion

The woody plant body of Mangroves has great ecological, economic and biological significance. The ecosystem of mangrove has a unique environment that harbors diverse groups of microorganisms that are either under explored or unexplored. This gives us an opportunity to discover new and potent microbial strains. Moreover, they are highly adapted to withstand extreme environments; the microorganisms colonizing the inner tissue of those mangrove plants are also subjected to such extreme habitats and are therefore often called extremophiles. During the past decades, these extremophiles have attracted the major focus of extensive and intensive research due to the potential biotechnological application associated with these microbes and their products. Although fungal endophytes are quite important, they remain relatively unstudied and unexplored. A few of these endophytes colonizing mangroves produce important bioactive metabolites. Several investigations suggest that endophytes colonizing different plants with medicinal properties can produce important and interesting metabolites. Therefore, if the microbial diversity of the mangrove plants is found to have medicinal values, more research could be focused on the study of endophytes associated with the mangroves to discover new and potent bioactive metabolites of pharmaceutical, industrial and agricultural importance. However, the population of mangroves is declining very rapidly throughout the globe due to over-exploitation and other biotic interference in mangrove forests. It is high time to conduct more studies on microbial diversity in general and endophytic fungi related to medicinal mangroves in particular may be taken up because once such a plant gets lost or extinct so does the entire suite of associated endophytes and bio-active metabolites.

Acknowledgement

I would like to acknowledge and give my warmest thanks to my Supervisor (Kumananda Tayung) whose necessary suggestions and advices helped me write this review in proper order. His guidance has carried me through all the stages of writing my review article. I would also like to thank Fatima Siddiqua for her brilliant comments and suggestions that helped me improve my writing ability. I am also grateful to her for critically revising and drafting the manuscript.

Finally, I would like to thank God, for letting me through all the difficulties. I will keep on trusting God for my future endeavours.

Author's Contributions

Collection of data on bioactive metabolites of microbes associated with Mangrove was done by Sushmita Paul. The review article was written by Sushmita Paul. Drafting and critical revision of the manuscript was done by Fatima Siddiqua. The entire design and concept of this review article was supervised by Kumananda Tayung.

Conflict of Interest

None.

References

Ananda, K., & Sridhar, K. R. (2002). Diversity of endophytic fungi in the roots of mangrove species on the west coast of India. *Canadian Journal of Microbiology,* 48(10), 871-878. doi: 10.1139/w02-080

Ananda Rao, T. (1998). Flowering phenology and pollination of the eumangroves and their associates to plan regeneration and breeding programmes. *Journal of Economic Taxonomy and Botany,* 22, 19-27.

Bills, G. F. (1996). Isolation and analysis of endophytic fungal communities from woody plants. *In: Systematics, Ecology and Evolution of Endophytic Fungi in Grasses and Woody Plants. S. Redlin and L. M. Carris, eds. APS Press, St. Paul, MN*, pp. 31-65.

Caroll, G. C. (1988). Fungal endophytes in stems and leaves: from latent pathogen to mutualistic symbionts. *Ecology,* 69, 2-9.

Chandrika, V., Nair, P. V. R., & Khambhadkar, L.R. (1990). Distribution of phototrophic thionic bacteria in the anaerobic and micro-aerophilic strata of mangrove ecosystem of Cochin. *Journal of Marine Biological Association of India,* 32(1-2), 77-84.

Chinnaraj, S. (1993)(a). Higher marine fungi from mangroves of Andaman and Nicobar Islands. *Sydowia,* 45(1), 109- 115.

Chinnaraj, S. (1993)(b). Manglicolous fungi from atolls of Maldives, Indian Ocean. *Indian Journal of Marine Sciences,* 22(2), 141-142.

Chitnis, V., Chitnis, D., Patil, S., & Kant, R. (2000). Hospital effluent: a source of multiple drug-resistant bacteria. *Current Science*, 79(7), 989-991.

Choudhury, S., Sree, A., Mukhurjee, S.C., Pattnaik, P., & Bapuji, M. (2005). In Vitro Antibacterial Activity of Extracts of Selected Marine Algae and Mangroves against Fish Pathogens . *Asian Fisheries Science,* 18, 285-294.

Cragg, G.M., & Newman, D.J. (1999). Discovery and development of antineoplastic agents
from natural sources. *Cancer Invest,* 17(2),153–163.

Daleyi, C. L. (2002). Transmission of multidrug-resistant tuberculosis limited by man or nature? *American Journal of Respiratory and Critical Care Medicine,* 165(6), 742-743. doi: 10.1164/ajrccm.165.6.2202007b.

Feng, Z., & Yongcheng, L. (2006). Marinamide, a novel alkaloid and its methyl ester produced by the application of mixed fermentation technique to two mangrove endophytic fungi from the South China Sea. *Chinese Science Bulletin* , 51, 1426-1430. https://doi.org/10.1007/ s11434-006-1426-4

Fisher, P.J., & Petrini, O. (1990). Comparative study of fungal endophytes in xylem and bark of Alnus species in England (UK) and Switzerland. *Mycological Research*, 94(3), 313-319. https://doi.org/10.1016/S0953-7562 (09)80356-0.

Harris, J.M. (1993). Widespread occurrence of extensive epimural rod bacteria in the hindguts of marine Thalassinidae and Brachyura (Crustacea: Decapoda). *Marine Biology,* 116(4), 615-629. https://doi.org/10.1007/ BF00355480

Hawksworth, D.L. (1991). The fungal dimension of biodiversity: Magnitude, significance, and conservation. *Mycological Research,* 95(6), 641-655. https:// doi.org/10.1016/S0953-7562 (09)80810-1.

Hayes, J.R., English, L.L., Carr, L.E., Wagner, D.D., & Josephi, S.W. (2004). Multipleantibiotic resistance of Enterococcus spp. isolated from commercial poultry production environments. *Applied and Environmental Microbiology,* 70(10), 6005-6011. doi: 10.1128/AEM.70.10.6005-6011.2004.

Huang, Z., Shao, C., Chen, Y., She, Z., Lin, Y., & Zhou, S. (2007). A new isocoumarin from mangrove endophytic fungus (No. dz17) on the South China Sea coast. *Chemistry of Natural Compounds,* 43, 655-658. https://doi.org/10.1007/ s10600-007-0221-z.

Hyde, K.D. (1990)(a). A comparison of the intertidal mycota of five mangrove tree species. *Asian Marine Biology,* 7, 93-108.

Kannan, L., & Vasantha, K. (1992). Microphytoplankton of the Pichavaram mangals, southeast coast of India: Species composition and population density. *Hydrobiologia* , 247, 77-86. doi:10.1007/BF00008206.

Kathiresan, K. & Bingham, B.L. (2001). Biology of mangroves and mangroves ecosystems. *Advances in Marine Biology,* 40, 81-251. http://dx.doi. org/10.1016/S0065-2881 (01)40003-4

Krishnamurthy, K., Choudhury, A., & Untawale, A.G. (1987). Status report – Mangroves in India. Ministry of Environment and Forests, Government of India, New Delhi.

Lee, S.Y. (1990). Primary productivity and particulate organic matter flow in an estuarine mangrove-wetland in Hong Kong. *Marine Biology,* 106, 453-463. http://dx.doi.org/10.1007/BF01344326.

Lange, L. (1996). Microbial metabolites- an infinite source of novel chemistry. *Pure and Applied Chemistry,* 68(3), 745-748. https://doi.org/10.1351/ pac199668030745.

Li, L., Sattler, I., Deng, Z., Groth, I,, Walther, G., Menzel K.D., Peschel, G., Grabley, S., & Lin, W. A-seco-oleane-type triterpenes from *Phomopsis* sp. (strain HKI0458) isolated from the mangrove plant Hibiscus tiliaceus. *Phytochemistry,* 69(2), 511-517. doi: 10.1016/j. phytochem.2007.08.010.

Liu, X., Xu, F., Zhang, Y., Liu, L., Huang, H., Cai, X., Lin, Y., & Chan, W. (2006). Xyloketal H from the mangrove endophytic fungus Xylaria sp. 2508. *Russian Chemical Bulletin,* 55, 1091-1092. https://doi.org/10.1007/ s11172-006-0383-z

Mohanraju, R., & Natarajan, R. (1992). Methanogenic bacteria in mangrove sediments. *Hydrobiologia,* 247, 187-193. https://doi.org/10.1007/ BF00008218.

Pal, A.K., & Purkayastha, R.P. (1992)(b). New parasitic fungi from Indian mangrove. *Journal of Mycopathological Research,* 30(2), 173-176.

Panchanadikar, V.V. (1993). Studies of iron bacteria from a mangrove ecosystem in Goa and Konkan. *International Journal of Environmental Studies,* 45(1), 17-21. https://doi.org/10.1080/00207239308710874.

Pedroche, F.F., West, J.A., Zuccarello, G.C., Senties, A.G., & Karsten, U (1995). Marine red algae of the mangroves in southern Pacific Mexico and Pacific Guatemala. *Botanica Marina,* 38(2), 111-119.

Phang, S.M., Shaharuddin, S., Noraishah, H., & Sasekumar, A.(1996). Studies on *Gracilaria changii* (Gracilariales: Rhodophyta) from Malaysian mangroves. *Hydrobiologia,* 326-327, 347-352.

Premanathan, N., Kathiresan, K., Yamamoto, N., & Nakashima, H. (1999). In-vitro anti-human immunodeficiency virus activity of polysaccharide from *Rhizophora mucronata* poir, *Biosci, Biotechnol, Biochem,* 63, 1187-91. doi: 10.1271/bbb.63.1187.

Petrini, O. (1986). Taxonomy of endophytic fungi of aerial plant tissues. *In: Microbiology of the Phyllosphere. N. J. Fokkema and J. van den Heuvel, eds. Cambridge University Press*, *Cambridge,* pp. 175-187.

Ramamurthy, T., Raju, R.M., & Natarajan, R. (1990). Distribution and ecology of methanogenic bacteria in mangrove sediments of Pitchavaram, east coast of India. *Indian Journal of Marine Sciences,* 19(4), 269-273.

Ravikumar, S. (1995). Nitrogen-fixing azotobacters from the mangrove habitat and their utility as bio-fertilizers. Ph.D. thesis., Annamalai University, India, pp.120.

Ravikumar, D.R., & Vittal, B.P.R. (1996). Fungal diversity on decomposing biomass of mangrove plant Rhizophora in Pichavaram estuary, east coast of India. *Indian Journal of Marine Sciences,* 25 (2), 142-144.

Raviraja, N.S. (2005). Fungal endophytes in five medicinal plant species from Kudremukh Range, Western Ghats of India. *J. Basic Microbiology,* 45(3), 230-235. doi: 10.1002/jobm.200410514.

Redlin, S.C., & Carris, L.M. (1996). Endophytic fungi in grasses and woody plants: systematics, ecology and evolution. APS Press, St. Paul, MN, USA.

Robertson, A. I., & Blaber, S. J. M. (1992). Plankton, epibenthos and fish communities. *In Tropical Mangrove Ecosystem (A.I. Robertson and D.M. Alongi, eds)., American Geophysical Union*, Washington DC, USA, pp. 173-224. https://doi.org/10.1029/CE041p0173

Rojas Hernandez, N.M., & Coto Perez, O. 1978. Antimicrobial properties of extracts from Rhizophora mangle, Rev. *Cubana Med Trop*, 30(3),181-

Samal, R.C., & Patnaik, J. M. (1989). Management strategies for Bhitarkanika mangroves forest in INDO-US workshop on wetlands, mangroves and Biosphere reserve: Government of India, Ministry of Env. And Forest, New Delhi, pp. 96-99.

Santra, S.C., Pal, U.C., & Choudhury A. (1991). Marine phytoplankton of the mangrove delta region of West Bengal. *Journal of Marine Biological Association of India,* 33(1- 2), 292-307.

Saikkonen, K., Faeth, S.H., Helander, M., & Sullivan, T.J. (1998). Fungal endophytes: A continuum of interactions with host plants. *Annual Review of Ecology and Systematics,* 29, 319–343.

Sengupta, A., & Choudhuri, S. (1990). Halotolerant Rhizobium strains from mangrove swamps of the Ganges River Delta. *Indian Journal of Microbiology,* 30(4), 483-484.

Sengupta, A., & Choudhuri, S. (1994). A typical root endophytic fungi of mangrove plant community of Sunderban and their possible significance as mycorrhiza. *Journal of Mycopathological Research,* 32(1), 29-39.

Sherman, R. E., Fahey, T.J., & Howarth, R.W. (1998). Soil-plant interactions in a neotropical mangrove forest: Iron, phosphorus and sulfur dynamics. *Oecologia,* 115(4),553-563.

Sheridan, R.P. (1991). Epicaulous, nitrogen-fixing microepiphytes in a tropical mangal community, Guadeloupe, French West Indies. *Biotropica*, 23 (4b), 530-541. https://doi.org/10.2307/2388391

Sivakumar, A. & Kathiresan, K. (1990). Phylloplane fungi from mangroves.*Indian Journal of Microbiology,* 30(2), 229-231.

Suryanarayanan, T.S., Kumaresan, V., & Johnson, J.A. (1998). Foliar fungal endophytes from two species of the mangrove Rhizophora. *Canadian Journal of Microbiol*ogy, 44(10), 1003-1006. https://doi.org/10.1139/ w98-087.

Swartz, M.N. (2000). Minireview: impact of antimicrobial agents and chemotherapy from 1972 to 1998. *Antimicrobial Agents and Chemotherapy,* 44(8), 2009-2016. doi: 10.1128/AAC.44.8.2009-2016.2000.

Strobel, G.A. (2002). Microbial gifts of rain forests, *Canadian Journal of Plant Pathology,* 24(1), 14-20. https://doi.org/10.1080/07060660109506965

Strobel, G.A., & Daisy, B. (2003). Bioprospecting for Microbial Endophytes and Their Natural Products, *Microbiology and Molecular Biology Reviews,* 67(4), 491-502. doi: 10.1128/MMBR.67.4.491-502.2003

Sturz, A.V., & Nowak, J. (2000). Endophytic communities of Rhizobacteria and the strategies required to create yield enhancing associations with crops. *Applied Soil Ecology,* 15(2), 183–190.

Tan, T.K., & Pek, C.L. (1997). Tropical mangrove leaf litter fungi in Singapore with an emphasis on Halophytophthora. *Mycological Research*, 101(2), 165-168. https://doi.org/10.1017/S0953756296002250

Tan, T.K., & Leong, W.F. (1992). Lignicolous fungi of tropical mangrove wood. *Mycological Research,* 96(6), 413-414.

Tan, R.X., & Zou, W.X. (2001). Endophytes: a rich source of functional metabolite. *Nat. Prod. Rep.* 18(4): 448-459. doi: 10.1039/b100918o.

Tejesvi, M.V., Mahesh, B., Nalini, M.S., Prakash, H.S., Kini, K.R., Subbiah, V., & Shetty, H.S. (2005). Endophytic fungal assemblages from inner bark and twig of *Terminalia arjuna* W. & A. (Combretaceae). *World Journal of Microbiology & Biotechnology,* 21, 1535-1540. https://doi. org/10.1007/s11274-005-7579-5

Uthoff, D. (1996). From Traditional use of total destruction- Forms and extent of economic utilization in the Southeast Asian mangroves. *In: Natural Resources and Development,* 43/44, 58-94.

Vicari, M. (1997). Endophytic Fungi in Grasses and Woody Plants, eds S. C. Redlin & L. M. Carris. 223 pp. St Paul, Minnesota: APS Press (1996). *The Journal of Agricultural Science, 128*, 123 - 126. https://doi. org/10.1017/ S0021859696233982.

West, J.A. (1991) (a). New algal records from the Singapore mangroves. *Gardens Bulletin,* 43, 19-21.

West, J.A. (1991) (b). New records of marine algae from Peru. *Botanica Marina,* 34(5), 459- 464.

Xu, M., Gessner, G., Groth, I., Lange, C., Christner, A., Bruhn, T., Deng, Z., & Li, X. (2007). Shearinines D–K, new indole triterpenoids from an endophytic *Penicillium* sp. (strain HKI0459) with blocking activity on large- conductance calcium-activated potassium channels. *Tetrahedron,* 63(2), 435-444. https://doi. org/10.1016/j.tet.2006.10.050.

Yin, W.Q., Ziu, J.M., She, Z.G., Vrijmoed, L.L.P., Gareth Jones, E.B., & Lin, Y.C. (2005). Two Cyclic Peptides Produced by the Endophytic Fungus # 2221 from *Castaniopsis fissa* on the South China Sea Coast. *Chinese Chemical Letters,* 16, 219-222.