**Endophytes: Hidden Allies in Plant Health and Ecosystem Resilience**

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**Abstract:**

Endophytes living inside the tissues of plants, play an important role in determining plant health and ecosystem resilience. It has drawn more and more attention in recent years in light of their mutualistic interactions with their host plants and the larger ecosystem. Endophytes have evolved to intricately interact with their hosts through evolutionary processes, which has benefited both parties in different ways. Endophytes have been discovered in a variety of plant species, including grasses, trees, and crops. These endophytes support a wide range of symbiotic relationships. These connections help plants better absorb nutrients, resist diseases and pests, and are more resilient to abiotic stresses like drought and severe temperatures. Endophytes’ ability to modulate plant growth and physiology has shown potential implications in sustainable agriculture, providing an eco-friendly alternative to traditional chemical interventions. Furthermore, their protective mechanisms have proven pivotal in promoting plant health in natural ecosystems, contributing to biodiversity conservation and ecosystem stability. The chapter explored different fascinating studies carried out to identify the mechanisms underlying endophyte-plant interactions. The complexity of these relationships has been revealed through different research into the underlying biochemical pathways and genetic components, opening up new opportunities for biotechnological applications in agriculture and ecological restoration. Also, hidden presence within the green tapestry of nature makes them an indispensable ally, underscoring the profound interdependence that governs life on Earth. Harnessing their potential could usher in a new era of sustainable practices, fostering harmony between human activities and the delicate balance of the natural world.

**Keywords:** Endophytes, Ecosystem, Symbiotic relationships, Endophyte-plant interactions

**1. Introduction:**

Interactions between plants and microbes offer several benefits, especially for good bacteria. Endophytes, or plant-associated bacteria, are internal inhabitants of plants. They have direct effect over the host plant cells and mediate reactions as a result of interactions without causing harm to the host or evoking severe defense reactions. Numerous studies have shown that endophytic bacteria, also known as plant tissue bacteria, are essential for the growth and fitness of a wide range of monocot and dicot plant species. Endophytes are bacteria and fungi that thrive in seemingly healthy internal plant tissues and are either facultative or obligatory symbiotic microbes. Gram-positive bacteria are recognized to affect plant physiology and development among endophytic microbes. The control of soil-borne diseases, plant growth, symbiotic-mutualistic, commensalistic, and trophobiotic interactions, as well as the support of the host plant’s defense against environmental stress (Ryan et al., 2008). The structure of an endophytic community can be influenced by a number of variables, including environmental circumstances, plant-microbe and microbe-microbe interactions, and others (Ryan et al., 2008). By producing phytohormones, low molecular weight compounds, enzymes, antimicrobial substances like antibiotics, and siderophores, several bacterial endophytes have been demonstrated to support plant growth and increase nutrient uptake. Some endophytes have higher pathogen resistance, which makes them perfect candidates for biological control. On Earth, plants play a significant role in the fixation of atmospheric CO2.Plants can synthesize an almost unlimited variety of carbonaceous molecules and reduce the carbon present in CO2 thanks to the energy they obtain from solar radiation. This makes plants particularly appealing as nutrient reservoirs for such bacteria because photosynthetic provide as key sources of carbon, nitrogen, and energy for bacteria and other plant-associated heterotrophic microorganisms. Endophytic bacteria perform and exhibit a variety of growth and biocontrol features through different physical, molecular and biochemical pathways. It has been demonstrated that bacterial endophytes inhibit the onset of disease by facilitating the de novo synthesis of new chemicals and antifungal metabolites. Different endophytic strains are used for novel compounds isolation and may lead to the discovery of new medications that can effectively treat diseases in people, plants, and animals. Many endophytes have demonstrated a natural potential for xenobiotic degradation or may function as vectors to introduce degradative features, in addition to the creation of new compounds. Endophytes are well known for promoting plant growth by increasing nitrogen fixation or secreting substances resembling plant hormones (Hurek and Reinhold Hurek 2003). They are also known to produce a variety of secondary metabolites with both industrial and medical uses. Furthermore, endophytes’ ability to control plant diseases is one of its beneficial traits since, unlike chemical pesticides, they can assist sustainable agriculture and do not harm the environment or have toxic side effects. It is believed that via rhizosphere, endophytic bacteria become colonise in various plant parts/tissues such as roots, stem, leaves, flowers, fruits, and seeds (James et al. 2002). Bacterial endophytes are better protected from abiotic stresses like extreme variations in temperature, pH, nutrient, and water availability as well as biotic stresses like competition than free-living, rhizosphere or phyllosphere microorganisms (Rosenblueth and Martinez-Romero 2006). In addition, endophytic bacteria colonise habitats that are better suited for developing mutualistic partnerships with plants. Endophytic bacteria have primarily been studied after being cultured in lab media, but a more comprehensive plan is emerging that makes use of techniques that do not require the bacteria to be cultured and that analyze sequences from bacterial genes obtained from DNA isolated from inside plant tissues. These beneficial effects have been the main focus of endophytic bacteria study to comprehend the interactions between bacterial endophytes and their hosts’ plants.

**2. Types of endophytes:**

Endophytes establish various associations with plants, residing within their tissues as either bacteria (such as actinomycetes or mycoplasma) or fungi. Over 200 genera across 16 bacterial phyla are known to engage with endophytes, with a significant representation from Actinobacteria, Proteobacteria, and Firmicutes. These endophytic bacteria encompass both gram-positive and gram-negative types, including *Achromobacter, Acinetobacter, Agrobacterium, Bacillus, Brevibacterium, Microbacterium, Pseudomonas, Xanthomonas* etc. The diversity extends further to bioactive metabolites, many with antimicrobial and anticancer properties. Streptomyces, for instance, contributes substantially to this diversity, with 76% of such compounds attributed to this genus.

Actinomycetes, classified within the *Actinobacteria* phylum, are prokaryotic microorganisms that resemble fungi due to their mycelium-like structures and spore formation (Chaudhary et al., 2013; Barka et al., 2016). Historically, they were thought to bridge the gap between fungi and bacteria (Barka et al., 2016), yet their likeness to fungi is only surface-level. While sharing some characteristics with bacteria, actinomycetes exhibit thin cells, a prokaryotic nucleoid-organized chromosome, and a peptidoglycan cell wall. Among endophytes, actinomycetes stand out for producing unique chemical compounds with medicinal significance (Gayathri and Muralikrishnan, 2013; Singh and Dubey, 2015). Many antimicrobial agents are attributed to endophytic actinomycetes, with the genus *Streptomyces* being notably prevalent (Zhao K. et al., 2011; Golinska et al., 2015). *Streptomyces species* have yielded diverse compounds of interest like munumbicins, naphthomycin, clethramycin, coronamycin, edarmycin, saadamycin, and kakadumycins. Other active compounds discovered from actinomycetes include paclitaxel from *Kitasatospora sp*.

Mycoplasma species have also been documented as endophytes in plants. Reports indicate that endophytic mycoplasma species establish a symbiotic relationship with certain red algae, including *Bryopsis pennata*, and *B. hypnoides* (Hollants et al., 2011). However, concrete evidence regarding their applications, extraction sources, or utilization against foodborne diseases or other pathogens remains unverified.

Fungi, as heterotrophic organisms, engage in diverse life cycles that encompass symbiotic associations with various autotrophic organisms (Dayle et al., 2001). Endophytic fungi are categorized into two primary groups based on their phylogeny and life history traits. These groups are clavicipitaceous, which primarily infect specific grasses in cooler regions, and non-clavicipitaceous endophytes, originating from asymptomatic tissues of non-vascular plants, ferns, allies, conifers, and angiosperms. The latter group is confined to the Ascomycota or Basidiomycota categories (Jalgaonwala et al., 2011; Bhardwaj and Agrawal, 2014).



Fig 1: Types of endophytes present in plants

Endophytic fungi contribute significantly to medicine production, yielding widely used antibiotics and anticancer drugs. For instance, Penicillenols extracted from Penicillium sp. exhibit cytotoxic effects against numerous cell lines. Taxol, isolated from Taxomyces andreanae, stands out as an effective anticancer drug derived from endophytic fungi. Various other compounds like clavatol (*Torreya mairei*), sordaricin (*Fusarium spp*.), jesterone (*Pestalotiopsis jesteri*), and javanicin (*Chloridium spp*.) showcase potent antibacterial and antifungal properties against numerous foodborne infectious agents (Jalgaonwala et al., 2011). Furthermore, pestacin, isolated from *P. microspora*, exhibits notable antioxidant characteristics.

**3. Diversity and Distribution of Bacterial Endophytes:**

More than 300,000 plant species have one or more endophytes. In plant tissues such as leaves, roots, seeds, stems, fruits, ovules, and tubers, endophytic bacteria have been seen, and they are typically found in intercellular spaces and xylem vessels (Reinhold Hurek and Hurek 1998). Both monocotyledonous and dicotyledonous plants, including herbaceous crop plants like sugar beetroot and maize as well as woody tree species like oak and pear have produced endophytic bacteria. Gram-positive and Gram-negative bacterial species isolated from a variety of host plants are both categorized as bacterial endophytes. Endophytic population diversity varies with bacterial species and host genotypes; it is also influenced by the host’s developmental stage and inoculum density. According to reports, endophytes are related with more than 200 genera and 16 phyla of bacterial species, the majority of which being *Actinobacteria, Proteobacteria*, and *Firmicutes.* These actinomycetes have historically been thought of as intermediate organisms between fungi and bacteria. Endophytic actinomycetes have the ability to create a wide range of chemical substances with distinctive structures that have significant medical value. Fungi are a heterotrophic group of organisms with a diversity of life cycles that include symbiotic partnerships with a wide range of autotrophic creatures. On the basis of their phylogeny and lifecycle characteristics, endophytic fungi have been divided into two major categories. These include the non-clavicipitaceous endophytes, which are from asymptomatic tissues of nonvascular plants, ferns and allies, conifers and angiosperms and are restricted to the Ascomycota or Basidiomycota group, as well as the clavicipitaceous endophytes, which infect some grasses restricted to cool regions and infect some grasses that are infected by them. Some of the most widely used antibiotics and anticancer medications are made by endophytic fungus. Numerous cell lines are cytotoxic to penicillenols, which are obtained from Penicillium species. The most successful and effective anticancer medicine ever isolated from endophytic fungi is called taxol, which was isolated from *Taxomyces andreanae*.

**4. Interaction of Bacterial Endophytes with Host:**

The relationship between endophyte and plant is referred to as symbiotic. Colonisation, which is influenced by genotype, growth stage, physiological status, type of plant tissue, agricultural practises, and environmental factors like temperature, water supply, and nutrients, governs the interaction between the host plants and the endophytic community. The glucuronidase reporter system can also be used to see endophytic bacteria colonising internal plant tissues (James et al 2002). The interface between the soil and the roots, known as the rhizosphere, is where the complex interactions between the soil microorganisms and the plant occur (Bulgarelli et al 2012). A variety of microorganisms that may endure in root exudates and compete with one another are found in the rhizosphere. Strains that were equally competitive for colonising the rhizosphere and inside root tissues were discovered by Rosenblueth and Martnez-Romero in 2004. Some bacteria must pass through crevices created at the zone of elongation and differentiation of the root or at the formation of lateral roots in order to colonise the plant. Early endophytic colonisation varied between cultivars in several experiments, but later endophytes were recovered from the various cultivars in about comparable numbers (Pillay and Nowak 1997). According to Araujo et al. (2001), fungal colonisation may influence endophytic bacterial colonisation, or it may be the other way around. *Rhizobium etli* strains differ from one another in their propensity to colonise, and these variations may be due to variations in the genome’s composition. Endophytes may actively contribute to colonisation as well. An important step towards endophytic colonisation is the adhesion to plant surfaces, which is accomplished by *Azoarcus* *sp*. Type IV pili. Additionally suggesting an active host role in the colonisation process, the plant hosts varied in how well the same bacterium could colonise them endophytically. However, phyllosphere bacteria may also be a source of endophytes. Some rhizospheric bacteria can colonise the interior roots and stems, demonstrating that these bacteria constitute a source for endophytes (Germaine et al. 2004). Furthermore, it’s possible that communication with the plant root and the following colonisation process are facilitated by bacterial quorum sensing chemicals. Given that some plant extracts have been demonstrated to have quorum quenching properties that could defend them against infections and that some quorum sensing molecules have been demonstrated to directly promote plant growth, plants are likely directly involved in quorum sensing as well (Schikora et al 2016). Additionally, LuxR homologs were discovered in a number of *Populus deltoides* endophytes, which are thought to be involved in reacting to chemicals derived from plants (Schaefer et al 2016). Additionally, this study discovered that several endophyte genomes had quorum sensing gene pairs of the LuxR-LuxI type, highlighting their significance in the endophytic and plant-microbe interactions in great detail (Hartmann et al 2014).

**5. Beneficial relationship between Endophytes and plants:**

The interaction between endophyte and plant is characterized as a symbiotic relationship because both are benefited in this association. The host plant offers the microbes safe havens, and they in turn create metabolites that boost nutrient absorption, altering plant development and biomass accumulation. Endophytes may acquire certain genetic information to create particular bioactive compounds comparable to the host plant as a result of this symbiotic relationship between endophytes and plants through horizontal gene transfer and involvement in metabolic pathway. As a result, in this host-endophyte relationship, the host provides nutrients to the microbial endophytes and in exchange, the microbial community gives their potential use in plant protection and biological control. Endophytes are distinct from biocontrol strains of rhizosphere bacteria, according to research on the impact of endophytic bacteria on plant development, as they not only promote the growth of plant but also prevent the growth of pathogenic microbes. Endophytic bacteria can control osmotic pressure, stomata function, or plant root development, which will benefit the health of the plants as a whole (Ulrich et at 2008). Therefore, it is necessary to develop economically viable means of using this endophyte trait in a variety of human activities related to plant culture, including food production, forestry, landscaping, and other related activities. For plants, Nitrogen is an essential mineral required to survive and grow. Numerous studies on nitrogen fixing bacteria have recently focused on translating the idea of symbiotic relationships seen in legumes to non-leguminous plants such maize, sorghum, wheat and sugarcane (de Carvalho et al 2011). As numerous studies have demonstrated, nitrogen is crucial, particularly for host plants that thrive in soils with low nitrogen levels. Diazotrophic (*Gluconacetobacteria diazotrophicus*) bacteria that fix nitrogen have recently been isolated from the tissues of sugarcane plants. Since this bacterium was able to multiply and fix nitrogen, it has been hypothesised that it can meet the host plant’s needs for nitrogen (Baldani et al 2014).

In addition to promoting plant disease resistance, phosphate serves as a precursor for the synthesis of several enzymes involved in different physiological processes in plants (Thakur et al 2014). Both organic and inorganic phosphates require the assistance of bacterial enzymes called phosphatases which are regulated by the presence of genes, to go through processes of solubilisation and mineralization in order to be converted into an accessible soluble form (Bashan et al 2013). Chelators, which are organic acids, are created during the phosphate solubilisation process by phosphate solubilizing bacteria and aid in the removal of metals (Singh et al 2020). Phosphate solubilizing bacteria enhance the functionality, diversity, and ecology of plants in environments by providing them with the essential nutrients. However, as endophytic phosphate solubilizing bacteria are essential for sustainable agriculture and environmental protection, additional study of these organisms is required, from the molecular level through their practical uses. However, as endophytic phosphate solubilizing bacteria are essential for sustainable agriculture and environmental protection, additional study of these organisms is required, from the molecular level through their practical uses. Some endophytic bacteria can solubilize the inaccessible potassium into forms that can be used by the plant. Due to their ability to penetrate and colonise the interiors of roots, endophytic bacteria have gained interest in agriculture for soil root inoculation (Yuan et al 2015). Endophytic bacteria that solubilize potassium have also been shown to reduce other environmental pressures, like salt stresses, and enhance output in general (Feng et al 2019). Unfortunately, the majority of endophytes that have been isolated and studied were chosen to study other growth promoting features like nitrogen and indole 3 acetic acid, omitting the significance of potassium for plant growth and defence. One of the crucial trace elements that plants and other living things require is zinc. Despite being a trace element, it affects the metabolism and enzymatic activity of plants. As a result, from the standpoint of the field to the products of crops that lacked zinc elements, the absence of zinc elements in plants is readily apparent. In order to boost the plant growth of the most significant crops and increase their nutritional content, zinc solubilizing endophytic bacteria need increased focus in research and practical applications. An environmentally friendly and safe alternative for providing and transforming applied inorganic zinc into a form that plant root may reach is zinc-solubilizing bacteria (Kamran et al 2017). This will ultimately provide food and nutrition security as well as environmental protection.

Plant growth promoting bacteria (PGPB) are bacteria that can help the plant in a variety of ways. Phyto-pathogens counteract several stresses on plants and aid in the restoration of harmed or degraded habitats. Endophytic bacteria have been associated with the growth promotion of several crops, including tomato, lettuce, potato, corn, cucumber, rice, and cotton. According to a report 10% of the bacterial isolates found inside potato tubers were found to encourage plant growth. In addition to a direct method, plant growth enhancement may also result from the endophyte’s introduction suppressing a harmful microbiota. Endophytes, on the other hand, provide another option for creating biological control techniques because of the various sites they have colonised. Endophytes have a reputation for causing host plants to become resistant to diseases. They are also well known for promoting host plant growth and development in a variety of environmental and ecological circumstances.

**6. Endophytes assisted nutrient uptake in plants:**

Endophytic bacteria are the helpful microorganisms for plants that live inside plants and can enhance plant growth in both easy and difficult situations. By enhancing plant nutrient intake and controlling phytohormones linked to growth and stress, they can directly benefit host plants. Here is a brief explanation of how plants absorb nutrients:

* **Colonization:** Endophytes, which are microorganisms like bacteria or fungi, colonize various parts of the plant, such as the roots, stems, and leaves. They establish a symbiotic relationship, residing within the plant’s tissues without causing harm.
* **Secretion of substances:** Endophytes produce substances like enzymes and metabolites that help break down organic matter in the soil so that nutrients are more readily available to plants. These substances aid in the transformation of complicated nutrients into simpler shapes that plants can absorb.
* **Nutrient mobilization:** Through their enzymatic activities, endophytes help release essential nutrients, such as nitrogen, phosphorus, and micronutrients, from organic matter in the soil or from mineral complexes that might otherwise be unavailable to the plant.
* **Increased surface area:** The presence of endophytes can lead to the formation of structures like mycorrhizae, which are fungal networks that extend the plant’s root system. This extended root network increases the plant’s capacity to explore a larger soil volume, thereby accessing a wider range of nutrients.
* **Increased nutrient uptake:** Endophytes can encourage plant root growth, which increases the plant’s ability to absorb nutrients from the soil. They might also make the nutrient transporters in the roots of the plant more active, which would make it easier for nutrients to be absorbed.
* **Nutrient exchange:** In some instances, endophytes absorb nutrients from the soil and trade them with the plant for other advantageous substances. This reciprocal exchange improves the plant’s access to nutrients.
* **Enhancement of plant growth:** Plants may experience greater growth and development as a result of improved nutrient uptake and utilisation. Increased biomass, improved root architecture, and generally healthier plant physiology are examples of this.
* **Stress tolerance:** Endophytes can also contribute to the plant’s stress tolerance, which indirectly aids nutrient uptake. By helping plants withstand environmental stresses like drought or high salinity, endophytes enable plants to continue nutrient uptake even under challenging conditions.

Endophyte-assisted nutrient uptake involves a range of mechanisms that collectively improve a plant’s access to essential nutrients in the soil. Through their enzymatic activities, enhanced root growth, and potential nutrient exchange, endophytes play a vital role in optimizing nutrient availability and uptake, contributing to the overall health and vitality of plants.



Fig. 2: Endophytes assisted nutrient uptake mechanism in plants

**7. Bioactive compounds of Endophytes:**

Endophytes are known to synthesize a range of bioactive compounds within a single plant or microorganism, offering a valuable resource for drug development against diverse diseases. These compounds hold potential applications across agriculture, medicine, food, and cosmetics industries (Strobel and Daisy, 2003; Jalgaonwala et al., 2011; Godstime et al., 2014; Shukla et al., 2014). These secondary metabolites encompass various functional groups such as alkaloids, benzopyranones, quinones, flavonoids, phenolic acids, terpenoids, steroids, saponins, tannins, tetralones, xanthones, and more.

The extraction of metabolites from endophytes is influenced by factors including the season of sample collection, climatic conditions, and geographical location (Shukla et al., 2014). Nonetheless, recent years have seen the development of a revolutionary synthetic process, enhancing the feasibility, efficiency, and convenience of extracting from plants and other natural sources (Hussain et al., 2012). The production of bioactive compounds by endophytes is intricately linked to the evolutionary trajectory of host microorganisms, which might have assimilated genetic information from higher plants. This incorporation allows them to adapt more effectively to the host plant's environment and fulfill functions like protection against pathogens, insects, and grazing animals (Strobel, 2003). Below, some commonly encountered secondary bioactive compounds from endophytes are detailed.

Taxol (paclitaxol), a complex diterpene alkaloid, is a promising anticancer agent derived from the endophyte Metarhizium anisopliae, found in Taxus tree bark. This compound stands as one of the most notable advancements in anticancer agents (Zhang et al., 2009; Visalakchi and Muthumary, 2010; Jalgaonwala et al., 2011). Camptothecin, sourced from Nothapodytes foetida, demonstrates cytotoxic and antifungal properties (Joseph and Priya, 2011; Han and Rahman, 2012). Huperzine A (HupA), originating from Huperzia serrata, functions as a cholinesterase inhibitor (Nair and Padmavathy, 2014). Lignans, like cathartics, emetics, and cholagogue from endophytic Podophyllum hexandrum, act as reported anticancer agents (Konuklugil, 1995). Resins, including etoposide and teniposide from P. emodi, exhibit potent anticancer activity (Konuklugil, 1995). Compounds such as oxacillin, ampicillin, catechin, gallic acid, and cefalexin demonstrate bactericidal activities (Akiyama et al., 2001). Terpenoids possess antineoplastic, antibacterial, antiviral effects, as well as gastrointestinal stimulation (Jalgaonwala et al., 2011; Godstime et al., 2014). The endophytic fungus *Cytonaema sp*. produces the triterpenoid helvolic acid, known for its strong antibacterial properties (Kumar et al., 2014).

**7.1. Antibacterial properties of metabolites from endophytic fungi:**

In recent times, fungi have gained recognition as a valuable source of novel bioactive compounds (Samuel et al., 2011). The groundbreaking discovery of penicillin marked a significant milestone, showcasing its efficacy against Gram-positive bacteria (Demain and Sanchez, 2009). Extracts from *Aspergillus ochraceus* and *Penicillium citrinum* displayed broad-spectrum antibacterial properties, effectively inhibiting the growth of various microorganisms, notably *Pseudomonas aeruginosa*. Hypericin, a naphthodianthrone derivative, and Emodin (C15H10O5), believed to be a primary precursor for hypericin synthesis, exhibited antimicrobial activity against bacteria and fungi such as *Staphylococcus sp., Klebsiella pneumoniae, Salmonella enterica, Escherichia coli, Aspergillus niger,* and *Candida albicans*. These effects were observed in an endophytic fungus isolated from a medicinal plant (Kusari et al., 2012). *Pichia guilliermondii*, an endophytic fungal strain from *Paris polyphylla* var. Yunnanensis, yielded three steroids—5a,8a-epidioxyergosta-6, ergosta-5,7,22-trienol, 22-dien-3b-ol, ergosta-7,22-dien-3b,5a,6b-triol—and the triterpenoid helvolic acid. These compounds exhibited potent antibacterial activity against a range of test bacteria (Zhao J. et al., 2010).

**7.2. Antiviral Properties of Metabolites from Endophytic Fungi:**

Another intriguing dimension involves harnessing secondary metabolites from endophytic fungi to suppress viral growth. While the isolation of antiviral compounds from endophytes remains a work in progress, some promising bioactive agents have already come to light. Given the rise of resistance and multi-resistance against existing medications, coupled with adverse effects and high costs associated with current therapies, the urgency for novel antiviral drugs has grown. This urgency is further underscored by the HIV/AIDS epidemic and the emergence of AIDS-associated opportunistic infections, including cytomegalovirus and polyoma virus.

Among notable discoveries, Cytonic acid A and B have been identified as human cytomegalovirus protease inhibitors. These compounds are sourced from the endophytic fungus Cytonaema sp., which is derived from *Quercus* sp. (Guo et al., 2008). In another significant finding, Fukami et al. (2000) conducted experiments on the fungus *Trichoderma atroviride* FKI-3849, leading to the identification of two new anti-influenza viral agents—wickerol A and B diterpene compounds characterized by a unique fused 6-5-6-6 ring skeleton. Derived from *T. atroviride* FKI-3737 fungi, the antiviral compound wickerol A demonstrated potent activity against the A/H1N1 flu virus strains (A/PR/8/34 and A/WSN/33) (Obuchi et al., 1990). This discovery not only showcases its effective antiviral potential but also paves the way for potential lead compounds in the development of novel anti-influenza drugs, featuring innovative structural characteristics. The fungal strain *Pestalotiopsis theae*, sourced from an undisclosed tree on Jianfeng Mountain, has yielded pestalotheol C. This compound, with anti-HIV properties, has been successfully produced by Chinese researchers (Li et al., 2008).

**7.3. Anti-cancer Properties of Metabolites form Endophytic fungi:**

Cancer encompasses a collection of diseases characterized by unchecked cell growth, leading to the loss of properties such as density and anchorage dependence in tumors, contact inhibition, and the inability to undergo apoptosis, thereby impeding organismal survival (Pimentel et al., 2010). Remarkably, endophytic fungal isolates have furnished evidence of yielding anticancer secondary metabolites, offering a prospective avenue for developing novel drugs from various sources, including plants, microorganisms, and marine entities (Firakova et al., 2007).

Endophytes have been under scrutiny for their potential anticancer activity, with bioactive compounds being explored for this purpose (Qi et al., 2009). Notably, the pioneering anticancer agent produced by endophytes was Taxol and its derivatives. Taxol, an intricately structured diterpenoid, originates from yew species of the Taxus genus (Bacon and White, 1994). These novel bioactive metabolites, Taxol, incite the polymerization of microtubules during cell division progression, influencing cellular processes (Tan and Zou, 2001). Endophytic fungi have yielded noteworthy anticancer drugs, including camptothecin, a potent anti-neoplastic agent extracted from *Camptotheca acuminata* Decaisne (Nyssaceae) in China (Wall et al., 1966). This compound serves as a pivotal precursor for the synthesis of topotecan and irinotecan, both recognized anticancer drugs, alongside 10-hydroxycamptothecin (Uma et al., 2008). An additional noteworthy compound is secalonic acid D, a mycotoxin classified as an ergochrome. Isolated from a mangrove endophytic fungal strain, this compound exhibits robust anticancer activity (Bills et al., 1996; Qi et al., 2009).

**7.4. Antifungal properties of metabolites form endophytic fungi:**

Endophytic fungi offer a diverse array of antifungal metabolites, pivotal in combating numerous pathogenic fungi. Altomare et al. (2000) and colleagues identified two potent alpha pyrones antifungal compounds, fusapyrone and deoxyfusapyrone, sourced from Fusarium semitectum. These compounds demonstrated substantial efficacy against pathogenic and mycotoxogenic filamentous fungi, including *Alternaria alternata, Aspergillus flavus, Botrytis cinerea, Cladosporum cucumerinum, Phoma tracheiphila,* and *Penicillium verrucosum.*

Pathogenic fungi like *Candida albicans*, *Cryptococcus neoformans,* and *Aspergillus fumigatus* pose health threats to humans. *Streptomyces sp*. Produces polyenes, including amphotericin B, nystatin, and natamycin, which exhibit broad-spectrum antifungal activity against various fungi, such as *Aspergillus* sp. And *Candida* sp. (Hay, 2003; Gupte et al., 2002; Iznaga et al., 2004; Gohel et al., 2006). Recent work by Wu et al. (2015) led to the isolation of two novel antifungal and cytotoxic components, namely (4S,6S)-6-[(1S,2R)-1,2-dihydroxybutyl]-4-hydroxy-4-methoxytetrahydro-2H-pyran-2-one (1) and (6S,2E)-6-hydroxy-3-methoxy-5-oxodec-2-enoic acid (2), as well as three other compounds, LL-P880 (3), LL-P880 (4), and Ergosta-5,7,22-trien-3b-ol (5), from *Dendrobium officinale*’s secondary metabolites. This investigation highlighted the remarkable antifungal prowess of compounds 1-4, effective against *Cryptococcus neoformans, Candida albicans, Aspergillus fumigatus,* and *Trichophyton rubrum*.

**7.5. Anti-diabetic properties of metabolites form endophytic fungi:**

Diabetes mellitus (DM), commonly known as diabetes, is a prevalent disorder marked by impaired insulin secretion and action, originating from beta cell dysfunction in the liver. The resultant insulin deficiency leads to elevated blood sugar levels (hyperglycemia), adversely affecting carbohydrate, fat, and protein metabolism. Diabetic complications such as retinopathy, neuropathy, nephropathy, cardiovascular issues, and ulceration further compound the complexities of this condition. This extensive range of diabetes encompasses heterogeneous diseases (Bastaki, 2005), prompting the development of numerous medications and drugs from diverse biological sources for its management. Endophytic microorganisms, sharing the capability to produce bioactive compounds with their host plants, offer a potential avenue for sourcing anti-diabetic materials (Dompeipen et al., 2011).

Among endophytic fungi, a-glucosidase inhibitors stand out as widespread oral agents employed to mitigate postprandial hyperglycemia (Hanefeld and Schaper, 2007). Alongside these, various natural products from medicinal plants and microorganisms show promise as a-glucosidase inhibitors (Suthindhiran et al., 2009; Elya et al., 2012). Similarly, Ramadanis et al. (2012) embarked on isolating and characterizing a-glucosidase anti-diabetic bioactive compounds from endophytic fungi found in *Swietenia macrophylla*. In the African forest, *Pseudomassaria* sp. Yielded a non-peptide fungal metabolite with insulin-like properties. This compound remains intact through the digestive tract and can be administered orally. Remarkably, it demonstrated significant blood glucose reduction in a two-mouse model, signaling potential advancements in diabetes treatment.

**7.6. Antioxidant Properties of Metabolites form Endophytic fungi:**

Endophytic fungi assume a crucial role in generating valuable antioxidant bioactive compounds. Sicentists investigated thirty-nine fungi derived from five Thai medicinal plants, observing their production of phenolic compounds. These phenolic compounds, renowned for their potent antioxidant properties and robust reducing capabilities, play a pivotal role. Among the fungi examined, *Eupenicillium* *shearii* CMU18 exhibited the highest phenolic compound content, along with notable ABTS+ radical scavenging ability, exceptional reduction potential, and a capacity to inhibit lipid peroxidation in rat liver tissue.

Additionally, *Paraconiothyrium spp*., isolated from the leaves of *Rheedia brasiliensis*, exhibited commendable antioxidant attributes. The crude extract from *Paraconiothyrium spp.* displayed the capacity to curtail cell growth of immortalized human keratinocytes while also exhibiting efficacy against psoriasis through free radical reduction.

**7.7. Insecticidal Properties of Metabolites form Endophytic fungi:**

Endophytic fungi play a vital role in producing insecticidal compounds that prove highly effective against a range of insect pests responsible for causing severe damage to crops. An endophytic fungus, *Nodulisporis* sp., derived from *Bonita daphnoides,* synthesizes noduliosporic acid and indole diterpenes. These compounds exhibit potential insecticidal properties, particularly against blowfly caterpillars (Demain, 2000). Similarly, *Muscodar* *vitigenus*, isolated from *Paullina* *paullinioides*, yields naphthalene, which serves as a potent insect repellent. From the endophytic fungus *Gaultheria* *procumbens*, two novel biopesticide compounds—5-hydroxy-2-(1-hydroxy-5-methyl-4-hexenyl) benzofuran and 5-hydroxy-2-(1-oxo-5-methyl-4-hexenyl) benzofuran—have been isolated, demonstrating high toxicity against spruce budworm and its larvae (Findlay et al., 1997). *M. vitigenus* not only exhibits insect inhibitory qualities but also functions as an insect repellent against the wheat stem sawfly (Daisy et al., 2002).

Recent studies have unveiled *Claviceps* *purpure* and *Claviceps* *chaetomium* from *Achnatherum* *inebrians* in China, showcasing their insecticidal potential against cotton aphids (Zhang et al., 2010). Prior research identified endophytic fungi in *Neotyphodium* sp., producing N-formilonine and a paxiline analogous element within the host *Echinopogum* *ovatus*. These bioactive compounds demonstrated repellent effects against *Listronotus* *bonariensis* and other insects. *Fusarium* *oxysporum* endophytic fungi offer protection against root knot disease caused by *Meloidogyne* *incognata* in tomatoes (Hallman and Sikora, 1994), while endophytic fungi from Central American banana plants regulate the burrowing nematode *Rhadopholus* *similis* (Pocasangre et al., 2000). Terpenes isolated from *Copaifera* sp. Showcased antiparasitic and synergistic activity in vitro (Izumi et al., 2012). In yet another instance, insecticidal compounds Azadirachtins A and B, extracted from endophytic fungi Penicillium (Eupenicillium) parvum within the neem plant (*Azadirachta* indica), demonstrated significant insecticidal effects (Kusari et al., 2012).

**Table 1:** Some of the endophytic bacteria that have been isolated, identified, and assessed fora their abilities to promote plant growth and provide biocontrol effects include:

|  |  |
| --- | --- |
| **Role** | **Bacteria** |
| Nitrogen Fixation | *Pseudomonas sp., Herbiconiux solani SS3, Flavobacterium aquidurense SN2r, Rhizobium herbae SR2r., Paenibacillus polymyxa P2b-2R,* |
| Phosphorous solubilization | *Pseudomonas sp. Burkholderia sp., Paraburkhoderia,* *Novosphingobium, Ochrobactrum, Paenibacillus polymyxa,*  |
| Potassium solubilization | *Paenibacillus polymyxa, Bacillus sp., Burkholderia sp. FDN2-1,**Alcaligenes spp., Enterobacter spp.* |
| Zinc solubilization | *Bacillus spp., Arthrobacter sp., Klebsiella spp., Pseudomonas spp.* |
| Hormones (indole-3-acetic acid jasmonic acid, salicylic acid) | *Klebsiella sp., Enterobacter sp., Bacillus amyloliquefaciens RWL-1;**Bacillus sp. PVL1, Bacillus sp. DLMB, Bacillus sp. MBL\_B17, Bacillus subtilis MBL\_B13, Leifsonia xyli SE134, Bacillus subtilis LK14,* |
| Antibiotics (Bacillomycin 2,4-diacetylphloroglucinol,  | *Bacillus subtilis fmbj, Bacillus subtilis CPA-8, Bacillus subtilis AU195* |
| Volatile organic compounds (2,3-butanediol, acetoin, 2-hexanone, | *Bacillus amylolicefaciens ALB629 and UFLA285,**Enterobacter TR1, Bacillus spp. Bacillus Velenzensis 5YN8, Bacillus Velenzensis DSN012* |

**Table 2:** Origin of bioactive compounds derived from endophytes and their application against pathogenic microorganisms.

|  |  |  |  |
| --- | --- | --- | --- |
| **Source of endophytes** | **Bioactive compounds** | **Active against pathogen** | **Mode of transmission**  |
| *Boesenbergia rotunda**Streptomyces coelicolor* | Munumbicins | *Escherichia coli* | Ground meats, raw or under pasteurized milk |
| *Chloridium sp.* | Javanicin | *Pseudomonas sp.* | Contaminated water or surgical instruments  |
| *Cladosporium sp.* | Cardiac glycosides, phenolic compounds | *Klebsiella pneumoniae* | Contaminated water and aerosols |
| *Cryptosporopsis quercina* | Saadamycin | *Campylobacter jejuni* | Raw or uncooked poultry and milk |
| *Cytonaema sp.* | Cytonic acids A and B | *Human cytomegalo virus**Hepatitis virus* | Shellfish, berries or contaminated water |
| *Diaporthe helianthi* | Fabatin, tyrosol | *Enterococcus hirae* | Nosocomial infection through hospitalized patients |
| *Fusarium proliferatum* | Beauvericin | *Clostridium botulinum* | Improperly processed, canned food |
| *Hypericum perforatum Diaporthe helianth* | Hypericin, emodin, tyrosol | *Salmonella sp* | Meat, eggs, and untreated tree nuts |
| *Nigrospora sp.* | Saadamycin | *Fusarium oxysporum* | Maize, cereals, groundnuts  |
| *Phomopsis sp.* | Munumbicins | *Aspergillus niger* | Maize, cereals, groundnuts, and tree nuts |
| *Saccharothrix mutabilis* | Capreomycin  | *Mycoplasm (TB)* | Uncooked meat, eggs or poultry |
| *Streptomyces sp. Kennedia nigricans* | Munumbicins  | *Vibrio cholerae* | Raw or undercooked shellfish  |

**8. Plants immunity by endophytes:**

Endophytes play a crucial role in enhancing the immunity of plants through their intricate interactions within the plant’s tissues. These microorganisms, including bacteria and fungi, establish a symbiotic relationship with the plant, residing within its various parts such as leaves, stems, and roots. This partnership often yields a myriad of benefits for the host plant. The production of secondary metabolites with antibacterial characteristics by endophytes is one of the main ways they support plant immunity. By preventing the growth and reproduction of possible infections, these substances serve as a first line of defence. Endophytes can successfully stop the invasion of harmful bacteria by doing this, which could otherwise result in diseases that are bad for the health of the plant. Moreover, endophytes can stimulate the plant’s own defense mechanisms. They can induce the production of phytohormones and other signaling molecules that trigger systemic acquired resistance (SAR) or induced systemic resistance (ISR). SAR involves the activation of defense responses throughout the entire plant, while ISR involves the systemic response initiated by localized infection. Both mechanisms bolster the plant’s ability to fend off pathogens upon subsequent attacks.

**8.1. Plant protection mechanism by endophytes:**

Endophytes shield plants by producing compounds that thwart pathogens, triggering immune responses, forming physical barriers, and bolstering stress tolerance. These microorganisms also compete for nutrients, induce systemic resistance, and in some cases, directly attack pathogens, enhancing plant protection. Through a variety of ways, endophytes protect plants, and there are primarily two types.

**8.1.1. Direct mechanism:**

* **Antibiosis:** Endophytes produce bioactive chemicals that are hazardous to prospective pathogens as part of their antibiosis mechanism. These substances act as a barrier for the host plant, inhibiting the growth, development, and survival of dangerous microorganisms. Through this method, harmful organisms are kept from colonizing plant tissues and causing disease. Endophytes successfully ward off diseases by releasing these bioactive compounds, which supports the plant’s general health and vitality.
* **Lytic enzyme secretion:** The lytic enzyme secretion mechanism of endophytes contributes to plant protection through various ways: pathogen disruption, biofilm penetrating, nutrient release, induced defense responses, direct antagonism, and detoxification.
* **Phytohormone production:** The phytohormone production mechanism of endophytes contributes to plant protection in the following ways: enhanced defense responses, systemic acquired resistance, induced systemic resistance, cross-talk and balance, regulation of growth and development.
* **Phosphate Solubilization:** The phosphate solubilization mechanism of endophytes improves nutrient uptake, root development, stress tolerance, and defense responses in plants. These combined effects contribute to the overall health and resilience of the plant, ultimately protecting it from potential threats like pathogens.
* **Siderophores Production:** Siderophores, which are molecule-producing endophytes, bind to iron ions in the soil, increasing their availability for uptake by plants. Iron is a critical component for plant growth and defense, therefore understanding this is important. Endophytes increase the availability of iron to plants by chelating it. This improved nutrition delivery encourages healthier plant growth and development, which in turn helps the plant resist infections. Endophytes’ synthesis of siderophores may reduce possible pathogens’ access to iron. Siderophores competition makes the environment unfavorable for pathogenic bacteria because iron is also necessary for their growth.

**8.1.2. Indirect Mechanism:**

* **Induction of plant resistance:** Induction of plant resistance refers to the process by which plants are primed to enhance their defense mechanisms in response to certain stimuli. This heightened state of readiness makes the plant more resistant to pathogens and other environmental stressors. Several key points characterize the induction of plant resistance are primed defense mechanism, SAR, hormonal signaling, environmental adaptation, natural and synthetic elicitors.
* **Simulation of plant secondary metabolites:** Simulation of plant secondary metabolites involves the creation of models or systems to replicate the production and accumulation of these specialized compounds within plants. Plant secondary metabolites are organic compounds that are not directly involved in essential growth processes but often serve various roles, such as defense against herbivores, attraction of pollinators, and response to environmental stress.
* **Promotion of plant growth and physiology:** Through their interactions with the host plant, endophytes can significantly influence the growth and physiology of plants. Here are some ways that endophytes might improve plant physiology and growth: nutrient uptake and solubilization, nitrogen production, hormone production, root development, symbiotic nitrogen fixation.
* **Hyper-parasitism and predation:** Hyper-parasitism and predation involving endophytes are interactions where these microorganisms engage in relationships with other microbes or organisms. Hyper-parasitism occurs when an organism (in this case, an endophyte) parasitizes another parasitic organism. Endophytes can act as hyper-parasites by targeting other microorganisms, such as fungi or bacteria that are already parasitizing plants. The endophytes establish themselves within these parasitic organisms, influencing their behavior, growth, or pathogenicity. Predation involves an organism (endophyte) consuming another organism (e.g., a pathogen) for nourishment. Some endophytes have been found to exhibit predatory behavior by attacking pathogens or other microorganisms within the plant’s environment. This can contribute to disease suppression by reducing the population of harmful pathogens.
* **Indolic compound production:** The production of indolic compounds by endophytes exemplifies the intricate chemical dialogues that occur within the plant microbiome. These compounds have far-reaching effects on plant growth, development, defense, and stress tolerance, making them valuable tools for enhancing agricultural practices and sustainable crop production.



Fig.3: Plant protection mechanism by endophytes

**9. Endophytes and plant relationship:**

Fossilized plant tissues from various parts have yielded compelling evidence for the relationships between plants and endophytes. The close and enduring bond between plants and microbes is evident through genetic exchanges that facilitate the transfer of information between both organisms.

Information exchanges contribute to better survival in both adverse and favorable conditions, enhancing the intimacy of the plant-endophyte association for heightened adaptation. The evolutionary bond between endophytic fungi and plants might facilitate improved adaptation, aided by endophytes secreting protective chemical compounds against pathogens and insects (Strobel, 2003; Kusari and Spiteller, 2012). Consequently, endophytic fungi synthesize diverse bioactive compounds, to contribute to their host plants. Coevolution between plants and endophytes suggests the potential for endophytes to generate bioactive secondary metabolites, supporting the plant’s chemical defense (Carroll, 1988; Li et al., 2008). This, in turn, bestows protection, growth, and survival benefits to their host, granting access to isolating and characterizing substances of substantial industrial potential, spanning agriculture and medicine (Strobel, 2003).

In its early stages, the endophytic fungus Piriformospora indica was harnessed for producing pyriform chlamydospores. P. indica exhibits a remarkable ability to establish root colonization in plants, augmenting their growth and development (Verma et al., 1998; Rai et al., 2001). In several aspects, P. indica shares similarities with arbuscular mycorrhizal fungi (Rai and Verma, 2005; Deshmukh et al., 2006). This fungus also demonstrates multifunctionality, serving as a biofertilizer, bioprotector, growth regulator, and contributor to drought tolerance (Sun et al., 2010). Notably, P. indica contributes to phosphate transportation from fungus to host plant, facilitated by a phosphate transporter gene (PiPT). This revelation deepens the understanding of phosphate transfer mechanisms in host plants.



Fig 4: Host-endophytes relation and their application

**10. Endophytic Bacteria in Phytoremediation:**

Due to their toxicity, hydrophobicity, and propensity to linger in the environment for an extended length of time, organic compounds discharged into the environment as a result of numerous human activities pose a severe threat to the ecosystem. The presence of organic compounds in soil, such as hydrocarbons, polyaromatic hydrocarbons, polychlorinated biphenyls, phenols, chlorophenols, toluene, trinitrotoluene, benzene, herbicides and pesticides, inhibits growth and metabolic activities of soil associated microbes, even at very low concentrations(Oleszczuk, 2006, Porteous Moore et al., 2006). In addition, organic chemicals can enter the food chain and, because of their toxicity, they can cause cancer and mutagenicity in both people and animals. As a result, one of the key problems in the field of environmental sciences and engineering is the removal of these organic compounds from soil and water. An effective, economical, and environmentally friendly 21st century technology is phytoremediation, or the use of plants to clean up polluted soil and water. Additionally, plants employed for phytoremediation could be used to produce biomass or biofuels as well as store carbon. When microorganisms and plants work together, the plant gives the related rhizosphere and endophytic bacteria a habitat and nutrition. By decomposing the contaminant, the bacteria help the plant increase its ability to withstand stress, grow better, and purify its surroundings. These interactions have been extensively investigated and employed to improve soil fertility, plant development, and phytoremediation of polluted soil and water. Plants and their associated microorganisms have complex and diverse interactions with one another. While endophytic bacteria colonise inside of plants without making their host plants pathogenic, *Rhizobacteria* colonise the area immediately around the roots of plants. Since many endophytic bacteria have close ties to plants and are important plant growth promoters, they have also attracted a lot of interest. Endophytic bacteria with metabolic and pollutant degradation pathways can reduce volatile organic compound evapotranspiration as well as phytotoxicity. Additionally, adding endophytic bacteria with plant growth promoting properties may help plants adapt to and thrive in contaminated soil. Many endophytic bacteria have recently been isolated from various plants, and many of them have demonstrated actions that both degrade pollutants and promote plant growth. Endophytic bacteria are therefore very promising for some phytoremediation approaches because of their pollutant degrading and plant growth promoting capabilities (Khan et al., 2013). It is still understated how crucial plant-endophyte synergisms are for removing contaminants from soil and water. Given that many endophytic bacteria exhibit pollutant degrading, plant growth promoting, or both activities, a deeper understanding of the mechanisms behind these endophytic activities can be used to enhance phytoremediation of organic pollutants found in soil and water. Although the role of endophytic bacteria to increase the phytoremediation of heavy metal contaminated soil has been reviewed in a number of recent review articles, the role of endophytic bacteria to enhance the phytoremediation of organic pollutants has largely gone unmentioned. It has been suggested that endophytic bacteria may improve three specific aspects of phytoremediation of organic pollutants: (a) plant growth and biomass production; (b) the bioavailability of organic pollutants; and (c) the population size and activity of native bacteria to degrade organic pollutants through horizontal gene transfer. Additionally, increased plant biomass output can lower the proportion of organic pollutants to plant tissue, reducing plant stress. The potential of genetically altered endophytic bacteria, horizontal gene transfer, and meta-genomic research to enhance plant endophyte partnerships for the cleaning up of contaminated soil and water will be highlighted in the last section.

**Future prospects:**

The future prospects of endophytes are promising and hold significant potential across various fields. Researchers and scientists have recognized the value of these hidden allies, and ongoing studies are paving the way for their practical applications. Endophytes offer a natural and eco-friendly approach to enhance crop productivity and protect plants from pests and diseases. By reducing the need for chemical pesticides and fertilizers, endophytes can contribute to sustainable agricultural practices, promoting environmentally friendly farming methods. Endophytes have the potential to assist plants in adjusting to shifting environmental conditions as climate change continues to have an impact on global ecosystems. Their capacity to increase plant resistance to stress, such as drought, may be significant in reducing the impact of climate change on agricultural productivity. The distinct biochemical characteristics and genetic diversity of Endophytes provide novel opportunities for biotechnological development. They might be employed in the creation of brand-new bioactive substances, biopesticides, and biofertilizers, advancing medical science, agriculture, and environmental management. In degraded ecosystems, introducing beneficial endophytes can aid in the restoration process. They can help establish and support native plant populations, promoting biodiversity and ecosystem stability. Some endophytes have shown potential in producing bioactive compounds with pharmaceutical properties. Research on endophyte-derived compounds may lead to the discovery of new medicines and therapies for human and animal health. Understanding endophyte-plant interactions can help researchers better understand the complex world of plant microbiomes. Understanding these connections can help us better understand the intricate microbial populations that affect plant health and ecosystem dynamics. Certain endophytes have demonstrated the ability to enhance plant biomass and bioenergy production. By improving the growth and productivity of bioenergy crops, they can contribute to renewable energy solutions. To ensure the safe and sustainable use of endophytes, it is essential to take into account potential obstacles including regulatory clearances, scalability, and potential ecological implications as research in this area progresses. Despite these difficulties, the continuous study and use of endophytes hold considerable potential for improving agriculture, environmental protection, and people’s quality of life in the years to come.

**Conclusion:**

Endophyte realm is an exciting and growing area of research that offers great potential in many areas. The relationship between the endophyte and its host plants highlights a dynamic evolutionary process in which the endophyte inhabits the plant tissues and often uses its chemical arsenal to support various aspects of the plant’s growth, health and defense. Endophytes have been shown to support plant health by stimulating growth, increasing nutrient uptake, improving abiotic stress tolerance and providing protection against a variety of pathogens. Endophytes, which come from bacteria, fungi and other families, produce a variety of bioactive metabolites that show anti-bacterial, anti-viral, anti-fungal and even anti-cancer activity. These endophyte compounds, derived from endophyte’s rich biochemical repertoire, hold great promise in pharmaceutical applications as well as bioremediations and agricultural strategies for sustainable crop production. In a world where innovation and green solutions are in high demand, endophytes provide an opportunity to explore the potential of nature’s invisible allies. The ability of endophytes to form complex biochemical networks within a plant’s physiology is an illustration of the beauty and intricacy of nature. As science continues to unravel the mysteries of these microcosm environments, endophytes will play a vital role in solving some of humanity’s greatest challenges, bridging the gap between the microscopic and macroscopic realms, and potentially pushing the boundaries of sustainable development.

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