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Endophytes: Hidden gems of secondary metabolites and interrelationship with microbiomes

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Abstract
Endophytes are microorganisms known to reside in plant tissues and play a significant role in plant microbiomes. Many microbial groups that colonize plant tissues, such as mycorrhizal fungi, pathogens, epiphytes, and saprotrophs, interact with and share functions with endophytes. While some fungal endophytes produce beneficial or intriguing secondary metabolites, others have an impact on plant growth and reactions to diseases, herbivores, and environmental changes. Metabolites such phenols, polyketides, saponins, and alkaloids support the plant immune system, combat pathogen attacks, and reduce stress caused by both abiotic and biotic factors. These metabolites can now be identified and characterized by comparative analysis of large omics datasets thanks to recent developments in multi-omics techniques. Biological control can be achieved by using certain endophytic manipulations that cause resistance or otherwise outcompete pathogens. Here, we emphasize on novel methods and strategies that can offer a comprehensive understanding of the function of fungal endophytes in the microbiome of plants. The function of many endophytic fungi linked to significant crops and thus are crucial agricultural development. Endophytes, which are hidden from view and frequently disregarded, are becoming more well-known now a days for plant development and survival and sustainability.

Keywords: Endophytes, microbiome, epihytes, biocontrol, pathogen, symbionts

Introduction

In 1886, German botanist Anton de Bary who is regarded as the founder of plant pathology Coined term "endophyte" to refer to microbes that colonizes the tissues of leaves and stem (Wilson D, 1995) [103]. endophytes may comprise latent pathogens, latent saprotrophs, and the initial stages of mycorrhizal fungi and rhizobial microbes in addition to mutualistic and commensalistic symbionts. Charles Bacon's 1975 discovery that pasture grass endophytes in the Clavicipitaceae family were poisonous to cattle brought to light the possible significance of endophytic fungi (Bacon *et al*., 1977) [35]. Later research revealed that endophytes and the toxicity syndromes they caused were common, costing the livestock sector an estimated $600 million annually (Hoveland *et al*., 1993) [62]. One of the most fascinating and significant instances of plant-fungal interactions are the clavicipitaceous endophytes of grasses (i.e., systemic endophytes in the family Clavicipitaceae), which have been examined from a variety of angles. They have served as a major source of inspiration for endophyte research, but when applied to other endophyte taxa, they frequently arouse expectations of mutualism, functional relevance, and coevolution that are not supported (Bacon CW & White JF, 2000) [36]. The five primary functional groups of plant-associated fungi usually divide into mycorrhizal, pathogenic, epiphytic, endophytic, and saprotrophic fungal groups. Few studies examine interactions between these groups or between bacteria and fungi; most solely concentrate on one of these groups.

What is microbiome?

Numerous microbes are frequently linked to land plants. Plant microbiota is the aggregate term for the communities of bacteria, fungi, archaea, and protists that live on the outside of plants and colonize their tissues (Turner, *et al*., 2013) [15]. Different plant tissues are home to different plant communities, which are generally classified as the endosphere (microbial communities that reside within plant tissues), phyllosphere (microbial communities of the outer surfaces of aerial plant parts), and rhizosphere (microbial communities associated with the root surface and adjacent soil layer) (Turner, *et al*., 2013) [15]. The entire collection of

microbial genomes connected to a host plant is known as the plant microbiome, or phytobiome (Guttman *et al*., 2014) [21].
It is widely acknowledged that plant-associated microorganisms are essential to the nutrition, health, and fitness of host plants (Vandenkoornhuyse *et al*., 2015) [22]. Particularly, some bacteria and fungi help plants grow and become more resilient to stress (Hardoim *et al*, 2015) [23]. Plant-microbial interactions can also be neutral (often called commensalism) or even harmful to the host (parasitism or pathogenicity), therefore not all symbiotic organisms benefit the host (Hardoim *et al*, 2015 [23], Porras-Alfaro *et al*., 2011) [24]. Numerous factors, such as host and microbial genotypes, interactions within the microbiota, and other abiotic factors, influence the overall effect of plant-associated microorganisms on host health and fitness (Hardoim *et al*, 2015) [23].

What is endophyte?: A complex entity known as the holobiont is formed by the diverse communities of microorganisms that make up the plant's microbiome (Berg *et al*., 2021) [39]. which can occasionally be expanded to include the pathobiome (Bez *et al*., 2021) [42]. In order to assess the host's health, the pathobiome concept has been used in certain situations where disease is thought to be caused by interactions between a group of organisms (primarily eukaryotic, microbial, and viral communities) within the plant and its biotic environment (Bass *et al*., 2019) [37]. The interactions range from mutualism to commensalism to amensalism to parasitism, and the organisms may reside inside the plant for their whole lives or just during specific phases (Jørgensen *et al*., 2020) [46]. There are numerous instances where an organism that is known to be a pathogen in one host plant can be found colonizing another plant species without causing disease in that host, proving that the organism is an endophyte in that species. These are examples of "true" endophytes that do not cause disease in plants. For instance, the barley pathogen *Ramularia collo-cygni* is a harmless endophyte in other cereals (Kaczmarek *et al*., 2017) [66]. and *Fusarium* species that cause head blight in cereals have been detected in carrots (Louran *et al*., 2013) [72]. Examples from other plant species where this has been observed include fungi such as *Verticillium dahliae* (Wheeler *et al*., 2019) [102]. Remarkably, Manzotti *et al*. (2020) [74] isolated six fungal species from tomato roots (*Colletotrichum coccodes, Plectosphaerella sp., Pyrenochaeta lycopersici, Thielaviopsis basicola, Alternaria infectoria, and Fusarium sp*.) that, when inoculated separately on tomato plants, caused disease. This finding bolsters the claim that a balanced microbiome is necessary for plant health (Berg *et al*., 2021) [39], with the pathogenic organisms being suppressed by the other organisms.
Two subgroups of the endophytic community can be distinguished: "obligate endophytes," which are endophytes that rely heavily on plant metabolism for their survival, and "facultative endophytes," which are endophytes that spend a portion of their life cycle outside of their host body and are primarily associated with plants that are present in their nearby soil environment (Hardoim *et al*., 2015; Abreu-Tarazi *et al*., 2010) [23, 1]. Of all the microorganisms that live in the rhizosphere, endophytic fungi, also known as fungal endophytes, have attracted major research interest. According to Radic and Strukelj (2012) [85], Uzma *et al*. (2018) [100], and El Enshasy *et al*. (2019) [51], this is because they can produce a variety of bioactive chemicals, including biostimulants and antimicrobial compounds, which can aid in the manufacture of essential oils. Essential oils are fragrant substances with a low boiling point and a high vapour pressure. *Streptomyces aureofaciens* SMUAc130-infected *Zingiber officinale Rosc*. roots yielded vanillin and 3-methoxy-4-hydroxytoluene (Taechowisan *et al*., 2005) [95].

How endophytic fungi interact with their hosts molecularly: Mutualistic, commensalistic, and pathogenic interactions are the three ways that endophytic fungi engage with their host plant. Both host plants and EFs gain from one another in mutualistic symbiosis, which promotes ecological and evolutionary success. The EFs change the metabolism of the host plant tissue as they colonise it, increasing the plant's resistance to environmental challenges including drought and heavy metals while also promoting growth and development and nutrient uptake. While the host plant offers the EFs shelter and enough nutrients for growth and life cycle completion, it can also shield the host plant from pests, herbivorous animals, and harmful microbes. EFs interact with the host plant in commensalistic or latent pathogenic relationships, and they may or may not have any positive effects.
Pattern-recognition receptors (PRRs), which are cell surface proteins that can identify microbial- or pathogen-associated molecular patterns (MAMPs/PAMPs) generated by the interacting microbe, allow plants to interact symbiotically with a wide variety of microorganisms in the rhizosphere. The initial layer of plant innate immunity is triggered by these PRRs. Signalling pathways that impede the growth of endophytic proliferation, such as miRNA-mediated pathways involved in plant defence mechanisms, are generally suppressed during the establishment of a mutualistic symbiotic relationship (Plett and Martin, 2018) [82]. Known as pattern-triggered immunity (PTI), this extracellular identification through MAMPs/PAMPs or damage-associated molecular patterns (DAMPs) has been found to result in the first layer of innate immunity via triggered defences (Tang *et al*., 2017; Saijo *et al*., 2018) [97, 89]. The breakdown of plant cell wall components like oligonucleotides, cellodextrins, and compounds released under stress (cutin monomers and small peptides) can activate another PTI upon cellular disintegration. This process produces endogenous signals known as DAMPs, which PRRs can also detect. The botrytis-induced kinase1 (BIK1) effector kinase of the pattern recognition receptors (PRRs) complex is activated when a microorganism infects the host plant. This activation leads to a rise in the cytosolic calcium ($Ca2+$) level mediated by cyclic nucleotide-gated channels (CNGCs). During pathogen-associated molecular pattern-triggered immunity (PTI), this increase in $Ca2+$ is known to be a critical signal for initiating the activation of pathogen-associated molecular pattern (PAMP) signals involved in plant immunity (Tian *et al*., 2019) [98]. Effector-triggered immunity (ETI), a stronger and more powerful defence mechanism of the plant, is activated when the pathogen successfully infects a plant by defeating PTI through effector-triggered susceptibility (ETS). Plant defence systems that react to microbial invasion include Pathogen-Triggered Immunity (PTI) and Effector-Triggered Immunity (ETI).

Distinct molecular characteristics of pathogens and endophytes: As previously stated, both endophytes and effective pathogens have evolved strategies to evade detection to the degree that colonisation is not impeded by the plant immune system (Lu *et al*., 2021) [73]. The exact reason why certain organisms become pathogenic while others adopt an endophytic path is currently unknown. Previously (Kogel *et al*. 2006) [4] addressed this problem by investigating particular molecular processes, among other things. The quantity and concentration of the organisms is another crucial aspect (Mishra *et al*., 2021) [5] endophytes are frequently found in far lesser amounts than infections, which means immunity might not be elicited.

Effector molecules are particularly interesting in understanding interactions as they modulate the biological activity of the interplay between microorganism and plant (Mishra *et al*.,2021, Bauters *et al*., 2021) [5, 6]. Several studies have examined the role of endophytic effector molecules. Constantin *et al*. (Constantin *et al*., 2021) [9] discovered homologues of known *Fusarium oxysporum* tors from pathogens in endophytic *F. oxysporum* strains while the latter often possessed fewer effector candidates than pathogenic strains. They maintained that research on the "effectorome" can be utilized to determine whether a given strain is likely to be harmful or helpful.

The outcome of interactions between microorganisms and plants depends on the regulation of the plant-defense hormone signalling (Pieterse *et al*., 2014) [7]. Indeed, plant pathogens can manipulate phytohormone levels to facilitate infection (Bauters *et al*., 2021, Collinge & Taylor, 2020] [6, 8]. Endophytes also control their hosts, especially in response to abiotic stress (Hilbert *et al*., 2012) [11], reviewed by (Khare *et al*., 2018, Lu *et al*., 2021 and Mishra *et al*., 2021) [5]. Other compounds have been demonstrated to confer signalling across kingdoms, typically to facilitate harmful or commensal partnerships. Therefore, some necrotrophic infections have the ability to create RNAi, which are tiny signalling RNA molecules that can inhibit host defences (Wang *et al*., 2016) [12]. Additionally, these molecules have been linked to interactions between the fungal endophyte Serendipita indica and the grass Brachypodium distachyon (Secic *et al*., 2016) [13] as well as to the modulation of endophytic signalling (Khare *et al*., 2018) [10].

Pathogen and insect pest biocontrol via endophytic fungi

Several strategies can be used to control insects and fungal pathogens: antagonism, parasitism, competition, or the generation of secondary metabolites; host defence induction; or host growth and vigour promotion (Alabouvette *et al*., 2009) [26]. A single endophyte may use multiple of these overlapping processes. The majority of research has suggested triggering host defences, particularly systemic acquired resistance (SAR) mechanisms. For instance, *Lecanicillium spp*. and *Trichoderma* spp. are both mycoparasites and insect parasites, however they also generate inhibitory metabolites, while *Beauveria bassiana* suppresses both fungal pathogens and insects, mostly through the production of secondary metabolites (Harman *et al*., 2004, Ownley *et al*., 2010) [57, 81].

1. Pathogen: Biological disease control is another result of interactions among plants, pathogens, and endophytes (Jorgensen *et al*., 2020, Collinge *et al*., 2019) [46, 40]. The necessity of creating sustainable (i.e., low input) yet efficient disease management strategies is the practical aspect of comprehending microbial lives. For many years, biological control in particular has been researched as a substitute for chemical disease management (Collinge *et al*., 2022) [2]. More attention is being paid to endophytes as a potential source of microbial biological control agents (Collinge *et al*., 2019) [40]. A range of fungal diseases can be effectively controlled by endophytic fungi. The endophyte is infected prior to exposure to the pathogen in the majority of the examples that follow. Endophyte-free plants serve as the control; these can be challenging to produce and care for, particularly in trees, as infection by airborne and rainborne inoculum must be avoided. Numerous studies have shown that endophytic fungi can lessen damage caused by significant diseases in cacao, such as *Moniliophtora roreri*, *Moniliophtora perniciosa*, and *phytopthora palmivora* (Arnold and Herre, 2003, Arnold *et al*., 2003, Mejia *et al*., 2008) [29, 33, 76]. Witches' broom disease in cacao can be reduced by up to 70% with the help of the endophyte *Glocladium catenulatum* (Rubini *et al*., 2005) [86]. Two endophytes (*Cordana sp*. and *Nodulisporium sp*., out of 723 cultures) shown possible efficacy against *Colletotrichum* in wild bananas (*M. acuminata),* as measured by a decrease in the pathogen's radial growth and growth inhibition through the generation of secondary metabolites (Nuangmek *et al*., 2008) [80].

2. Pests: Although the effects of horizontally transmitted endophytes on insects that feed on shoots vary greatly (Hartley & Gange, 2009) [59], multiple studies have shown promise in this regard. Out of fifty foliar fungal endophytes that were isolated from the needles of *Picea rubens* (red spruce), three of them were poisonous to the eastern spruce budworm *Choristoneura fumiferana* (Sumarah *et al*., 2010) [94]. *Aspergillus parasiticus*, *Beauveria bassiana*, and *Lecanicillium lecanii* are entomopathogens that can be effectively inoculated in the field and have been found to be endophytes in a variety of plants (Gim´enez *et al*., 2007) [55].

Sources of New Secondary Metabolites: Endophytes

Numerous bioactive substances with a broad spectrum of biological activities, such as insecticidal, antioxidant, antifungal, antiviral, antibacterial, and cytotoxic qualities, can be produced by endophytic fungus. Terpenoids, phenols, alkaloids, polyketides, quinones, steroids, enzymes, and peptides are just a few of the chemical classes to which these substances belong. It is well recognized that endophytic fungi secrete these beneficial chemicals, which help the host plant defend against biotic and abiotic stresses. The activation of quiet biosynthetic pathways, epigenetic changes, and other strategies are approaches to increase the capacity of endophytic fungi to produce these secondary metabolites. Terpenoids are one of these secondary metabolites that have become a particularly significant class of compounds with considerable uses in human health and agriculture. Therefore, a promising new source for the bioproduction of these important terpenoid chemicals is endophytic fungus.

Table 1: Secondary metabolites produced by endophytic fungus

Secondary Metabolites	Endophytic Fungi	Function	Reference
Terpenoids	*Pestalotiopsis microspora, Penicillium brevicompactum, Aspergillus terreus, Fusarium oxysporum, Colletotrichum gloeosporioides*	Intervenes in the interaction between endophytic fungus and the microbiome and helps to moderate cross-talk between endophytic fungi and host plants.	De la Porte *et al.* (2020) [49], Schulz-Bohm *et al.* (2017) [91], Ditengou *et al.* (2015) [50], Kaddes *et al.* (2019) [67], and Ancheeva *et al.* (2020) [28]
Steroids	*Alternaria alternata, Aspergillus fumigatus, Colletotrichum gloeosporioides, Xylaria sp. Neosartorya sp., Nodulisporium sp.*	Biologically active lipid-based substance with a variety of anti-inflammatory, anti-cancer, and anti-parasitic effects. Ergosterol, stigmasterol, campesterol, 22-hydroxycholesterol, brassicasterol, and aspergilolide are a few examples.	Alam *et al.* (2021) [27], Zhang *et al.* (2019) [105], Nowak *et al.* (2016) [79], and Yang *et al.* (2015) [104]
Quinones	*Alternaria sp., Fusarium sp., Xylaria sp., Phoma sp., Pestalotiopsis sp., Aspergillus sp., Talaromyces assiutensis*	These have a variety of therapeutic uses. Quinones with antibacterial qualities include phomol and phomenone. Other derivatives, such as fusaric acid, pestaloside, and xylarione, are being researched as possible anti-cancer medications because of reports of their anti-tumor properties.	Lou *et al.* (2013) [71], Christiansen *et al.* (2021) [47], Mishra R. C. *et al.* (2021) [77], and Ancheeva *et al.* (2020) [28]
Mycorrhizin	*Plectophomella sp., Pezicula sp.*	Significant cytotoxic, nematoidal, antibacterial, and antifungal effects are displayed by these secondary metabolites. Possessing such unique antimicrobial properties also suggests possible application in the food industry.	Adeleke and Babalola (2021) [25], Preethi *et al.* (2021) [84], McMullin *et al.* (2017) [75], Hussain *et al.* (2014) [63], and Schulz *et al.* (2015)

Endophytes: In Regulation of biotic stress

Any material, microbe, or adverse circumstance that has an impact on a plant's growth and development, metabolism, or nutrition, whether directly or indirectly, is considered stress. Numerous causes, including temperature, mineral deficiencies, extended periods of precipitation, issues with desiccation, insects and infections, pesticides and herbicides, pollution, climatic extremes like drought or floods, elevated UV radiation, and more, can cause stress on vegetation. Based on the LICHTENTHALER model of stress in plants (Lichtenthaler, 1998) [69], stress can be separated into several discrete phases. The first stage, known as the response phase, is when stress first appears and is distinguished by an alarm reaction. The plant then moves into a stage of resistance and continues to be under stress during the reparation phase. After prolonged stress, the plant enters the third phase, known as the terminal phase, where it reaches a state of exhaustion. Lastly, the regeneration phase enables the plant to recuperate and revitalize following a stressful event. These stress phases provide a detailed description of the alterations that take place in the plant under adverse or stressful circumstances.

Because endophytic fungi are viewed as possible infections, when they interact with their host plant, the plant's defences are triggered to combat their presence and have ability to circumvent these defences and take over the host plant. The growth of pathogens and herbivores invading the host plant in the presence of endophytic fungi is then inhibited by the bioactive compounds that these fungi produce, including terpenoids, phenols, alkaloids, steroids, quinones, poly-ketones, and peptides (Lu *et al*., 2021) [73]. The host plant has a defence mechanism against harmful microbes thanks to this event. Endophytes produce a variety of terpenoids that aid host plants in fending off biotic and abiotic stressors. For instance, *C. sphaerospermum* and *Cladosporium cladosporioids*. Persicaria minor commonly known as kesum is herbaceous plant extensively found in south-east Asia and is particularly essential for flavonoid and terpenoid synthesis. According to a Samad *et al*. (2019) [90], the terpenoid biosynthesis triggered by *Fusarium oxysporum* was post-transcriptionally controlled by six miRNAs of *Persicaria minor.*

Discovering secondary metabolites from endophytes using multi-omics technologies: The soil has a wide variety of microorganisms that interact with the plants that grow there. Plant-microbe interaction is the term used to describe these interactions. These interactions are crucial for creating a balanced, healthy ecology. Because plants produces a variety of organic and inorganic nutrients, the soil becomes nutrient-enriched, which is highly advantageous for the microbial consortia that develop there. One instance of plant-microbe interaction is the presence of endophytes in plants. Because of their ability to counteract biotic and abiotic challenges and their use in agriculture, these interactions between plants and different microorganisms, such as bacteria and fungi, are advantageous and have drawn the attention of several researchers.

Microorganisms produces wide variety of secondary metabolites throughout their life cycle identification of these secondary metabolites is challenging for researchers for a number of reasons, including the following: (1) metabolites are secreted by plants in very small amounts; (2) the metabolites that are secreted and synthesized are also actively metabolized; (3) they have a variety of physical and chemical characteristics that necessitate the use of particular assays to ascertain their structures and functions; and (4) these metabolites are secreted at specific stages of the plant's life, making it challenging for researchers to find them (Luo *et al*., 2022) [58]. Implementing interdisciplinary approaches is essential to overcoming the challenges in the research of plant secondary metabolites.

A multi-omics approach, for instance, has proven essential in the identification of these metabolites via the methodical comparative study of enormous datasets by researchers. via a broader perspective, "omics" are the scientific domains that are related to quantifying biological molecules via high throughput technologies. This covers a wide range of biological disciplines, including transcriptomics, proteomics, metagenomics, metabolomics, phenomics, epigenomics, and genomics. A multi-omics strategy is used when all of these areas are investigated together in order to find a biological molecule. A scientific experiment can be created to match the structure and function of the metabolite by utilising one or more omics techniques.

The study of an organism's entire genome, including its structure, function, evolution, mapping, and editing, is known as genomics in biology. The entire sequence of an organism's DNA is called its genome. Essential information regarding the control of gene expression, such as promoter regions, untranslated regulatory regions, and splicing sites, as well as the protein-coding sequence that establishes a gene's function within an organism, are found in DNA, the basic genetic material (Chu *et al*., 2020) [65]. Advanced technologies like single nucleotide polymorphism (SNP) chips, which allow the identification and analysis of genetic variations among individuals, and high-throughput DNA sequencing methods like Illumina HiSeq, PacBio, and Nanopore sequencing are driving the field of genomics.

Mostly produced by endophytes, compounds such as alkaloids, flavonoids, minerals, polyphenols, and vitamins help plants adapt to harsh environments and support their health (Balestrini *et al*., 2021) [34]. Techniques like gas chromatography-mass spectroscopy (GC-MS), Fourier transform infrared (FT-IR), nuclear magnetic resonance (NMR) spectroscopy, metabolite fingerprinting, time-of-flight mass spectrometry (TOF-MS), Orbitrap Mass Spectrometer (Orbitrap-MS), and flash chromatography can be used to identify and analyse these molecules. The signaling pathway start and colonization factors related to host cell and endophytic contacts can be analysed on the basis of proteomics research. Nevertheless, new omics methods such as epigenomics, ionomics, fluxomics, lipidomics, nutrigenomics, and toxicogenomics are now accessible to understand the fungal genome.

Endophytes variability over time and space

In various locations, climates, seasons, and conditions, endophytic fungal communities can differ significantly within a single host species (Carroll 1995, Gamboa *et al*. 2002.) [44, 52]. Numerous variables, including as the plant host, plant density, nutrient availability, environmental circumstances, and interactions with external microbiomes (such as soil fungus and bacteria), can affect the composition of the mycobiome.

There is variation at every level. Endophytic community differences within a single host species may exhibit no discernible variation (Herrera *et al*., 2010, Khidir *et al*., 2010.) [61, 68] or may increase with distance (Arnold and Herre, 2003.) [29]. In the dominant members of their endophytic communities, a single plant's leaves, roots, and woody stems frequently change significantly (reproductive structures have received less attention), and they may even exhibit functional variations (Gazis, Chaverri 2010, Herrera *et al*., 2010, Pocasangre *et al*., 2000) [54, 61, 83]. For instance, various fungi that produce a variety of secondary metabolites colonize the leaves, stems, and roots of lucerne plants (Weber, Anke 2006) [101]. These variations in endophytes among roots, stems, and leaves could be as indicative of variations in the external environment as biological variations among organs and tissues. There were no discernible variations in the endophytic communities of epiphytic orchids (genus Lepanthes), whose leaves and roots are equally exposed to light and air (Bayman *et al.,* 1997) [38]

Comparing endophytes with epiphytes

Epiphytes, which reside on the outside of plants, are sometimes compared with endophytes (Santamarıa & Bayman,2005) [20]. In actuality, endophytes cannot be inactivated by surface sterilization, which often involves ethanol and sodium hypochlorite to break surface tension, but epiphytes can be removed from plant surfaces. Therefore, it is possible to suppose that an epiphyte that grows in culture and survives surface sterilization is an endophyte (Arnold & Lutzoni, 2007) [19]. Comparisons inside pine and coffee leaves show that endophytic communities are different from epiphytic ones, despite the fact that they may reside less than a millimetre apart, despite the paucity of research comparing phylloplane and endophytic fungal populations of the same leaves (Legault *et al*., 1989, Santamarıa & Bayman, 2005) [16, 20].

Additionally, when internal tissues are exposed, endophytes may transform into epiphytes and aid in shielding the exposed tissues from the outside world reference. Hyphae of the endophytes *Rhodotorula minuta* and *Hormonema dematioides*, as well as related biofilms, were shown to cover the calli in tissue cultures of Pinus sylvestris obtained from shoot tips (Pirttila *et al.,* 2002) [17]. How such endophytes coordinate function, interact with other microbiome biofilm components, and affect plant fitness deserves additional investigation.

Endophytes: In Phytoremediation

Plants can become more proficient at absorbing and breaking down xenobiotic substances in the soil with the help of bacterial endophytes. For instance, compared to plants on uncontaminated soil, plants in petroleum-contaminated soil had endophyte communities with greater frequencies of bacteria that break down hydrocarbons (Siciliano 2001) [92]. Increased toluene tolerance and reduced toluene transpiration to the atmosphere were observed in plants treated with the engineered endophytic bacteria VM1330 (Newman, Reynolds 2005) [78]. Compared to uninfected plants, Festuca grasses infected with endophytic clavicipitaceous fungus extracted more polycyclic aromatic hydrocarbons from soils contaminated with oil (Soleimani 2010). An increase in plant resistance to zinc toxicity was seen in a study of *Lolium perenne* infected with the endophyte *Acremonium lolii* (Bonnet *et al*., 2000) [43]. In a similar vein, mycorrhizal fungal communities are known to help plants survive in contaminated soils and to respond differently to heavy metals (Gaur A, Adholey A. 2004) [53]. Improvements in nutrition, defence against infections, or the direct breakdown or buildup of heavy metals in certain structures could all lead to phytoremediation augmentation (Gaur, Adholey 2004, Tonin *et al*., 2001) [53, 99].

Responses of endophytes and plants to climate change

It is anticipated that plant microbiomes would affect how plants and ecosystems react to climate change since they have an impact on plant establishment, survival, and resilience to environmental stress (Rudgers *et al*., 2004) [87]. The fact that plant microbiomes are dynamic and exhibit significant seasonal and host variation, particularly among sympatric plant species, complicates research on how plant fungal systems react to environmental cues (Collado *et al*., 1999) [48]. For instance, Ranunculus acris had high rates of colonization by both AMF and DSE during the summer, *Trollus europaeus* had lower colonization, and *Alchemilla glomerulans* saw a drop-in colonization by DSE fungi during the summer (Ruotsalainen *et al*., 2002) [88]. Long-term studies show that root biomass and diversity, which are impacted by the degree of mycorrhizal and endophytic fungal colonization, have a favourable relationship with ecological stability. Although many species are required to maintain ecosystem functioning, particularly in places with extensive land use (Loreau *et al*., 2001) [70], little is known about the impact of endophytic fungi on plant and ecosystem stability. To comprehend the functions of plant microbiomes in reactions to climate change, long-term monitoring studies and quantitative, standardized methodologies are crucial.

Dual Nature of Endophytes in Sustainable Agriculture

As seen in the preceding sections, the fluidity of the boundaries between endophytes and other functional groups calls into doubt the safety of using endophytes in the field for biocontrol. Will environmental changes (such as host gene expression or nutrition availability) cause the fungus to move from a mutualistic to a pathogenic state? Will the endophyte do harm to adjacent plants? Each specific application should take these considerations into account because it has been demonstrated that some endophyte-host pairings cause all of these behaviors to occur while others do not.

To protect turfgrasses from insect pests, for instance, commercial preparations of clavicipitaceous endophytes of grasses are available (Clay, 1989) [18]. Utilizing an endophyte for biocontrol is thought to provide the benefit of shielding the organism from unfavourable external circumstances due to its internal residence within the plant. Although a number of biocontrol organisms have been recovered from the plant's interior, it's possible that their biocontrol action was not confirmed to be endophytic (Latz *et al*., 2018) [30]. Even yet, an organism may still have an effective biocontrol effect, which likely indicates that it may only be endophytic for a portion of its life cycle. In two recent investigations, fungal endophytes obtained from healthy wheat tissues under disease pressure were efficient biological control agents of *Septoria tritici* blotch (Latz *et al*., 2020) [32] and *Fusarium* head blight (Rojas *et al*., 2020) [31] when applied as sprays.

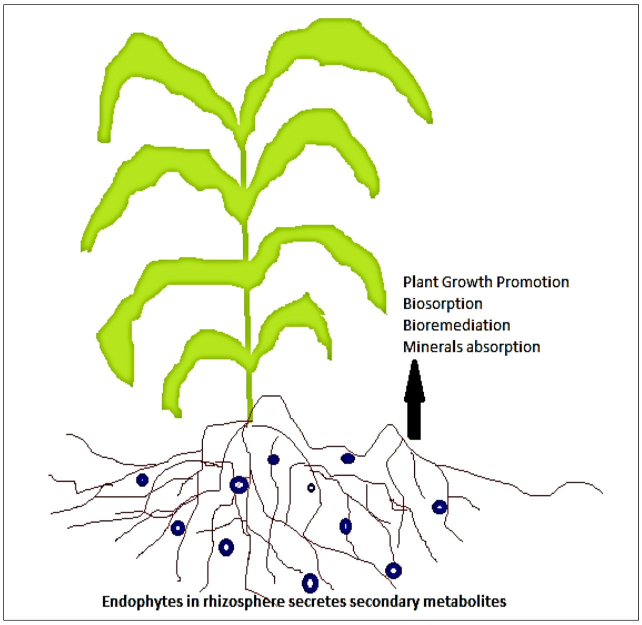

Fig 1: Endophytes in Rhizosphere Secretes Secondary Mtabolites

Conclusion

The majority of endophytes will likely never have a significant impact on the host as individuals, but they may have an impact as part of the microbiome and functional metagenome. The fact that different organs of a single host contain different communities increases its phenotypic plasticity (Herre, Mejia *et al*., 2007) [60], which may be advantageous in unpredictable environments. This is an emergent property made possible by the complex interactions between microbiomes and plants. A portion of the significance of endophytes is self-contradictory, since some do not continue to be endophytes, as it is becoming more evident that they overlap with other functional groups of plant-associated microorganisms, such as the DSEs that create relationships that operate similarly to mycorrhizae. Understanding the functions of fungal endophytes will be aided by our growing capacity to visualise intricate interactions within the microbiome. We believe that there are unknown but essential endophytes and effects of endophytes yet to be found. Agriculture will have to do more with less as population expansion, rising prosperity, and climate change put more strain on the world's food supply.

It has been demonstrated that endophytes shield a variety of plants from a broad spectrum of diseases and insect pests. Some work by creating host defenses, causing antagonism, or enhancing the nutrition and health of plants. In harsh conditions where neither the host nor the endophyte can live on their own, certain endophytes help plant hosts to survive. This emerging characteristic suggests that endophytes may have an impact on how plants react to climate change. Endophytes are a bioprospecting gold mine. Many intriguing cases have not yet been found, based on the number of new endophytes and metabolites that have been reported in the last 20 years.While less evident, we think it will be just as crucial to comprehend and control the intricate relationships of plant microbiomes.

Fungal endophytes exhibit functional overlap and intricate relationships with mycorrhizal fungi, pathogens, saprotrophs, epiphytes, and bacteria in their interactions with plants and the environment. Endophyte cultivability was a limiting factor until recently. It is possible to identify unculturable species using direct PCR from plant tissue. The investigation and simultaneous identification of active components of the entire microbiome are made possible by metagenome methods and other PCR techniques. Emergent characteristics can be seen in certain interactions between endophytes, other microbiome elements, host plants, diseases, and pests. These intricate relationships can be analysed and integrated through the study of plant microbiomes as a system.

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