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ENDOPHYTIC FUNGI: BIODIVERSITY AND FUNCTIONS

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ABSTRACT

Fungal endophytes are broad spectrum microorganisms which colonizes the plants without causing any symptoms. They occur ubiquitously in all plants, including a wide range of hosts in ecosystems. During the course of co-evolution, a mutualistic relationship occurs between endophytes and their host plant. Their population is influenced by location and climatic condition of host. In recent years remarkable attention is given to their ability to produce useful bioactive compounds for plant growth, protection and their sustenance in certain hostile condition. The present review focuses on the diversity, classification and beneficial roles of fungal endophytes and their significance on host plants and the future applications.

KEYWORDS: Endophytic fungi, biodiversity; co-evolution relations, plant inhabitants, fungal metabolites, biological activities.

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INTRODUCTION

Fungi are one of the important components of ecosystem, closely associated with essential processes i.e. recycling, decomposition and transportation of nutrients in different type of environments. This is estimated that there are millions of fungal species present on earth, from which only 5% have been identified for its role[1]. Recent studies showed the ubiquity fungi, approx. 1 million species of endophytic fungi inhabit the plants [2]. Microbes which resides in any part of the plant cells especially root, stem and leaves, spent at least one period of life cycle and shows no apparent symptoms to the host called as endophytes [3]. The “endophyte” term given by De Bary and defined by Petrini [4] .i.e. “all microbes which inhabits the plant organs and colonize the living, inter and/or intracellular tissues of host plant below the layer of epidermis without causing any symptomatic effect on plant’. Earlier endophytes were considered as neutral but later it was recognized as a beneficial for plants by that time it also shows the good result in phytoprotection against pathogens and predators. Plants serve as a large reservoir of microbes known as endophytes [5]. Host plant roots are infected or colonized by many fungal species it could be endophytic or mycorrhizal. The fungal endophyte lives inside the plant tissue without showing any symptoms in host [6, 7]. Host endophyte relationship is different from mycorrhizal association in three aspects which are lacking: absence of cellular interface, no synchronized growth between host and endophytes, no significant benefits between both the partners [8]. The best known root endophytic fungi are dark septate endophytes (DSE) and colonize the hyphae by producing melanin [9]. The impact of root endophytic fungi colonization on plants ranges from negative [10] to positive [11, 12]. Positive response includes plant growth promotion *via* mineralization of nutrient [11, 13] and by production of phytohormones [7, 14].

Occurrence and biodiversity of fungal endophytes

Endophytic fungi are crucial, quantifiable and integral component of fungal biodiversity, and influenced by community diversity of plants and its structure [15, 16]. Endophyte represents the wide range of microbial diversity and adaptation which developed in unusual and sequestered habitats. Their diversity and functional habituation makes a new and exciting area of research for novel drug or medicine. Endophytes fungi influence the ecology, distribuition, biochemistry and physiology of the host plant [17]. Darwin (1872) suggested that diversity affects the ecosystem processes [18]. Many theories reported the functions of diversity which includes the increase in primary productivity [19], nutrient flow [20], nutrient retention [21], water availability and pathogen resistance [22]. Fungal endophytic diversity depends not only on the host specificity, but also the types of benefits that they provide to the host plant [5]. Several fungal endophytes are isolated from all variety of plants and it ranges from large trees [23, 15] to lichen [24]. Most of the endophytes are ascomycetes and basidiomycetes [25]. The isolation of fungal endophytes and rate of colonization from plant to plant varies. Mainly medicinal plants harbor more fungal endophytic than others. Some of the fungal endophytes are common in many plant hosts and some are very specific to their host plant [26, 27]. Tropical plant contains a great diversity of fungal endophytes and many of them are unidentified and possibly belong to the new genera and species and some of them having potential biotechnological importance as a pharmaceutical active compound, biological control agents, secondary metabolites, and other benefits could be found by exploration of tropical fungal endophytes. Dreyfuss and Petrini, (1984) isolated and screened endophytic fungi from plants of family araceae, bromiliaceae from South America [28]. Rodrigues and Samuels isolated, eleven species of endophytic fungi from a palm tree in Queensland, Australia and got one novel species i.e. *Idriella licualne*. Other most occurring endophytic fungi are Xylariaceous fungi [29]. Previous studies also reported that [30] isolated eighty one endophytic fungi with fifteen Xylaria species from *Euterpe oleracea*. Ascomycocetes and Deuteromycetes were frequently isolated with *Letendraeopsis palmarum* and *Xylaria cubensis* are the most occurring endophytes. Silva (1997) found 17 different taxa of endophytic fungi in roots, stems, leaves and seeds of maize, with unidentified yeast, sterile mycelia and filamentous fungi [31]. It also colonizes grasses, marine algae, ferns and mosses [32]. Endophytes presents in all organs of a host plant [33]. Endophytes can transfer from one plant to other via seeds [34]. Plant roots possess the characteristic assemblage with fungal endophytes which are different from above ground plant tissues [35, 36]. Root endophytic fungi serve as a significant component of below ground microbes associated with plant root and as important as mycorrhizal fungi [9, 37]. Boreal trees mainly harbor the fungal root endophytes which includes the species of, *Oidiodendron* [38], *Cryptosporiopsis* [39], *Rhizoscyphusericae* aggregate" (Helotiaceae) [40] *Umbelopsis* [41], and *Phialocephala fortinii*, members of dark septate endophtes" with melanized hyphae. Endophytes are found ubiquitously in nature and their hosts are from wide range of families, orders, genus and species [42, 43, 44].

Other fungal root endophytes

Several fungal endophytes are recovered from roots of *Alnus* species in Europe. These include *Heliscus lugdunensis*, *Tricladium splendens*, *Lunulospora curvula*, and *Varicosporium elodeae* [45]. *Campylospora parvula* is isolated from the submerged aquatic roots *of Lyonia ovalifolia* [46] and *Alnus glutinosa* [47]. Eleven aquatic hyphomycete species were isolated from submerged roots of *Picea glauca* [48, 49]. *Penicillium* species have been reported as root endophytes in *Picea mariana* [36]. *Penicillium nodositatum* and *Penicillium janczewskii* have been found associated with the roots of *Alnus incana* and *A. glutinosa* respectively [50]. Many *Fusarium* species have been isolated from the plants belonging to family Leguminosae [51] and roots of many vegetables. The most dominant among all is endophytic *F. oxysporum* and *F. solani* [52]. They also have reported from the roots of *Holtuslanatus,* a type of grass that grows in humid water logged soils [53], *Oryza sativa* [54] and *Oryza granulate* [55] and Rhizophoraceae mangrove trees [56]. Many *Fusarium* species are plant pathogenic but it has been reported *F. graminearum, F. nivale* and *F. culmorum* [57], and *F. crookswellense* [58] causes symptomless infections with other plants [59]. Thus, the root of *Axonopus compressus* provides an ecological niche to *F. oxysporum* and many other *Fusarium* species. *Fusarium* species isolated from cultivated rice roots has been proved to be an effective biocontrol agent against root knot nematode. Root endophytic fungi reported from orchids and aquatic hypomycetes submerged in freshwater are listed in Table 1.

Table 1
Root endophytic fungi reported from orchid roots, aquatic hypomycetes submerged roots and mangroves

Fungi	Substate	References
Orchids		
Phialocephala fortinni	*Amerorchis rotundifolia*	60
Fusarium spp	*Cypripedium reginae*	61
Russulaceae (22 species)	*Corallorhiza mertensiana*	62
Thelephora-tomentella	*Corallorhiza trifida*	63
Acremonium, Colletotrichum, Fusarium, Guignardia, Humicola, Pestalotia, Phomposis, Trichoderma, Xylaria	*Lepanthes rupestris*	64
Submerged roots		
Mycocentrospora acerina	*Avicennia officinalis*	65
Triscelophorus acuminatus	*Rhizophora mucronata*	65
Lunulospora curvula Ingold	*Angiopteris evecta*	66
Anguillospora filiformis Greath	*Acer spicatum*	66; 49
Mangroves		
Aureobasidium sp., *Fusarium solani, Massarina* sp., *Penicillium pinophilum*	*Ceriops tagal*	56
Cladosporium cladosorioides, Aureobasidium	*Rhizophora stylosa*	56
Fusarium solani, Massarina sp, *Pestalotiopsis clavispora*	*Rhizophora apiculata*	56
Pestalotiops isoxyanthi, *Cladosporium cladosorioides, Aspergillus tubinegensis*	*Brugiera sexangula var. rhynchopetala*	56

Relationship between endophytic fungi and host Plant

Studies on the relationship between endophytic fungi and their host plant helps to understand the ecology and evolution of endophytic fungi plant symbiosis. Ecological factors affect the strength and direction of symbiotic interaction between them [6]. The association between host plant and endophytic fungi variety of relationships co-exists which ranges from symbiosis or mutualism to antagonism [7, 67, 44]. The host-endophyte relationships depend upon the many factors, host-recurrence [68], host-specificity, host preference [69] or host-selectivity [70]. These fungal endophytes adapt themselves in plants with different mechanisms [71]. In order to maintain a symbiotic interaction these endophytes produces a metabolites for plant growth promotion [72, 73]. In host-specificity relationship endophytes are restricted to one host plant or group of related plant species, which implies the occurrence of complex biochemical interaction between endophytes and its host [74, 75]. Some host-specific strain has morphologically indistinguishable features with different physiological traits [4]. For example *Pestalotiopsis microspora* is the commonly found fungal endophytes in species of *Taxa* (yews). Bio-chemical interaction between endophyte and its host plants raising tremendous variability between fungal endophytes, by genetic crossing, mutation, unsubstantiated mechanisms like developing genetic system which allows the transfer of information between host plants and themselves [32, 76]. Some endophytic fungi are reported as single host specificity for the plants which are also affected by microclimatic and microhabitat conditions [77, 78, 79]. But some are there which has wide host range like genera of *Phoma*, *Phomopsis*, *Phyllosticta* and *Colletotrichum*, colonizes the host plant [80, 81, 82]. Endophytic fungi also exhibit the tissue and organ specificity because of their adaptation in different physiological conditions in host plants [83]. Some selective pressures occur in plant tissue which affects the endophytic inhabitants. Therefore, different endophytic fungi are dominated in particular tissue and forming specific characteristic communities [67, 84]. Comparisons between the community of endophytes of foliar and root showed small overlap [85, 42].

Classification of endophytes

In natural ecosystems plants are symbiotically associated with fungal endophytes and a fossil record also indicates symbiotic relationship [16]. The endophytic colonization plays the important role in evolution of life. Mycorrhizal fungi colonize the plant roots grow in rhizosphric zone of plants but endophytic fungi resides within plant tissues and grow and sporulate within plant roots [86].

Class 1 Clavicipitaceous endophytes

C-endophytes (Class 1 endophytes) group of organisms that is phylogenetically related clavicipitaceous species that grows fastidiously in culture and limited to extreme conditions. The Clavicipitaceae (Ascomycota) includes free living and symbiotic species that is associated with fungi and insects (e.g. *Cordyceps* sp.) or grasses (e.g. *Balansia* sp., *Epichloë* sp., *Claviceps* sp.) [5]. This lineage includes plant pathogens, endophytes many of them also produces the bioactive metabolites. Class 1 endophytes transmitted vertically from maternal plants to offspring via seeds [87]. This class of fungus helps in increasing the plant biomass confers drought tolerance and production of toxin chemicals for animals and decreasing herbivory [88]. Moreover, these benefits depend upon the host species, genotype an environmental condition [89]. Clay and Schardl (2002) reported that three types of clavicipitaceous endophytes are there from symptomatic or pathogenic species (Type I) to mixed interaction (Type II) and asymptomatic endophytes (Type III) [90.] But type III C-endophytes are like the Non Clavicepteous endophytes as they in the plant tissues without causing any symptoms. These endophytes do not colonize root tissues but they enhance the host resistance by insect feeding [91, 92] anti nematode activity [93]. It also produces the compounds that inhibit the growth of other fungi for e.g. Yue et al. (2000) showed the production of indole derivatives, a diacetamide and a sequiterpene from *Epichloë festucae* [94].

Nonclavicipitaceous endophytes (NC)

These NC endophytes form the symbiosis with host plants, conferring fitness benefits like biotic and abiotic stress tolerance, enhance growth, yield and nutrient acquisition [95, 14, 96]. NC endophytes are further classified into three groups based on the life style, ecological interactions and other related traits. Class 1 endophyte promotes the ecophysiology of plant and confers the tolerance to abiotic stresses like drought and metal contamination [97].

Class 2 endophytes

This includes diverse groups of species and all belong to member of Dikarya (Ascomycota or Basidiomycota). Most of them are from ascomycota and lesser of basidiomycota. Class 2 endophytes differs from other group of NC endophytes because they colonize the roots, stem and leaves of host plants and form extensive interaction and transmitted via seed coats and rhizomes and confer habitat as well as nonhabitat adapted fitness advantages. In stress condition the colonization frequency increases to 90-100 %. These groups colonize the plants by forming appresoria or by direct penetration into host tissue *via* hyphae. Growth of endophytes is mainly intercellular with harming the host plant [98]. They are transmitted vertically *via* seed coats [99]. These endophytes also confer stress tolerance when they are present in symbiosis with host tissue e.g., *Curvularia protuberata* colonizes the tissue of geothermal plant *Dichanthelium lanuginosum* and in nonsymbiotic condition none of them tolerate the temperature stress above $40^{o}C$. With symbiosis association both the partners tolerate the stress for e.g. *Fusarium culmorum* colonizes the non-embryonic tissues of host plant dune grass (*Leymus mollis*) tolerates the seawater salinity (300–500 mM NaCl) but their growth retarded as they are separated from each other [96]. Class 2 endophytes not only protect the plant from adverse climatic condition but also enhance the root and shoot biomass of host plant due to induction of phytohormone by host or biosynthesis of hormone by endophytic fungi [100] protect host tissue from pathogens [101], secondary metabolites production [102], and systemic resistance [103]. Endophytic fungi i.e., *Fusarium oxysporum* and a *Cryptosporiopsis* sp. confer disease resistance from virulent pathogens in *Hordeum vulgare* and *Larix decidua*, respectively [102] and it is due to phenol concentration increases in host plants.

Abiotic stress (heat, salt and drought) induces the similar plant response including increased osmolyte production, altered water relations, production of signaling molecules such as abscisic acid and reactive oxygen species generation [104, 105]. Class 2 endophyte-colonized and noncolonized plants showed no significant correlation between osmolytes and symbiotically conferred stress tolerance [96]. Similar results were seen in drought tolerance condition where Class 2 endophyte-conferred drought tolerance does not increase osmotic potential as in drought stress osmotic potential increases in plants [96]. Although non-colonized plants showed no increase in osmotic potential under same stress but they wilt much earlier compared to symbiotic plant.

Class 3 endophytes

They are classified based on the occurrence, horizontal transmission; formations of highly localized infection and confer benefits, not habitat specific. It consists of hyper diverse group of endophytic fungus present in leaves of tropical trees [106]. This type of group of endophytes are member of Dikaryomycota (ascomycota or basidiomycota), reproduce by fragmentation of hyphae or by production of spores [107].

Class 4 endophytes

This group consists of pigmented brown to brackish colored fungus associated with plant roots. These sterile also called as mycelium radices atrovirens (MRA). They co-exist with mycorrhizal fungi and referred as pseudomycorrhizal fungi. Presently, these fungi called as dark septate endophytes (DSE). They are mainly ascomycetous fungi present as conidial or sterile form with melanised structure and associated with roots of shrubs, trees and conifers. Mandyam and Jumpponen (2005) reported that DSE symbiosis with roots provides multifunctional benefits in host growth; protect plants from pathogens by minimizing the availability of carbon sources in rhizosphere [9].

Functions of endophytes

Endophyte provides the protection to the host plant by producing the plethora of compounds. It is known as a chemical synthesizer in their host plants [108]. Bioactive natural metabolites produce by fungal endophytes has promising potential benefits in safety in plants as well as in human health [75, 74, 109]. The members of endophytic fungi are mainly from Ascomycota as well as some of Basidiomycota, Oomycota and Zygomycota [110], can produce many bioactive compounds [111, 112, 113, 114], promote host plant growth [115] and resistance to unfavourable environmental stress condition [116, 117] and decomposition of litter [44, 43]. Therefore, fungal endophytes are one of the important components of ecosystems and plays a key role in nutrient and energy recycle. Endophytic fungi confers the plants in many important ways like modification in physiological properties, resistance to stress condition and production of plant hormones and other metabolites of biotechnological interests i.e., enzymes and drugs. Besides, these economical importance endophytic fungi have become a good research topic for scientists, concerning the discovery and identification of new and unique microbial species.

a) Biological role of fungal endophytes

Fungal endophytes play various important roles with broad spectrum in host plants, human being and on environment. It is capable to synthesize the bioactive agents which can be used by host plants as a defense agent against pathogen, stimulation of plant growth and in the process of drug discovery.

1. Natural products

Diverse group of endophytic fungi is a rich source of important and novel bioactive metabolites promising applications in food industry [118], agricultural applications and drug discovery [119, 120, 121]. Large number of bioactive metabolites are extracted and characterized from fungal endophyte which includes flavonoids, alkaloids, terpenoids, steroids, polyketones, peptides, quinols, phenols and some chlorinated compounds [122, 32, 123]. Production of natural products from endophytic fungi adapts a very specific and unique function in nature therefore to explore the novel secondary molecules should focus on fungi which inhabit novel biotopes. Schulz et al. (2002) isolated and screened 6500 endophytic fungi from plants for biologically active metabolites and found positive correlation between bio-activity and biotope [124]. Medicinal plants are recognized as a good repository of endophytic fungi having capacity to produce the novel metabolites of unique structure with industrial importance [125, 126]. Some medicinal plants harbor the endophytic fungi which produces the secondary metabolites for eg. Anticancer drug taxol produces by the endophytic fungi of host plant *Taxus brevifolia*, *T. mairei*, *T. chinensis var. mairei*, *T. celebica*, and *T. wallachiana*, many scientists have done the research on this context [127, 128, 129]. Endophytic fungi are natural source of pesticides which provides resistance to the plants against pathogens [130].

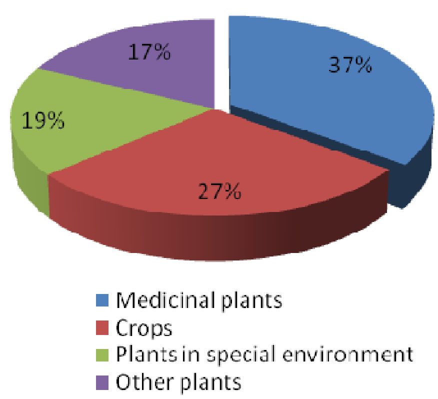

Figure 1
Distribution of bioactive endophytic fungi from different sources.

The relationship between host plants and endophytic fungi are mainly mutualistic to each other. Host plant supply easeful habitation and plenteous nutriment for the survival of fungal endophytes on other hand endophytes produces a variety of bioactive metabolites to benefits the host plant and increase its tolerance to biotic and abiotic stress condition [131, 132]. Some fungal endophyte has the ability to produce the same bioactive metabolites as their host plant produces and this is the beneficial to study the relation between plants and endophytes so that the demands of valuable bioactive metabolites and this can be replaced by plant derived products [133, 134]. Endophytic fungi produce the bioactive compounds such as podophyllotoxin, paclitaxel, vinblastine, camptothecine, diosgenin and hypericin which are also produce by their host.

Table 2
list of endophytic fungal metabolites showing antifungal activity

Endophytic fungi	Host plant	metabolite	Biological activity	References
Phomopsis sp.	*Gossypium hirsutum*	Epoxycytochalasin H , Cytochalasin N , Cytochalasin H	Antifungal	135
Penicillium vinaceum	*Crocus sativus*	(-)-(1R,4R)-1,4-(2,3)- indolmethane-1-methyl-2,4-dihydro-1H-pyrazino-[2,1-b]-quinazoline-3,6-dione	Antifungal and cytotoxic	136
Phoma sp.	*Arisaema erubescens*	b-sitosterol	Antifungal	137
Xylaria sp.	*Piper aduncun*	Dihydroisocoumarins	Antifungal	138
Penicillium sp.	*Alibertia macrophylla*	(R)-7- ydroxymellein , (3R, 4R)-4, 7-dihydroxymellein	Antifiungal	138
Phoma sp.	*Arisaema erubescens*	(3S)-3,6,7-trihydroxy-a-tetralone,Cercosporamide	Antifungal	137

2. Host growth and nutrient uptake

The potential function of root endophytic fungi is reported as it facilitates the uptake of nutrient in plants which leads to the growth stimulation. Improvement in nutrition and growth has the indirect positive effects on other functions, like pathogen resistance or greater stress tolerance in plants [139]. An ideal example is Basidiomycete *Piriformospora indica*, a root endophytic fungus serves the host growth, nutrient uptake, and fitness promotion. This Hymenomycete fungus colonizes the inter- and intracellularly roots and forms round bodies [140, 141]. *P. indica* has the ability to mobilize the unavailable phosporus by secreting the extracellular enzyme phosphatases, simultaneously mediating its uptake and translocation via an energy dependent process [142]. There is also a report on nitrogen accumulation by *P. indica* in the shoots of *Arabidopsis thaliana* and *Nicotiana tobaccum*. The nitrogen content increased by 22% in *N. tobaccum,* which indicates the 60% transfer of substrate N in the plants. *P.indica* has wide host range enhance growth of *Zea mays*, *Bacopa monniera*, *Nicotiana tobaccum*, *Petroselinum crispum*, *Artemisia annua*, *Populus tremula*, *Sorghum vulgare*, *Oryza sativa*, *Triticum sativum*, *Cicer arientinum*, *Glycine max*, *Solanum melongera*, and orchids like *Dactylorhiza purpurella*, *D. majalis* , *D. fuchsia* and *D. inacrnata* [143, 144, 145, 146].

3. Production of phyto-hormones

Fungal endophytes enhance the growth by producing plant hormones with no apparent facilitation of nutrient uptake. The endophytic fungi increase the biomass with the help of production of growth hormones or induction the production of hormone [7]. Rommert et al. (2002) reported that the mycelial extract of fungus *Phialocephala fortinii* induced the similar enhancement in root and shoot biomass of *Larix decidua* as fungal filtrate [147]. Growth promotion was attributed by the IAA production by fungus *in vitro*. Similar results were seen with fungal culture filtrate of *P. indica*, when 1% w/v of filtrate was mixed with maize seedlings for four weeks, the shoot biomass increased and it was similar as that of live fungal biomass [141, 148,149,150].

4. PIGMENT PRODUCTION

Quercetin glycoside an orange isolated from a fungal endophyte belongs to *Penicillium* sp. [151]. *Penicillium purpurogenum* SX01, identified from *Ginkgo biloba* L, was able to produce sufficient soluble red pigments which used as a natural food coloring substances [152]. One of the pigments isolated from fungal endophyte *Monodictys castaneae* inhibits the human pathogenic bacteria *Klebsiella pneumonia, Staphylococcus aureus*, *Vibrio cholera* and *Salmonella typhi,* and proved more effective than streptomycin [153].

5. *Hosts tolerance to abiotic stress* *Salt* stress

Salinizatrion is one of the serious problems in arid and semi arid regions [154]. Significance of salinity in soils is enormous [155] it affects the growth and development of plants and reduces the productivity [156, 157]. Direct effects of salinity on plants are: (a) diminution in the osmotic potential of soil which reduces the available water to the plants and cause drought to prevent this problem plant should maintain the internal osmotic potentials to prevent the water movement from roots to the soil [158, 159] (b) the excessive toxicity of Na^+ and Cl^- ions disrupt the structure of enzymes, macromolecules, plasma membrane and cell organelles and hamper the process of photosynthesis, protein synthesis and respiration [160, 158] and (c) causes imbalance in nutrient in plants by nutrient uptake or transport to the plant shoot which leads to ion deficiencies [161, 162] , a root-endophytic fungus *Piriformospora indica*, improve the plant resistance from leaf and root diseases and alleviate the salt stress tolerance in barley [95].

Drought stress

Piriformospora indica, a root endophyte effectively helps the plants to enhance the tolerance against abiotic stress condition like drought. For e.g., endophyte increases tolerance in Chinese cabbage (*Brassica campestris L.* sp. *Chinensis*) and *Arabidopsis thaliana* [163, 164, 165], result showed that colonized plants were more drought tolerant than uncolonized plant [163, 165]. Under drought condition colonized host plants had more chlorophyll content and photosynthetic efficiency compared to noncolonized plants [163, 166]. Various mechanisms are used behind the stress tolerance in host plants by microbes. Production of phytohormones like gibberellins, indole acetic acid, which results in increased in the root surface area, root length, and number of root tips, that leads to enhance the nutrient uptake and therefore improving the plant growth under stressed environments [167]. Fungal endophytes helps the host plants to withstand and tolerate the unfavourable environmental conditions like drought, high temperatures and salts [97]. *Dichanthelium lanuginosum*, the herbal plant growing in soil where temperatures reach to 57 °C, because of presence of *Curvularia* sp. an endophytic fungus. The colonized plants can survive in high temperature and water stressed areas than uncolonized plants [99]. These beneficial effects were observed by systemically alternation in distal leaves, with increases the anti-oxidative capacity because of activation of glutathione ascorbate cycle in plants and results in grain yield. Therefore, such symbioses are required as they can help the plants to adapt in global climate changing atmosphere [168].

6. HOSTS TOLERANCE TO BIOTIC STRESS

Endophytes are effective in protecting the plants from pathogens and pests [169, 170]. Foliar and systemic endophytes reduce the herbivory by excreting the alkaloids toxic to vertebrates and insects [171]. It can also induce the resistance to diseases, by mechanisms associated with nutritional status of host plant, and increase in the growth of plants by their tolerance to abiotic stress condition [99, 172]. First mechanism is the competition between fungal endophyte and the pathogen for same resources [173]. For eg. endophytic non-pathogenic *F. oxysporum* inhibits the growth of pathogenic *F. oxysporum* f. sp. *radicis-lycopersici* by which it reduces the root rot in tomato [174.] The spores of *F. oxysporum* compete with pathogen for carbon source, and reducing the availability of nutrient for pathogen. The second mechanism is based on the ability of fungal endophytes to induce the host to produce the phytoalexins, and biocidal compounds, or the capacity of endophyte itself for the production of fumigants and antimicrobial compounds. For eg. *Spilanthes calva* inoculated with the spores of *Piriformospora indica*, and then it produces antifungal compounds which inhibit the growth of soil-borne pathogens *Trichophyton mentagrophytes* and *F. oxysporum* [175, 145, 176.]

7. Production of volatile antibiotics

The fascinating use of fungal endophytes in the area of soil fumigation. One of the endophytic fungus of Xylariaceaous family i.e. *Muscodor albus* from *Cinnamomum zeylanicum* completely inhibits or kills the microbes by releasing the mixture of volatile chemicals [177]. These compounds are identified by gas chromatography and use as a mycofumigation. Another report on fungal endophyte, *Muscodor roseus* obtained from tree growing in Northern region of Australia showed the inhibition or death on test organisms. In addition to this, a nonmuscodor fungus, *Gliocladium* sp. was first time discovered as a producer of volatile antibiotic and these compounds are different from *M. roseus* or *M. albus* [178].

b) Environmental role of fungal endophytes

Fungal endophytes are also known for its role in ecological community by decreasing the range of environmental degradation, biodiversity loss, spoilage of water and land due to toxic insecticide, poisonous gases and industrial sewage. Endophyte is a biological method and widely used to control the growth of insects, pathogens and remediate the environment[179]. Application of fungal endophytes in phytoremediation i.e., eradication of heavy metals and xenobiotics from soil assisted by plants [180]. The process of phytoremediation depends on the microbes and ability of plant to accumulate and tolerate the high concentrations of metal pollutant, with high yield. Endophytes used for bio-accumulating the pollutants and heavy metals from environment while increasing the plant growth through the process of mobilization/ immobilization [180]. Endophyte contributes directly or indirectly in the process of phytoremediation and degradation of toxins from environment. Indirectly by enhancing the plant growth which having the ability of phytoremediation and directly through accumulating or degrading the pollutants by endophyte itself. As the industrialization increasing various types of anthropogenic chemicals like petroleum hydrocarbons (PHC), halogenated hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), solvents, heavy metals, pesticides and salt, are introduced in the environments and cause many problems [181, 180, 182].

1. Bio-Technological applications

Endophytes has the high ability to secrete the various novel enzymes that have the major application in the area of biotechnology like the use of degradative enzymes for environment remediation, biological transformations of organic compounds [183] and medical applications [183].

2. Enzymes production

Endophytes mainly produce the extracellular enzymes to colonize the plant tissues. It has been reported that most of the endophytes utilizes the cell components and nutrients of plant *in vitro* for eg. endophytes utilize pectin and xylan and, shows the lipolytic activity and produces other enzymes like peroxidases, chitinase, laccases, and glucanase [184].

3. Pharmaceutical applications

Endophytes are also known as the chemical synthesizers inside the plants [108]. Many fungal endophytes are reported to produce the novel antifungal, antibacterial, anti-inflammatory, antiviral, antitumor, and also other compounds like steroid, alkaloids, terpenoids, flavonoid derivatives [34, 185, 186]. The best example is Vm-J2 endophytic fungus produces the same bioactive metabolite, vincamine, as the host plant produces [187]. Hence, the production of natural metabolites by endophytes help to protect and conserve the natural resources and satisfy the demands of drugs of plant-derived by fermentation.

4. Anti- cancer agents from endophytes

Endophytic fungi produce the bioactive compounds which could be alternative method to discover the novel anticancer drugs [179, 188]. Chandra (2012) also reported many endophytic fungi as sources of anticancer molecules [189]. The anticancer compounds obtained from endophytic fungus *Fusarium solani* of *Camptotheca acuminata* are Camptothecin and analogues (10-hydroxycampto-thecin and 9-ethoxycamptothecin and) [190]. Several reports are there on endophytes producing other Camptothecin and analogues producing [191, 192, 193, 194]. Endophytic fungi also have the capacity to produce natural antioxidants from *Scapania verrucosa* a medicinal plant [195].

CONCLUSION

The internal space of host plants harbor the diverse form of endophytic fungi and their association varies from symbiotic to pathogenic. They are rich and best reliable source of bioactive compounds with higher level of biodiversity and of pharmaceutical importance. They cause physiological modifications in the host plant and make them more tolerable in adverse climatic condition and help plants to adapt. They have excellent potential for implementation as a biocontrol agent and plant growth and improvement. To consider all these benefits fungal endophytes has proven to be a boon and accomplish the requirements in biotechnology, agricultural and industrial areas.

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REFERENCES

1. Hawksworth D.L., The fungal dimension of biodiversity, magnitude, significance and conservation. Mycol Res, 95: 641-655, (1991).
2. M.M. Dreyfuss and I.H. Chapela. Potential of fungi in the discovery of novel, low-molecular weight pharmaceuticals. In: V.P. Gullao (ed.), *The Discovery of Natural Products with Therapeutic Potential*, Butterworth-Heinemann, London, UK, , pp. 49-80, 1994.
3. J.L. Azevedo. Microorganismos endofíticos. In: I.S. Melo and J.L. Azevedo (eds.), *Ecologia Microbiana,* Editora EMBRAPA, Jaguariuna, São Paulo, Brazil, pp. 117-137, 1998.
4. Petrini O., Fungal endophytes in tree leaves. In: J.H. Andrews, and S.S. Hirano (eds.), *Microbial Ecology of Leaves*, Springer, New York, pp. 179-197, 1991.
5. Bacon, C.W., and White, J.F.. Microbial endophytes. Marcel Decker, Inc., New York, 2000.
6. Saikkonen K., Faeth S.H., Helander M., Sullivan T.J., Fungal endophytes, A continuum of interactions with host plants. Annu Rev Ecol Syst, 29: 319-343, (1998).
7. Schulz B., Boyle C., The endophytic continuum. Mycol Res, 109:661–686, (2005).
8. M.C. Brundrett. Understanding the roles of multifunctional mycorrhizal and endophytic fungi. In: B. Schulz, C. Boyle, T.N. Sieber (eds.), Microbial root endophytes, Soil microbiology, Springer, Berlin, vol 9, pp. 179–190, 2006.
9. Mandyam K., Jumpponen A., Seeking the elusive function of the root-colonising dark septate endophytic fungi. Stud Mycol, 173–189, (2005).
10. Tellenbach C., Grunig C.R., Sieber T.N., Negative effects on survival and performance of Norway spruce seedlings colonized by dark septate root endophytes are primarily isolate-dependent. Environ Microbiol, 13:2508–2517, (2011).
11. Upson R., Read D.J., Newsham K.K., Nitrogen form influences the response of *Deschampsia Antarctica* to dark septate root endophytes. Mycorrhiza, 20:1–11, (2009).
12. Wu L.Q., Lv Y.L., Meng Z.X., Chen J., Guo S.X., The promoting role of an isolate of dark-septate fungus on its host plant *Saussurea involucrata* Kar. et Kir. Mycorrhiza, 20:127–135, (2010).
13. Newsham K.K., A meta-analysis of plant responses to dark septate root endophytes. New Phytol, 10:783–793, (2011).
14. B. Schulz. Mutualistic interactions with fungal root endophytes. In: B. Schulz, C. Boyle, T.N. Sieber (eds.), *Microbial root endophytes*, Soil microbiology, Springer, Berlin, vol 9, pp. 261–279, 2006.

15. Gonthier P., Gennaro M., Nicolotti G., Effect of water stress on endophytic mycota of *Quercus robur*. Fungal Divers, 21: 69–80, (2006).
16. Krings M., Taylor T.N., Hass H., Kerp H., Dotzler N., Hermsen E.J., Fungal endophytes in a 400-million-yr-old land plants: infection pathways, spatial distribution, and host response. New Phytol, 174: 648–657, (2007).
17. Sridhar K.R., Raviraja N.S., Endophytes- a crucial issue. Curr Sci, 69 (7): 570-574, (1995).
18. Darwin C., The origin of species, 6th Edn, Thompson and Thomas, London, Chicago, (1872).
19. Tilman D., Knops J., Wedin D., Reich P., Ritchie M., Siemann E., The influence of functional diversity and composition on ecosystem processes. Science, 277:1300- 1302, (1997a).
20. Cardinale B.J., Palmer M.A., Collins S.L., Species diversity enhances ecosystem functioning through interspecific acilitation. Nature, 415: 426-429, (2002).
21. Tilman D, Lehman C.L., Thomson K.T., Plant diversity and ecosystem productivity, theoretical considerations. Proc Nat Acad Sc, 94:1857-186, (1997b).
22. Levine J.M., D'Antonio C.M., Elton revisited a review of evidence linking diversity and invasibility. Oikos, 87: 15-26, (1999).
23. Oses R., Valenzuela S., Freer J., Sanfuentes E., Rodriguez J., Fungal endophytes in xylem of healthy Chilean trees and their possible role in early wood decay. Fungal Divers, 33: 77-86, (2008).
24. Li W.C., Zhou J., Guo S.Y., Guo L.D., Endophytic fungi associated with lichens in Baihua mountain of Beijing, China. Fungal Divers, 25: 69-80, (2007).
25. Rungjidamai N., Pinruan U., Choeyklin R., Hattori T., Jones E.B.G., Molecular characterization of basidiomycetous endophytes isolated from leaves, rachis and petioles of the oil palm, *Elaeis guineensis*, in Thailand. Fungal Divers, 33: 139-161, (2008).
26. Bettucci L., Simeto S., Alonso R., Lupo S., Endophytic fungi of twigs and leaves of three native species of Myrtaceae in Uruguay. Sydowia, 56: 8-23, (2004).
27. Huang W.Y., Cai Y.Z., Hyde K.D., Corke H., Sun M., Biodiversity of endophytic fungi associated with 29 traditional Chinese medicinal plants. Fungal Divers, 33: 61-75, (2008).
28. Dreyfuss M., Petrini O., Further investigations on the occurrence and distribution of endophytic fungi in tropical plants. Bot Helv, 94: 33-40, (1984).
29. Rodrigues K.F., Samuels G.J., Preliminary study of endophytic fungi in a tropical palm. Mycol Res, 94: 827-830, (1990).
30. Rodrigues K.F., Leuchtmann A., Petrini O., Endophytes species of Xylaria, cultural and isozymic studies. Sidowia, 45: 116-138, (1993).
31. Silva A.C., Isolamento de fungos endofiticos de milho (Zea mays, L.) Piracicaba, Tese de Mestrado, Universidade de Sao Paulo, ESALQ, (1997).
32. Tan R.X., Zou W.X., Endophytes: a rich source of functional metabolites. Nat Prod Rep, 18: 448–459, (2001).
33. Hyde K.D., Soytong K., The fungal endophyte dilemma. Fungal Divers, 33: 163–173, (2008).
34. Aly A.H., Debbab A., Proksch P., Fungal endophytes: unique plant inhabitants with great promises. Appl Microbiol Biotechnol, 90: 1829–1845, (2011).
35. Addy H.D., Piercey M.M., Currah R.S., Microfungal endophytes in roots. Can J Botany, 83:1– 13, (2005).
36. Summerbell R.C., Root endophyte and mycorrhizosphere fungi of black spruce, *Picea mariana*, in a boreal forest habitat: influence of site factors on fungal distributions. Stud Mycol, 53:121–145, (2005).
37. Weishampel P., Bedford B., Wetland dicots and monocots differ in colonization by arbuscular mycorrhizal fungi and dark septate endophytes. Mycorrhiza, 16:495–502, (2006).
38. Schild D.E., Kennedy A., Stuart M.R., Isolation of symbiont and associated fungi from ectomycorrhizas of *Sitka spruce*. Eur J Forest Pathol, 18:51–61, (1988).
39. Wang W., Tsuneda A., Gibas C., Currah R.S., Cryptosporiopsis species isolated from the roots of aspen in central Alberta:

identification, morphology and interactions with the host, in vitro. Can J Botany, 85:1214–1226, (2007).
40. Hambleton S., Sigler L., Meliniomyces, a new anamorph genus for root-associated fungi with phylogenetic affinities to *Rhizoscyphus ericae* (Hymenoscyphus ericae), Leotiomycetes. Stud Mycol, 53:1–27, (2005).
41. Hoff J.A., Klopfenstein N.B., McDonald G.I., Tonn J.R., Kim M.S., Zambino P.J., Hessburg P.F., Rogers J.D., Peever T.L., Carris L.M., Fungal endophytes in woody roots of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). Forest Pathol, 34:255–271, (2004).
42. Ghimire S.R., Charlton N.D., Bell J.D., Krishnamurthy Y.L., Craven K.D., Biodiversity of fungal endophyte communities inhabiting switchgrass (*Panicum virgatum* L.) growing in the native tallgrass prairie of northern Oklahoma. Fungal Divers, 47:19–27, (2011).
43. Sun X., Guo L.D., Hyde K.D., Community composition of endophytic fungi in *Acer truncatum* and their role in decomposition. Fungal Divers, 47:85–95, (2011).
44. Purahong W., Hyde K.D., Effects of fungal endophytes on grass and non-grass litter decomposition rates. Fungal Divers, 47: 1–7, (2011).
45. Fisher P.J., Petrini O., Webster J., Aquatic hyphomycetes and other fungi in living aquatic and terrestrial roots of *Alus glutinosa.* Mycol Res, 95: 543-547, (1991).
46. Sati S.C., Belwal M., Aquatic Hyphomycetes as root endophytes of Riparian plant roots. Mycologia, 97(1): 45- 59, (2005).
47. Fisher P.J., Petrini O., Two aquatic hyphomycetes as endophytes in *Alus glutinosa* roots. Mycol Res, 92: 367-368, (1989).
48. Sridhar K.R., Barlocher F., Endophytic aquatic hyphomycetes of roots from spruce, birch and maple. Mycolgia Res, 92: 305-308, (1992a).
49. Sridhar K.R., Barlocher F., Aquatic hyphomycetes in spruce roots. Mycolgia, 84:580-584, (1992b).
50. Valla G., Capellano A., Hugueney R., Moiroud A., *Penicillium nodositatum* Valla, a new species inducing myconodules on Alnus roots. Plant soil, 114(1):142-146, (1989).
51. Marcia-Vicente J.G., Jansson H.B., Abdullah S.K., Descols E., Salinas J., Lopez-Llorca L.V., Fungal endophytes from natural vegetation in Mediterranean environments with special reference to *Fusarium* species. FEMS Microbiol Ecol, 64: 90 – 105, (2008).
52. Kim H.Y., Choi G.J., Lee S.W., Lim H.K., Jang K.S., Son S.W., Lee S.O., Cho K.Y., Sung N.D., Kim J.C., Some fungal endophytes from vegetable crops and their anti-oomycete activities against tomato late blight. Lett Appl Biol, 44: 332 – 337, (2007).
53. Sanchez Marquez S., Bills G.F., Dominquez Acuna L., Zabalgogeazcoa I., Endophytic mycobiota of leaves and roots of the grass *Holcus lanatus*. Fungal Divers, 41: 115–123, (2010).
54. Yuan Z.L., Zhang C.L., Lin F.C., Kubaik C.P., Identity, diversity and molecular phylogeny of the endophytic mycobiota in the roots of rare wild rice (*Oryza granulata*) from nature reserve in Yunnan, China. Appl Environ Microbiol, 76 (5): 1452 – 1652, (2010).
55. Naik B.S., Sashikala J., Krishnamurthy Y.L., Study on the diversity of endophytic communities from rice (*Oryza sativa* L) and their anatagonistic activities in vitro. Microbiol Res, 164: 290 – 296, (2009).
56. Xing X.K., Guo S.X., Fungal endophyte communities in four Rhizophoraceae mangrove species on the south coast of China. Ecol Res, 26(2): 403–409, (2011).
57. Sieber T., Risen T.K., Muller E., Fried P.M., Endophytic fungi in four winter wheat cultivars (*Triticum aestivum*) differing in resistance against *Stagonaspora nodorum* (Berk.) Cast Germ = Septorianodorum (Ber.) Berk. J Phytopathol, 122: 289 – 306, (1988).
58. Boshoff W.H.P., Pretorius Z.A., Swart W.J., Jacobs A.S., A comparison of scab development in wheat infected by *Fusarium graminearum* and *Fusarium crookswellense*. Phytopathol, 86: 558-563, (1996).

59. Leslie J. F., Summerbell B.A., 2006. The *Fusarium* laboratory manual. Ed. Blackwell Publishing, Iowa, USA.
60. Currah R.S., Sigler L., Hambleton S., New record and taxa of fungi from the mycorrhizae of terrestrial orchids of Alberta. Can Journal Bot, 65: 2473-2482, (1987).
61. Vujanovic V., St-Arnaud M., Barabe D., Thibeautl G., Viability testing of orchid seed and the promotion of colouration and germination. Ann Bot, 86: 79-86, (2000).
62. Taylor D.L., Bruns T.D., Szaro T.M., Hodges S.A., Divergence in mycorrhizal specialization within *Hexalactris spicata* (Orchidaceae), a nonphotosynthetic desert orchid. Am J Bot, 90: 1168-1179, (2003).
63. McKendrick S.L., Leake J.R., Read D.J., Symbiotic germination and development of mycohetrotrophic plants in nature: transfer of carbon from ectomycorrhizal *Salix repens* and *Betula pendula* to the orchid *Corallorhiza trifida* through shared hyphal connections. New Phytol, 145:539-548, (2000).
64. Bayman P., Gonzalez E.J., Fumero J.J., Tremblay R.L., Are fungi necessary? How fungicicides affect growth and survival of the orchid *Lepanthes ruoestris* in the field. J Ecol, 90: 1002-1008, (2002).
65. Ananda K., Sridhar K.R., Diversity of endophytic fungi in roots of mangrove species on the west cost of India. Can J Microbiol, 48: 871-878, (2002).
66. Raviraja N. S., Sridhar K. R., Barlocher F., Endophytic aquatic hyphomycetes of roots of plantation crops and ferns from India. Sydowia, 48, 152-160, (1996).
67. Arnold A.E., Understanding the diversity of foliar endophytic fungi: progress, challenges, and frontiers. Fungal Biol Rev, 21: 51–66, (2007).
68. Zhou D., Hyde K.D., Host-specificity, host-exclusivity, and host-recurrence in saprobic fungi. Mycol Res, 105: 1449–1457, (2001).
69. Suryanarayanan T.S., Kumaresan V., Endophytic fungi of some halophytes from an estuarine mangrove forest. Mycol Res, 104: 1465–1467, (2000).
70. Cohen S.D., Host selectivity and genetic variation of *Discula umbrinella* isolates from two oak species: analyses of intergenic spacer region sequences of ribosomal DNA. Microbial Ecol, 52: 463–469, (2006).
71. Dudeja S. S., Giri R., Saini R., Suneja-Madan P., and Kothe E., Interaction of endophytic microbes with legumes. J Basic Microbiol, 52: 248–260, (2012).
72. Chadha N., Mishra M., Prasad R., Varma A., Root endophytic fungi: Research update. J Biol Life Sci, 5 (2): 135-158, (2014).
73. Lee S., Flores-Encarnaci´on M., Contreras-Zentella M., Garcia-Flores L., Escamilla J. E., Kennedy C., Indole-3-acetic acid biosynthesis is deficient in *Gluconacetobacter diazotrophicus* strains with mutations in *Cytochrome c* biogenesis genes. J Bacteriol, 186(16): 5384–5391, (2004).
74. Strobel G.A., Endophytes as sources of bioactive products. Microb Infect, 5 (6): 535–544, (2003).
75. Strobel G., Daisy B., Bioprospecting for microbial endophytes and their natural products. Microbiol Mol Biol Rev, 67 (4): 491–502, (2003).
76. Firáková S., Šturdíková M., Múčková M., Bioactive secondary metabolites produced by microorganisms associated with plants. Biologia, 62(3): 251–257, (2007).
77. Higgins K.L., Arnold A.E., Miadlikowska J., Sarvate S.D., Lutzoni F., Phylogenetic relationships, host affinity, and geographic structure of boreal and arctic endophytes from three major plant lineages. Mol Phylogenet Evol, 42:543–555, (2007).
78. Saikkonen K., Forest structure and fungal endophytes. Fungal Biol Rev, 21:67–74, (2007).
79. Hoffman M.T., Arnold A.E., Geographic locality and host identity shape fungal endophyte communities in cupressaceous trees. Mycol Res, 112:331–344, (2008).
80. Jeewon R., Liew E.C.Y., Hyde K.D., Phylogenetic evaluation of species nomenclature of Pestalotiopsis in relation to host association. Fungal Divers, 17:39–55, (2004).

81. Murali T.S., Suryanarayanan T.S., Geeta R., Endophytic *Phomopsis* species: host range and implications for diversity estimates. Can J Microbiol, 52:673–680, (2006).
82. Sieber T.N., Endophytic fungi in forest trees: are they mutualists? Fungal Biol Rev, 21:75–89, (2007).
83. Rodrigues K.F., Samuels G.J., Fungal endophytes of *Spondias mombin* leaves in Brazil. J Basic Microbiol, 39:131–135, (1999).
84. Gazis R., Chaverri P., Diversity of fungal endophytes in leaves and stems of wild rubber trees (*Hevea brasiliensis*) in Peru. Fungal Ecol, 3:240–254, (2010).
85. Kumar D.S.S., Hyde K.D., Biodiversity and tissue-recurrence of endophytic fungi in *Tripterygium wilfordii*. Fungal Divers, 17:69–90, (2004).
86. J.K. Stone, J.D. Polishook, J.R.J. White. Endophytic fungi. In: G. Mueller, G.F. Bills and M.S. Foster (eds.), *Biodiversity of fungi: inventory and monitoring methods*, Elsevier, Burlington, MA, USA, pp. 241–270, 2004.
87. Saikkonen K., Ion D., Gyllenberg M., The persistence of vertically transmitted fungi in grass metapopulations. Proc R Soc B: Biol Sci, 269: 1397–1403, (2002).
88. Clay K., Fungal endophytes of grasses: a defensive mutualism between plants and fungi. Ecology, 69(1):10–16, (1988).
89. Faeth S.H., Gardner D.R., Hayes C.J., Jani A., Wittlinger S.K., Jones T.A., Temporal and spatial variation in alkaloid levels in *Achnatherum robustum*, a native grass infected with the endophyte *eotyphodium*. J Chem Ecol, 32: 307–324, (2006).
90. Clay K., Schardl C.L., Evolutionary origins and ecological consequences of endophyte symbiosis with grasses. Amer Nat, 160:S99–S127, (2002).
91. Clay K., Fungal endophytes of grasses. Ann Rev of Ecol, Evol, and Syst, 21: 275–295, (1990).
92. Patterson C.G., Potter D.A., Fanin F.F., Feeding deterrence of alkaloids from endophyte-infected grasses to Japanese beetle grubs. Entomol Exp Appl, 61: 285–289, (1991).
93. Kimmons C.A., Gwinn K.D., Bernard E.C., Nematode reproduction on endophyte infected and endophyte free tall fescue. Plant Dis, 74:757-761, (1990).
94. Yue C., Miller C.J., White J.F.J., Richardson M., Isolation and characterization of fungal inhibitors from *Epichloë festucae*. J Agric Food Chem, 48: 4687–4692, (2000).
95. Waller F., Achatz B., Baltruschat H., Fodor J., Becker K., Fischer M., Heier T., Huckelhoven R., Neumann C., von Wettstein D., Franken P., Kogel K.H., The endophytic fungus *Piriformospora indica* reprograms barley to salt-stress tolerance, disease resistance, and higher yield. PNAS J, 102: 13386–13391, (2005).
96. Rodriguez R.J., Henson J., Van Volkenburgh E., Hoy M., Wright L., Beckwith F., Kim Y., Redman R.S., Stress tolerance in plants via habitat-adapted symbiosis. International Society of Microb Ecol, 2: 404-416, (2008).
97. Malinowski D.P., Belesky D.P., Adaptations of endophtye-infected cool-season grasses to environmental stresses: mechanisms of drought and mineral stress tolerance. Crop Sci, 40: 923–940, (2000).
98. Gao K.X., Mendgen K., Seed-transmitted beneficial endophytic *Stagonospora* sp. can penetrate the walls of the root epidermis, but does not proliferate in the cortex, of *Phragmites australis*. Can J Bot, 84: 981–988, (2006).
99. Redman R.S., Sheehan K.B., Stout R.G., Rodriguez R.J., Henson J.M., Thermotolerance conferred to plant host and fungal endophyte during mutualistic symbiosis. Science, 298(5598): 1581. (2002).
100. B. Tudzynski, A. Sharon. Biosynthesis, biological role and application of fungal phyto-hormones. In: H.D. Osiewacz (ed.), *The mycota X. Industrial applications*, Springer-Verlag, Berlin, Germany, pp. 183–212, 2002.
101. Campanile G., Ruscelli A., Luisi N., Antagonistic activity of endophytic fungi towards *Diplodia corticola* assessed by in vitro and in planta tests. Eur J Plant Pathol, 117: 237–246, (2007).
102. Schulz B., Rommert A.K., Dammann U., Aust H.J., Strack D., The endophyte-host

interaction: a balanced antagonism? Mycol Res, 10: 1275–1283, (1999).
103. Vu T., Hauschild R., Sikora R.A., *Fusarium oxysporum* endophytes induced systemic resistance against *Radopholus similis* on banana. Nematol, 8: 847–852, (2006).
104. Wang W., Vincur B., Altman A., Plant responses to drought, salinity and extreme temperatures: towards genetic engineering for stress tolerance. Planta, 218: 1–14, (2003).
105. Apel K., Hirt H., Reactive oxygen species: metabolism, oxidative stress, and signal transduction. Annu Rev Plant Biol, 55: 373–399, (2004).
106. Gamboa M.A., Bayman P., Communities of endophytic fungi in leaves of a tropical timber tree (*Guarea guidonia*: Meliaceae). Biotropica, 33: 352–360, (2001).
107. E.A. Herre, S.A.V. Bael, Z. Maynard, N. Robbins, J. Bischoff, A.E. Arnold, E. Rojas, L.C. Mejía, R.A. Cordero, C. Woodward, D.A. Kyllo. Tropical plants as chimera: some implications of foliar endophytic fungi for the study of host plant defense, physiology, and genetics. In: D.F.R.P. Burslem, M.A. Pinard and S.E. Hartley (eds.), *Biotic interactions in the tropics*. University Press, Cambridge, UK, 2005, pp.226–240, 2005.
108. Owen N. L., Hundley N., Endophytes—the chemical synthesizers inside plants. Sci Prog, 87(2): 79–99, (2004).
109. L. Zhang, R. An, J. Wang et al., Exploring novel bioactive compounds from marine microbes. Curr Opin Microbiol, 8(3): 276–281, (2005).
110. Guo L.D., Hyde K.D., Liew E.C.Y., Detection and identification of endophytic fungi within frond tissues of *Livistona chinensis* based on rDNA sequence. Mol Phylogenet Evol, 20: 1–13. (2001).
111. Liu L., Bruhn T., Guo L.D., Götz D.C.G., Brun B.R., Stich A., Che Y.S., Bringmann G.,. Chloropupukeanolides C–E, cytotoxic pupukeanane chlorides with a spiroketal skeleton from *Pestalotiopsis fici*. Chem Eur J, 17: 2604–2613, (2011).
112. Aly A.H., Debbab A., Kjer J., Proksch P., Fungal endophytes from higher plants: a prolific source of phytochemicals and other bioactive natural products. Fungal Divers, 41: 1–16, (2010).
113. Xu J., Ebada S.S., Proksch P., *Pestalotiopsis* a highly creative genus: chemistry and bioactivity of secondary metabolites. Fungal Divers, 44: 15–31, (2010).
114. Tejesvi M.V., Kajula M., Mattila S., Pirttilä A.M., Bioactivity and genetic diversity of endophytic fungi in *Rhododendron tomentosum* Harmaja. Fungal Divers, 47: 97–107, (2011).
115. Doty S.L., Growth-Promoting Endophytic Fungi of Forest Trees. Forestry Sci, 80:151–156, (2011).
116. Saikkonen K., Saari S., Helander M., Defensive mutualism between plants and endophytic fungi? Fungal Divers, 41: 101–113, (2010).
117. Ownley B.H., Gwinn K.D., Vega F.E., Endophytic fungal entomopathogens with activity against plant pathogens: ecology and evolution. BioControl, 55:113–128, (2010).
118. Verma V.C., Kharmar R.N., Strobel G.A., Chemical and functional diversity of natural products from plant associated endophytic fungi. Nat Prod Commun, 4: 1511-1532, (2009).
119. Keller N.P., Turner G., Bennett J.W., Fungal secondary metabolism-from biochemistry to genomics. Nat Rev Microbiol, 3:937–947, (2005).
120. Strobel G., Harnessing endophytes for industrial microbiology. Curr Opin Microbiol, 9:240–244, (2006).
121. Porras-Alfaro A., Bayman P., Hidden fungi, emergent properties: endophytes and microbiomes. Annu Rev Phytopathol, 49:291–315, (2011).
122. Strobel G., Daisy B., Castillo U., Harper J. Natural products from endophytic microorganisms. J Nat Prod, 67: 257-268, (2004).
123. Tejesvi M.V., Kini K.R., Prakash H.S., Subbiah V., Shetty H.S., Genetic diversity and antifungal activity of species of *Pestalotiopsis* isolated as endophytes from medicinal plants. Fungal Divers, 24: 37-54, (2007).
124. Schulz B., Boyle C., Draeger S., Rommert A.K. Endophytic fungi, a source of novel biologically active secondary

metabolites. Mycol Res, 106: 996-1004, (2002).
125. Kumar D.S.S., Lau C.S., Wan J.M.F., Yang D., Hyde K.D., Immunomodulatory compounds from *Pestalotiopsis leucothos* (HKUCC 10197), an endophytic fungus of *Tripterygium wilfordii*. Life Sci, 78: 147-156, (2005).
126. Wiyakrutta S., Sriubolmas N., Panphut W., Thongon N., Danwiserkanjana K., Ruangrungsi N., Meevootisom V., Endophytic fungi with antimicrobial, anti-cancer, antimalarial activities isolated from Thai medicinal plants. World J Microbiol Biotechnol, 20: 265-272, (2004).
127. Lin X., Lu C., Huang Y., Zheng Z., Su W., Shen Y., Endophytic fungi from a pharmaceutical plant, *Camptotheca acuminata*: isolation, identification and bioactivity. World J Microbiol Biotechnol, 23(7):1037–1040, (2007).
128. De Siqueira V.M., Conti R., De Araújo J.M., Souza-Motta C.M., Endophytic fungi from the medicinal plant *Lippia sidoides* Cham and their antimicrobial activity. Symbiosis, 53(2):89–95, (2011).
129. Kumaran R.S., Kim H.J., Hur B.K., Taxol promising fungal endophyte, *Pestalotiopsis* species isolated from *Taxus cuspidata*. J Biosci Bioeng, 110(5):541–546, (2010).
130. Yang R.Y., Feng P.Y., Li Q., Research advances on the activity of endophyte pesticides. Agrochem, 45(7):440–444, (2006).
131. Rodriguez R.J., White J.F., Arnold A.E., Redman R.S., Fungal endophytes: diversity and functional roles. New Phytol, 182: 314-330, (2009).
132. Silvia F., Sturdikova M., Muckova M., Bioactive secondary metabolites produced by microorganisms associated with plants. Biologia, 62: 251-257, (2007).
133. Gunatilaka A.A.L., Natural products from plant-associated microorganisms: distribution, structural diversity, bioactivity, and implications of their occurrence. J Nat Prod, 69: 505-526, (2006).
134. L. Zhou, J. Zhao, L. Xu, Y. Huang, Z. Ma, J. Wang, W. Jiang. Antimicrobial compounds produced by plant endophytic fungi. In: P. De Costa, and P. Bezerra (eds.), *Fungicides: Chemistry, Environmental Impact and Health Effects*, Nova Science Publishers, New York, pp. 91-119, 2009.
135. Fu J., Zhou Y., Li H.F., Ye Y.H., Guo J.H., Antifungal metabolites from *Phomopsis* sp. By254, an endophytic fungus in *Gossypium hirsutum*. Afr J Microbiol Res, 5:1231–1236, (2011).
136. Zheng C.J., Li L., Zou J.P., Han T., Qin L.P., Identification of a quinazoline alkaloid produced by *Penicillium vinaceum*, an endophytic fungus from *Crocus sativus*. Pharm Biol, 50:129–133, (2012).
137. Wang L.W., Xu B.G., Wang J.Y., Su Z.Z., Lin F.C., Zhang C.L., Kubicek C.P., Bioactive metabolites from *Phoma* species, an endophytic fungus from the Chinese medicinal plant *Arisaema erubescens*. Appl Microbiol Biotechnol, 93:1231–1239, (2012).
138. Oliveira C.M., Regasini L.O., Silva G.H., Pfenning L.H., Young M.C.M., Berlinck R.G.S., Bolzani V.S., Araujo A.R., Dihydroisocoumarins produced by *Xylaria* sp. and *Penicillium* sp., endophytic fungi associated with *Piper aduncum* and *Alibertia macrophylla*. Phytochem Lett, 4:93–96, (2011).
139. S.A. Kageyama, K.G. Mandyam, A. Jumpponen. Diversity, Function and Potential Applications of the Root-Associated Endophytes. In: A. Varma (edn.), *State of the Art, Genetics and Molecular Biology, Eco-Function, Biotechnology, Eco-Physiology, Structure and Systematics*, Mycorrhiza, 2008.
140. Verma S., Varma A., Rexer K.H., Hassel A., Kost G., Sarbhoy A., Bisen P., Butehorn B., Franken P., *Piriformospora indica*, gen. et sp. nov., a new root-colonizing fungus. Mycologia, 90: 896–903, (1998).
141. Varma A., Verma S., Sudha, Sahay N., Butehorn B., Franken P., *Piriformospora indica*, a cultivable plant-growth-promoting root endophyte. Appl and Environ Microbiol, 65: 2741–2744, (1999).
142. Malla R., Prasad R., Giang P.H., Pokharel U., Oelmueller R., Varma A., Characteristic features of symbiotic

fungus *Piriformospora indica*. Endocyt Cell Res, 15(2): 579-600, (2004).
143. A. Varma, I. Sherameti, S. Tripathi., R. Prasad et al. The symbiotic fungus *Piriformospora indica*: Review. In: B. Hock, (ed.), *Fungal Associations, The Mycota IX*, Springer-Verlag, Berlin Heidelberg, pp. 9: 231-254, 2012.
144. Varma A., Sree K.S., Arora M., Bajaj R., Prasad R., Kharkwal A.C. Functions of novel symbiotic fungus-*Piriformospora indica*. PNAS, 80 (2): 429-441, (2014).
145. R. Prasad, M. Sharma, S. Kamal, M.K. Rai, A.K.S. Rawat, P. Pushpangdan, A. Varma. Interaction of *Piriformospora indica* with medicinal plants. In: A. Varma, (ed.), *Mycorrhiza*, Springer-Verlag, Germany, pp. 655-678 , 2008.
146. Prasad R., Kamal S., Sharma P.K., Oelmueller R. Varma A, Root endophyte *Piriformospora indica* DSM 11827 alters plants morphology, enhances biomass and antioxidant activity of medicinal plant *Bacopa monniera*. J Basic Microbiol, 53 (12): 1016-1024, (2013).
147. A.K. Rommert, M. Oros-Sichler, H.J. Aust, T. Lange, B. Schulz. Growth promoting effects of endophytic colonization of the roots of larch (*Larix decidua*) with *Cryptosporiopsis* sp. and *Phialophora* sp. 7th International Mycological Congress, Oslo, Norway, pp 309, 2002.
148. Bagde U.S., Prasad R. and Varma A., Interaction of *Piriformospora indica* with medicinal plants and of economic importance. Afr J Biotechnol, 9 (54): 9214-9226, (2010).
149. Bagde U.S., Prasad R., Varma A., Influence of culture filtrate of *Piriformospora indica* on growth and yield of seed oil in *Helianthus annus*. Symbiosis, 53:83–88, (2011).
150. Bagde U.S., Prasad R., Varma A., Impact of culture filtrate of *Piriformospora indica* on biomass and biosynthesis of active ingredient aristolochic acid in *Aristolochia elegans* Mart. Int J Biol, 1(6): 29-37(2014).
151. Liu L., Liu S.C., Jiang L.H., Chen X.L., Guo L.D., Che Y.S., Chloropupukeananin, the first chlorinated pupukeanane derivative and its precursors from *Pestalotiopsis fici*. Org Lett, 10: 1397–1400, (2008).
152. Qiu M., Xie R., Shi Y. et al., Isolation and identification of endophytic fungus SX01, a red pigment producer from *Ginkgo Biloba* L. World J Microbiol Biotechnol, 26(6): 993–998, (2010).
153. Visalakchi S., Muthumary J., Antimicrobial activity of the new endophytic *Monodictys castaneae* SVJM139 pigment and its optimization. African J Microbiol Res, 3(9):550–556, (2009).
154. Al-Karaki G.N., Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water. Sci Hort, 109: 1–7, (2006).
155. Tester M., Davenport R., Naþ tolerance and Naþ transport in higher plants. Ann Bot, 91: 503–527, (2003).
156. Giri B., Kapoor R., Mukerji K.G., Influence of arbuscular mycorrhizal fungi and salinity on growth, biomass and mineral nutrition of *Acacia auriculiformis*. Biol Fert Soils, 38: 170–175, (2003).
157. Mathur N., Singh J., Bohra S., Vyas A., Arbuscular mycorrhizal status of medicinal halophytes in saline areas of Indian Thar Desert. In J Soil Sci, 2: 119–127, (2007).
158. Feng G., Zhang F.S., Li X.I., Tian C.Y., Tang C., Rengel Z., Improved tolerance of maize plants to salt stress by arbuscular mycorrhiza is related to higher accumulation of soluble sugars in roots. Mycorrhiza, 12: 185–190, (2002).
159. Jahromi F., Aroca R., Porcel R., Ruiz-Lozano J.M., Influence of salinity on the in vitro development of *Glomus intraradices* and on the in vivo physiological and molecular responses of mycorrhizal lettuce plants. Microb Ecol, 55: 45–53, (2008).
160. Juniper S., Abbott L.K., Vesicular-arbuscular mycorrhizas and soil salinity. Mycorrhiza, 4: 45–57, (1993).
161. Marschner H., Ed. Mineral nutrition of higher plants, 2nd Edn, Academic Press, New York, (1995).
162. Adiku G., Renger M., Wessolek G., Facklam M., Hech-Bischoltz C., Simulation of dry matter production and seed yield of common beans under

varying soil water and salinity conditions. Agr Water Manage, 47: 55–68, (2001).

163. Sherameti I., Tripathi S., Varma A., Oelmu¨ller R., The root colonizing endophyte *Pirifomospora indica* confers drought tolerance in *Arabidopsis* by stimulating the expression of drought stress-related genes in leaves. Mol Plant Microbe, 21:799–807, (2008).
164. Sun C., Johnson J.M., Cai D., Sherameti I., Oelmu¨ller R., Lou B., *Piriformospora indica* confers drought tolerance in Chinese cabbage leaves by stimulating antioxidant enzymes, the expression of drought-related genes and the plastid localized CAS protein. J Plant Physiol, 167:1009–1017, (2010).
165. Vadassery J., Tripathi S., Prasad R., Varma A., Oelmu¨ller R., Monodehydroascorbate reductase 2 and dehydroascorbate reductase 5 are crucial for a mutualistic interaction between *Piriformospora indica* and *Arabidopsis*. J Plant Physiol, 166:1263–1274, (2009).
166. R.J. Strasser, M. Tsimilli-Michael, D. Dangre, M. Rai. Biophysical phenomics reveals functional building blocks of plant system biology: a case study for the evaluation of the impact of mycorrhization with *Piriformospora Indica*. In: A. Varma and R. Oelmueller (eds.), *Advanced techniques in soil microbiology*, Springer, Heidelberg, pp. 319–338, 2007.
167. Egamberdieva D., Kucharova Z., Selection for root colonizing bacteria stimulating wheat growth in saline soils. Biol Fertil Soil, 45:561–573, (2009).
168. Rodriguez R.J., Redman R.S., Henson J.M., The role of fungal symbioses in the adaptation of plants to high stress environments. Mitig adapt strategies glob chang, 9:261–272, (2004).
169. Arnold A.E., Mejia L.C., Kyllo D., Rojas E.I., Maynard Z., Robbins N., Herre E.A., Fungal endophytes limit pathogen damage in a tropical tree. PNAS J, 100:15649–15654, (2003).
170. Akello J., Dubois T., Gold C.S., Coyne D., Nakavuma J., Paparu P., *Beauveria bassiana* (Balsamo) vuillemin as an endophyte in tissue culture banana (*Musa* spp.). J Invertebr Pathol, 96: 34–42, (2007).
171. Schardl C.L., *Epichloe festucae* and related mutualistic symbionts of grasses. Fungal Genet Biol, 33: 69–82, (2001).
172. Bae H., Kim S., Sicher Jr R.C., Kim M.S., Strem M.D., Bailey B.A., The beneficial endophyte, *Trichoderma hamatum*, delays the onset of drought stress in *Theobroma cacao*. Bio Control, 46: 24–35, (2008).
173. J.L. Lockwood. Exploitation competition. In: G.C. Carroll and D.T. Wicklow (eds.), *The fungal community– its organization and role in the ecosystem*, Dekker, New York, pp.243–263, 1992.
174. Bolwerk A., Lagopodi A.L., Lugtenberg B.J.J., Bloemberg G.V., Visulaization of interactions between a pathogenic and a beneficial *Fusarium* strain during biocontrol of tomato foot and root rot. Mol Plant-Microbe In, 18:710–721, (2005).
175. Rai M.K., Varma A., Pandey A.K., Antifungal potential of *Spilanthes calva* after inoculation of *Piriformospora indica*. Mycoses, 47: 479–481, (2002).
176. Mishra M., Prasad R., Varma A., Rootonic with Bio-Zinc to accelerate *Pennisetum glauccum* seed germination and plant growth. Int J Pl An and Env Sci, 4 (3): 552-561,(2014).
177. Worapong J., Strobel G.A., Ford E.J., Li J.Y., Baird G., Hess W.M., *Muscodor albus* gen. et sp. nov., an endophyte from *Cinnamomum zeylanicum*. Mycotaxon, 79: 67-79, (2001).
178. Worapong J., Strobel G.A., Daisy B., Castillo V., Baird G., Hess W.M., *Muscodor roseus* anna. nov. an endophyte from *Grevillea pteridifolia*. Mycotaxon, 81: 463-475, (2002).
179. Guo B., Wang Y., Sun X., Tang K., Bioactive Natural Products from Endophytes: A Rev App Biochem and Microbiol, 44: 136–142, (2008).
180. Ma Y., Prasad M.N.V., Rajkumar M., Freitas H., Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. Biotechnol Adv, 29: 248–258, (2011a).
181. Rajkumar M., Ae N., Prasad M.N.V., Freitas H., Potential of siderophore-producing bacteria for improving heavy

metal phytoextraction. Trends Biotech, 28:142–149, (2010).
182. Ma Y., Rajkumar M., Luo Y., Freitas H., Inoculation of endophytic bacteria on host and non-host plants—effects on plant growth and Ni uptake. J Hazard Mater, 195:230–237, (2011b).
183. Pimentel M.R., Molina G., Dionísio A.P., Junior M.R.M., Pastore G.M., The use of endophytes to obtain bioactive compounds and their application in biotransformation process. Biotechnol Res Int, 1–11, (2011).
184. Li H.M., Sullivan R., Moy M., Kobayashi D.Y., Belanger F.C., Expression of a novel endophytic fungal chitinase in the infected host grass. Mycologia, 96: 526–536, (2004).
185. De Souza J.J., Vieira I.J., Rodrigues-Filho E., Braz-Filho R., Terpenoids from endophytic fungi. Molecules, 16:10604–10618, (2011).
186. Gutierrez R.M., Gonzalez A.M., Ramirez A.M., Compounds derived from endophytes: A review of phyto-chemistry and pharmacology. Curr Med Chem, 19(18): 2992-3030, (2012).
187. Yin H., Sun Y.H.,Vincamine-producing endophytic fungus isolated from *Vinca minor*. Phytomedicine, 18: 802-805, (2011).
188. Debbab A., Aly A.H., Proksch P., Bioactive secondary metabolites from endophytes and associated marine derived fungi. Fungal Divers, 49: 1–12, (2011).
189. Chandra S., Endophytic fungi: novel sources of anticancer lead molecules. Appl Microbiol Biotechnol, 95(1):47-59, (2012).
190. Kusari S., Zühlke S., Spiteller M., An endophytic fungus from *Camptotheca acuminata* that produces camptothecin and analogues. J Nat Prod, 72:2–7, (2009).
191. Amna T., Puri S.C., Verma V., Sharma J.P., Khajuria R.K., Musarrat J., Spiteller M., Qazi G.N., Bioreactor studies on the endophytic fungus *Entrophospora infrequens* for the production of an anticancer alkaloid camptothecin. Can J Microbiol, 52:189–196, (2006).
192. Rehman S., Shawl A.S., Verma V., Kour A., Athar M., Andrabi R., Sultan P., Qazi G.N., An endophytic *Neurospora* sp. from *Nothapodytes foetida* producing camptothecin. Appl Biochem Microbiol, 44: 203–209, (2008).
193. Liu K., Ding X., Deng B., Chen W., 10-Hydroxycamptothecin produced by a new endophytic *Xylaria* sp., M20, from *Camptotheca acuminate*. Biotechnol Lett, 32: 689–693, (2010b).
194. Shweta S., Zuehlke S., Ramesha B.T., Priti V., Kumar M.P., Ravikanth G., Spiteller M., Vasudeva R., Shaanker U.R., Endophytic fungal strains of *Fusarium solani*, from *Apodytes dimidiate* E. Mey. ex Arn (Icacinaceae) produce camptothecin, 10- hydroxycamp-tothecin and 9-methoxycamptothecin. Phytochem, 71: 117–122, (2010).
195. Zeng P.Y., Wu J.G., Liao L.M., Chen T.Q., Wu J.Z., Wong K.H., *In vitro* antioxidant activities of endophytic fungi isolated from the liverwort *Scapania verrucosa*. Genet Mol Res, 10: 3169–3179, (2011).