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Role of Endophytes in Patchouli Growth and Development

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ABSTRACT

Patchouli (*Pogostemon cablin* Benth.) is an important aromatic plant cultivated for its essential oil whose application is widespread in the fragrance, cosmetics, medicine, and aromatherapy industries. Soil conditions, nutrient supply, environmental stresses, and interactions with microorganisms have an influence on its development, biomass production, and oil yield. The importance of endophytic microorganisms, including bacteria and fungi, which colonize plant tissues without causing any noticeable disease, has been recognized. With reference to patchouli, endophytes can positively affect its growth through the following mechanisms: biological nitrogen fixation, phosphate solubilization, the production of siderophores, phytohormone synthesis, and nutrient uptake enhancement. They can improve the ability of plants to resist biotic and abiotic stresses by triggering antioxidant defense, regulating hormonal processes in plants, as well as the production of antimicrobial and other bioactive metabolites. In addition, endophytic microorganisms can play a role in the secondary metabolism and essential oil synthesis processes which can, in turn, influence the quality and quantity of patchouli oil. This review article provides an overview of the diversity and functional role of endophytic bacteria and fungi in connection with patchouli oil. The account discusses how various bacteria and fungi act as endophytes in patchouli plants with a stress on their acting as plant growth promoters and their role in helping to combat stresses.

Keywords:- Endophytic fungi, Endophytic bacteria, secondary metabolites, PGPR, patchouli.

INTRODUCTION

As the world population continues to rise, so too does the demand for medicinal plants because of the important role that they play in the treatment of diseases(Latif & Nawaz, 2025). Approximately 80 percent of the world's population uses phytomedicine because of its low cost, ease of use, and lack of toxicity. Increasing usage of these phytomedicines threatens the biodiversity of plant species due to human activity and pathogenic organisms. To help address this issue, we must look to source bioactive compounds from alternate sources than plants, most notably higher fungi (fungi that occur with plants) that are found inside the stems, roots, leaves, and flowers of those plants(Meng et al., 2026).

It has been shown that bioactive compounds derived from food crops (plants that people use for food), such as those with antimicrobial, antioxidant, and anti-diabetic properties, are becoming increasingly important as bacteria develop resistance to traditional antibiotics. There is relatively little information available about the potential that bioactive compounds that are derived from microbes will have as alternatives to bioactive compounds that are derived from plants and that they will support pharmaceutical efforts in the development of new medications. Endophytic fungi have demonstrated the ability to produce bioactive compounds; therefore, endophytic fungi may also represent a potential source for the production of bioactive compounds that are of interest to pharmaceutical researchers(Nagib et al., 2026).

Sunflowers (Helianthus annuus) are a drought-resistant plant that is domesticated all over the world, and although the medicinal properties of both the sunflower plant and its associated endophytes are recognized, further research must be conducted to provide specific data on the relative bioactive metabolites produced by the endomycorhizal community associated with this plant(Dhiman et al., 2025). One reason for increased interest in this plant is that much of the structure of the plant may have previously been used for medicinal purposes. In addition, the history and tradition of use in herbal medicine has documented many medicinal uses of specific parts of the sunflower plant, but insufficient documentation exists to describe the bioactive metabolites produced by the plant's endomycorhizal community.

The fact that traditional medicinal plants (like the African Geranium Pelargonium sidoides) in South Africa have a great deal of endophytic microbial life is giving pharmacologists a new area of opportunity to search for new medicines(Tiwari et al., 2025b). Research has shown many bioactive compounds in the endophytes growing on Pelargonium sidoides, therefore additional research into how fungi interact with the plants and maximal methods of metabolite production should be performed.

2.1 Historical Background of Endophytes

Microbes exist in many different environments including, water, air, soil, and surfaces such as human skin, and have had a large impact on fields such as medicine, pharmacy, and agriculture(Anbarasu & Yuvarajan, 2025). The role of endophytic microbes has been of great interest considering that research on this group of microorganisms has expanded to include the characterization, diversity, and functions of microbes found within the endosphere (the specialized niches of the plant tissue) in agronomy. Endophytes are essential to plant health by colonizing sterile regions of plant tissues. Unlike rhizobacteria and endomycorrhizae which enter through the plant's root rhizosphere, endophytes are found naturally within different parts of plants, particularly in non-sterile areas of stems, roots, and flowers. The population of microbes within the root zone is much higher compared to aboveground plant tissues due to exudates from roots, which attract many types of microorganisms(Riseh et al., 2025).

Characterization of endophytes has occurred in economically important crops such as wheat, rice and sugarcane with potential to improve the yield of those crops. The term endophyte was first used by German botanist Johann Heinrich Friedrich Link in 1809; however, the term developed through scientists, such as Béchamp who first classified endophytes as plant parasitic fungi, and Heinrich Anton De Bary who first defined endophyte as any microbe that was found in healthy tissue of plants and did not cause disease(Fadiji et al., 2025). De Bary's findings included that the disease of the potato blight caused by the fungus Phytophthora infestans has provided the first link between pathogenic fungi and plants. Prior to the work of Victor Galippe in 1887, which found that bacteria had been found to be inside of plant tissue, it was thought that plants could only survive in sterile environments because there were no understandings regarding endophytes. In 1986, Carroll explained that an endophyte does not cause a disease (symptomatic) infection in a plant; therefore, this understanding has continued to evolve in respect to the relationships between endophytes and plants, supported by research in this area by Petrini and Müller since that time(Malik et al., 2025). In addition, today the term 'endophytes' represents all lineages of microorganisms that can live as intracellular organisms within the tissues of plants as they are growing and throughout their life cycles and represent how endophytes are integral to understanding the relationship between plants and microorganisms and the potential impact on agriculture.

The endophytes are microorganisms that live inside the tissues of plants. They are essential for assisting in the growth of plants as well as providing them with an improved immune response. Currently, numerous endophytic microbes have been discovered; however, there are still many that cannot be grown(Liao et al., 2025). Endophytes demonstrate significant potential in agricultural biotechnology through bioprospecting. Endophytes are asymptomatic within the host plant; however, they are required for the continued health and vitality of the plant. There are an estimated one million species that can be classified as endophytes that can be associated with certain plants, and the diversity of endophytes is dependent upon environmental conditions such as host plant (species, age, genotype), and soil type.

In medicinal plants specifically, these factors (plant habitat and genetics, in particular) will also influence the level of quality and amount of chemical compounds produced(Zhang et al., 2025). The majority of identified endophytic fungi belong to the ascomycete or fungi imperfecti phylum. Endophytes and the host plant form a mutualistic relationship, and endophytic fungi play a role in the synthesis of metabolites that have many uses in biotechnology. Research suggests that nearly every plant that has well-defined supporting tissues contains endophytic microorganisms, which may or may not be beneficial to the host plant(Tariq et al., 2025).

The presence of beneficial endophytes promotes plant growth by increasing the acquisition of nutrients through the production of growth regulators (gibberellins, cytokinins) and the hormone indole-3-acetic acid, as well as acting as biocontrol agents against plant pathogens. This mutualistic association helps plants adapt to their environment, while

also enhancing the production of bioactive metabolites, which further support the microbial network in the soil(Araque Gelves et al., 2025).

While there are more than 3 million species of plants on our planet, each has an associated set of endophytes, representing potential new sources of bioactive natural products; it is important to recognize that documentation of endophytes is inadequate, and that more research needs to be done in the area of studying the biotechnological applications of endophytes, especially regarding their use in the production of bioactive compounds(da Silva et al., 2025). The production of bioactive compounds by endophytes is often due to coevolution between the endophyte and host plant, which allows for co-adaptive interactions and protection for the plant from pathogens and pests.

Endophytes have been shown to produce various beneficial substances, and the selection of these metabolites by the host plant will ultimately determine the types of metabolites produced. As such, metabolite synthesis will occur with the intent of producing non-toxic products for use by higher organisms(L. Liu et al., 2025). The pharmaceutical industry has great potential to benefit from the use of bioactive compounds obtained from endophytes. At the same time, challenges associated with how to collect, process, and produce bioactive compounds from endophytes have resulted in a growing dependence on manufactured/synthetic products.

2.2 Biodiversity of Endophytes

All of the described endophytes are fungus or bacteria (including actinomycetes). Endophytes include endophytic fungi, bacteria, and actinomyces.

2.2.1 Endophytic fungi

(Fadiji et al., 2025). This group encompasses an extensive range of different species which reside in the stems, leaves and even roots of plants. Endophytes remain in living plant tissue in the form of mycelial hyphae for a limited time; thus, the actual presence of hyphae within living plant tissue is essential for their classification as true endophytes. Hyphae can be visualized within plant tissues using various techniques including bleaching and staining; however, modern techniques such as acridine orange fluorescence microscopy now enable quick observation of hyphae in orchid mycorrhizal roots. Identifying fungi from a hyphal perspective is a complex task; therefore, immunofluorescence assay and DNA sequencing techniques are necessary for accurate identification. Fungi are recognized as being functionally endophytic when located in asymptomatic plant tissues, and most endophytic fungi are ascomycetous in nature(Bala et al., 2025).

Endophytic fungi can be found living in different species of plants, from liverworts to seed plants, in every climate zone (arctic to tropical), and within every type of ecosystem (such as agricultural fields and tropical forests). Endophytes do not develop specialized interfaces with their host plants that regulate the timing of their development with that of the plant and do not offer direct nutrient advantages, unlike mycorrhiza(Moora et al., 2025). Despite this, they may enhance the plant's tolerance to herbivory, disease and environmental stressors such as drought and salinity. Studies also indicate that the stress response of endophytes can be more effective than that of non-symbiotic plants in improving heat tolerance.

Dark septate endophytes (DSE) possess distinct characteristics such as their melanized, septate hyphae that help identify them from other endophytes and mycorrhizal fungi. Taxonomic classification of DSE is somewhat difficult due to the rarity of their reproductive structures(de Oliveira & Pereira, 2025). While many endophytes do not share visual features with mycorrhizal fungi, they nevertheless contribute to a plant's health or resilience. A significant discovery was made with the isolation of Taxomyces anderanae, the first endophytic fungus found from the medicinal plant Taxus brevifolia and two additional strains found in Nerium oleander. Fungi are also found in marine plant systems; for example, Ascochyta salicorniae is found in green algae(Burkin & Kononenko, 2026).

Their potential benefit for promoting plant growth and disease and pest resistance continues to receive increased attention. They produce many types of bioactive compounds with potential therapeutic effects, including anticancer (antitumor) and immunosuppressive agents, and some may help to provide thermal protection to plants. Endophytic fungi are classified ecologically into two groups: balansiaceous (grass endophytes) and non-balansiaceous, both of which play important roles in plant health and resilience(Mohammed et al., 2026).

Balansiaceous endophytes or Grass endophytes

The genera Epichloe and Balansia comprise the essential balansiaceous endophyte fungi that have considerable ecological as well as economic impact. They thrive in all the aerial portions of their host grass plants, thus enabling them to be transmitted vertically through seeds. They also produce a variety of secondary metabolites, including some toxic alkaloids (peramine, lolines, loliterm B, ergovaline, etc.) and other natural products(S. Liu et al., 2025). The overall relationship between endophytes and plants is one where the fungi receive nutritional benefits from the host's plant tissue and protection from abiotic stress, and the plants derive protection from herbivores due to the toxic metabolites that the fungi produce. The initial colonization of the host plants occurs via intercellular spaces and the endophytes utilize the apoplastic nutrient pool of the host for their nutrition requirements. There are indications that some of the endophyte fungi can enhance the fitness of their host plants through mechanisms of induced resistance, while other endophytes are neutral or negative towards their host, contributing little to enhancing the host's fitness. Therefore, the role of physiological signaling in the symbiotic relationship between E. festucae and its host will be critical for any future studies(S. Liu et al., 2025).

Non-Balansiaceous endophytes:

There is a large number and variety of non-balansiaceous endophytes that occur as intracellular or intercellular mutualists of plants. A variety of different life history strategies are exhibited by non-balansiaceous endophytes; for example, some exhibit a non-aggressive lifestyle and infect a wide variety of different types of plants (both monocots and dicots)(Luo et al., 2025). Classification of endophytes has led to a categorization of four different types of endophytes based on the endosymbiotic relationships they establish with the host's tissues:

Class I is represented by balansiaceous endophytes that develop a specialized relationship with a single or very few host plants. These fungi are highly diverse among hosts, but there is low diversity among endophytes isolated from individual hosts(Geng et al., 2025). These endophytes typically reside between cells (intercellularly) in the plant and are generally transmitted from one plant to another through seed. By developing a mutually beneficial symbiotic relationship with host plants, these endophytes increase the ability of their hosts to survive and/or thrive under conditions of environmental stress(Rodriguez et al., 2009).

Class II endophytes can colonize multiple host plants by both vertical (through seeds) and horizontal (by way of rhizomes) transmission, and at the same time provide host plants with increased tolerance to extreme physiological condition. Class II endophytes also have the ability to synthesize toxic metabolites to protect their hosts from fungal pathogens(Xu et al., 2021).

Class III endophytes establish localized infections (within a host plant) on the above-ground growth of the infected host plants. Class III endophytes provide protection to their host plants against other fungal species (so they are beneficial) but may also act as pathogens to host plants under drought conditions.

Class IV endophytes develop asexual reproductive structures and are associated with dark-septate-fungi found in root tissue of host plants. Class IV endophytes have a low degree of host specificity and are frequently found in areas of environmental stress and may provide assistance to their hosts against fungal diseases(Verma et al., 2022).

2.2.2 Endophytic bacteria

Endophytic bacteria have been found to be present in of a lower density than rhizobial and pathogenic bacteria. It remains difficult to determine the role of endophyte bacteria in helping plants and how much benefit they may have compared to rhizobial organisms, but they may be more protected from the surrounding environment(DeFries et al., 2005). Endophytes belong to many different genera, and Species; they are capable of inhibiting nematodes and may help provide rotational crops for their host plants as a result of their differences. Endophytes typically find a habitat in intercellular spaces and vascular tissue of the plant, but many studies have previously documented them from cotton, sweet corn and peas. Endophytes have been isolated into over 129 different general and species of endophytes, including both gram-positive and gram-negative types, found in 54 genera with many being identified in the genera of Pseudomonas or within the Enterobacteriaceae family(Microbiology & 2022, 2022). Studies indicate that the community structure of endophyte bacteria is dynamic and influenced by various abiotic and biotic factors, including soil conditions,

biogeographical locations, the species of plant being studied and the interactions between the bacteria and other microbes as well as between the bacteria and the plant species. Several bacterial endophytes that have been shown to promote plant growth have had limited consistency and success in increasing plant productivity when tested in field trials. Scientists have also used molecular techniques to study the endophyte bacteria and verify that they do promote growth and yield, provide pathogen resistance, help the removal of contaminants, solubilize phosphorus, and potentially provide nitrogen to the plants(Bhardwaj et al., 2014).

2.2.3 Endophytic actinomyces

Actinomycetes are a type of bacterium Associated with plants. They promote healthy plant growth, soil health, and plant health. Of the bacteria identified as Endophytes, the most commonly isolated Actinobacteria are from the genus Streptomyces, occurring primarily in plant roots, stems, and leaves(Govindasamy et al., 2014). The presence of Streptomyces, however, is highest in root tissue and acts as the main source of isolation for Endophytic Actinobacteria coming from plants that can be used to produce secondary metabolites of medicinal value. Also, many Endophytic Actinobacteria are present within the internal tissue of agriculture plants. For these Endophytes, they are considered dormant, they do not harm the plant species they inhabit; rather, they are inactive and will not produce any detrimental effects on the host when they remain inactive. Another study investigated the effects of Endophytes on the productivity and disease mitigation of various crops and concluded that Endophytes provide protection from many insect pest species through the production of some alkaloids toxic to livestock that graze on plants. The studies outlined above demonstrate that Endophytic Actinobacteria resides in Agriculture Ecosystems and play an essential role in enhancing plant resistance and productivity(R. Singh & Dubey, 2018).

2.3 Endophyte Diversity

The presence of endophytic fungi without symptoms in plants has been noted since the 19th century. It is estimated that there are over 1 million species of these fungi, which can be found in a ratio of about 1:4 or 1:5 fungi for each vascular plant species(Hawksworth et al., 2017). Additionally, there are known to be over 200 genera and 16 phyla of endophytic bacteria associated with these plants; however, very few have actually been isolated and identified. The importance of endophytes has been magnified lately because of the increasing commercial and industrial uses of endophytes, particularly following the report of cattle toxicosis caused by the endophytic fungus Neotyphodium coenophialum that inhabits Festuca arundinacea. This episode demonstrated that there are many endophytes present in plants, including some that may be dormant, and that systemically infected plants may not show signs of infection until it is too late and significant damage has already occurred(HAMMOND et al., 1985).

The endophytes that occur in cultivated and wild plants may differ based on the adaptation and evolution of those endophytes relative to their hosts. The classification of endophytes from the traditional microbial approach (based on morphology) has been particularly challenging for bacteria because of their small size. As a result, bacterial endophytes must be identified using physiological characteristics and conditions that differ from other microbes. New molecular biology tools, including genetic barcoding, are now critical to reliably identifying these types of organisms(Antil et al., 2022). As DNA barcoding techniques for animals and plants have advanced, scientists are applying similar techniques to microorganisms. For taxonomic and identification purposes, ribosomal DNA is preferred over mitochondrial DNA, specifically because it is evolutionarily stable.

In the discipline of endophyte research, the Internal Transcribed Spacer (ITS) region functions as the main DNA barcode for molecular identification of these organisms (typically), used in ecological ecology or diversity studies. Improved identification of endophyte diversity can now be made by using advanced molecular biology techniques and integrating microscopy into the analysis, thereby enabling researchers to clarify the ecological functions and/or applications of endophytes in a variety of ecological settings(Fišer Pečnikar & Buzan, 2013).

2.4 Isolation and Identification of Endophytes from Different Sources

The criteria used to separate bioactive molecules from endophytes are based on factors including importance of the host plant, bioactive compounds produced by the plant, the rarity of bioactive compounds produced by the plant and the geographic origin of the host plant and its environment. Endophytes are isolated from plant tissue by first disinfecting the surface and then culturing on synthetic medium, which may or may not contain host tissue extracts(Baker et al.,

2000). As obligate parasites do not grow well on synthetic media, there is the potential for loss of important information regarding these organisms. Endophytes can be separated from all parts of the plant, including leaves, stems, roots and even meristems. Endophytes are identified by morphological characteristics of the colony, including vegetative hyphae and type of spore, similar to other fungi. Advances in molecular biology techniques now allow for more accurate identification of these fungi using molecular markers and have allowed for an increased understanding of previously unknown endophytes in relationship to each other. In addition, these technologies are important for investigating the phylogenetic relationships between different groups of organisms(Azpurua et al., 2010).

2.5 Endophytes and Plant Protection

Endophytes may live in a symbiotic relationship with host plants and provide many different types of benefits as protection to the host plants. In addition to allowing plants to survive in extreme environments, such as hot springs, they deter herbivores and other pests through the production of toxic alkaloids to prevent them from feeding on the host plant, and provide protection against insects(Leigh Anderson et al., 1985). Evidence has shown that the interaction between endophytes and invading pathogens differs according to the plant species of the host and produces physiological changes in the plant that can prevent the growth of pathogens, alter the availability of nutrients in favour of the endophyte, or improve the host plants' ability to defend against an invading pathogen(Arnot et al., 1993). Many endophytes produce both antibiotics and antifungal agents, which help to protect the host plants from pathogens while limiting the number of pathogens that can cause damage to the host. Endophytic fungal colonization can enhance the resistance of plants to nematodes by an unknown mechanism of action(Fišer Pečnikar & Buzan, 2013).

Endophytes play an important role in the development of pathosystem dynamics, and ultimately influence the survivorship, diversity, and conservation of plants. The existence of over 1,000 insect-pathogenic fungi has been identified as endophytes, and are generally classified as belonging to Chytridiomycetes or Basidiomycetes. A few endophytes, such as Claviceps and Epichlo have demonstrated a close association with specific types of grasses. The potential for endophytes to protect a host plant from a variety of herbivores and/or pests through the cross-protection mechanism has also been investigated in relation to a viral pathogen(Antil et al., 2022).

2.6 Endophytes and Metabolites

Several well-known pharmaceutical compounds such as vincristine, vinblastine, and camptothecin have been derived from plant sources. Additionally, more than 8,500 different bioactive metabolites have been identified that are of fungal origin(Besansky et al., 2003). This has created an interest in identifying additional endophytic fungi, given the recent discovery of Taxomyces andreanae (an endophytic fungus associated with Taxus baccata) which is known for its ability to produce taxol. Not only can new metabolites potentially be discovered through this approach, but also valuable information about the evolutionary relationship between these microorganisms and their plant hosts. However, there are still many obstacles to isolating and identifying endophytic fungi, especially given the complexity of linking the presence of an endophytic fungus to the biosynthesis of bioactive molecules produced by endophytes(Burzyński et al., 2003).

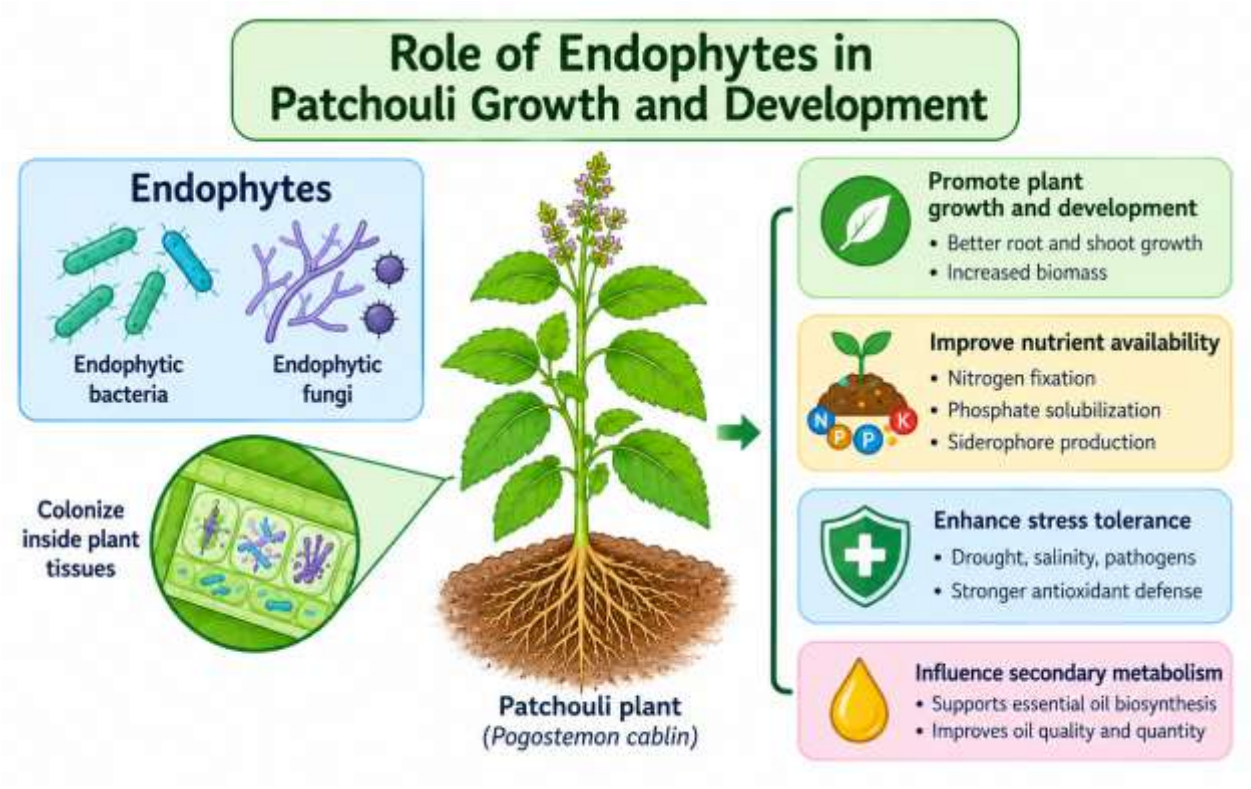


Fig 1. Schematic representation of the role of endophytic bacteria and fungi in promoting patchouli (*Pogostemon cablin*) growth.

The wide range of compounds produced by endophytes is evidenced by the gibberellins produced by *Fusarium oxysporum* fungi, which are associated with rice diseases. Endophytes can produce many different secondary metabolites including alkaloids, essential oils, terpenes, azadirachtins, coumarins, flavonoids, and lignans. Many of the compounds produced by endophytic fungi have been shown to have therapeutic value in treating various diseases including cancer(Burns et al., 2008). Examples of bioactive molecules produced by endophytes include azadirachtin A and B, camptothecin, and cytochalasin N.

Table 1. Previous studies on isolation and identification of endophytic bacteria and fungi from medicinal and aromatic plants

Author(s)	Plant	Endophytes Isolated	Major Findings
Golinska, Patrycja et al. (2015)	Medicinal plants	Endophytic actinobacteria	Reported high diversity of culturable endophytic bacteria with significant ecological and biotechnological importance.
Wu, Wei et al. (2021)	Various medicinal plants	Endophytic bacteria	Reviewed the beneficial association of bacterial endophytes with medicinal plants and highlighted their diversity and identification methods.
Tripathi, Arpita et al. (2022)	Medicinal and aromatic plants	Bacterial and fungal endophytes	Reported that medicinal plants harbor diverse endophytes contributing to plant health and adaptation.
Gao, Yuan et al. (2025)	Medicinal plants	Endophytic fungi	Summarized the diversity, distribution, and identification of fungal endophytes associated with medicinal plants.
Kumari, Poonam et al. (2023)	Medicinal plants	Endophytic bacteria and fungi	Described plant–endophyte interactions and emphasized the importance of endophyte diversity in medicinal plants.

In addition, endophytes can also catalyze a biotransformation, which changes an original compound into a much more potent derivative of the original compound, such as semisynthetic forms of taxol and podophyllotoxin that are more effective than their parent compounds(Barrett & Hebert, 2005). Developing valuable chemicals is essential to the health care, agriculture, and industrial sectors. An integrated approach, involving molecular biology to identify the endophytes, chemical methodologies to characterize the metabolites produced by endophytes and biotechnological methods for developing commercially applicable methods of producing the biochemical, is thus required(Hollingsworth et al., 2009). The role endophytes play in regards to host plant growth and nutrition, as well as their effects on the production of secondary metabolites through similar processes as those employed by plants and fungi, has led to a better understanding of how to utilize endophytic bacteria through isolating endophytes for the identification of their metabolic pathways and then applying various techniques of production on an industrial scale(Chen et al., 2009). There has been an increased interest in the development and characterization of cyclic and non-cyclic peptides that have been isolated from various endophytes and their use in anticancer therapy, as well as the potential role of endophytes in immunosuppression and antifungal therapies. Overall, this comprehensive review demonstrates that endophytes are an important source of bioactive metabolites and can contribute to numerous beneficial bioactive molecules(Chase et al., 2005).

2.7 Endophytes in Agriculture

Agriculture is vital to the economy and the ability to have food for millions of people, especially in developing countries(H. Liu et al., 2017). With a growing population worldwide, there is an increase in the need for agricultural production and increased productivity. This leads us to search for new and creative ways to produce more food with fewer resources. One area of great potential for innovative solutions is through the study of endophytes. Endophytes play an important role in improving plant growth by providing protection from a variety of environmental stresses and enhancing seed yields through the use of hormones(de Souza et al., 2020). Therefore, endophytes can provide a key benefit to sustainable agricultural practices by enhancing crop quality.

For example, many of the wild relatives of wheat, such as Triticum dicoccoides and Aegilops sharonensis, have a greater diversity of beneficial endophytes compared to cultivated wheat varieties. By using modern agricultural techniques, such as the use of chemical fertilizers and pesticides, we have disrupted the natural balance between endophytes and their plant hosts by changing the soil's structure and function(Syed Ab Rahman et al., 2018). The chemical environments in which cultivated plants are grown are not conducive to supporting endophyte growth; rather, endophytes thrive when cultivation methods do not include these chemicals. Furthermore, the use of modern breeding techniques has changed the genetic makeup of cultivated crops, which has positively affected their ability to resist certain types of pests and diseases. These genetic changes have altered the agricultural attributes of cultivated crops and how they interact with endophytes(Carvalho, 2017). The use of bacterial endophytes has great potential for promoting environmentally friendly agricultural practices that will lead to improved agricultural productivity by improving not only the health and quality of crops but also improving holistic health and nutritional outcomes; establishing a basis for ongoing advancements in sustainable agricultural practices.

2.8 Description of Patchouli (Pogostemon cablin) Plant

Patchouli, also called Pogostemon cablin (Blanco) Benth., is a perennial aromatic herb in the family Lamiaceae. Patchouli is mainly grown in tropical and subtropical areas (e.g., India, Indonesia, China, Malaysia, The Philippines) — it has soft, hairy stems and large, serrated leaves. In terms of agriculture, P. cablin thrives in warm humid areas with sufficient reproductive biomass and requires a very productive soil with a high amount of water(Rahim Pouran et al., 2015). Recent years have seen a shift in pharmacological research on the global stage to include plant-based bioactive compounds due to their relatively low toxicity and high level of therapeutic use; as such, P. cablin is an important species, an ethnomedically valuable herb with extensive histories of use in Traditional Chinese Medicine (Pogostemon Herba). Historically, P. cablin has been used to treat internal dampness, has nontoxic antipyretic actions against external syndromess, to suppress nausea and promote appetite(Kamilaris & Prenafeta-Boldú, 2018). Historically, it has also been used in the cosmetic and personal care industries.

The overall therapeutic potential of patchouli has been attributed to many secondary metabolites, including a diverse quantity and diversity of terpenoid compounds (i.e., monoterpenoids, sesquiterpenoids, and triterpenoids), flavonoids, lignins, phytosterols, organic acids, glycosides, aldehydes, alcohols, and pyrones(S. Kumar et al., 2022).

TAXONOMY

Kingdom: Plantae

Division: Magnoliophyta (Angiosperms)

Class: Magnoliopsida (Dicotyledons)

Subclass: Asteridae

Order: Lamiales

Family: Lamiaceae (Mint family)

Genus: Pogostemon

Species: Pogostemon cablin (Blanco) Benth.

Patchouli (Pogostemon cablin (Blanco) Benth.), which has been used in traditional medicine for many generations, belongs to the family Lamiaceae or mint family(Shukla et al., 2024a). The mint family is the second largest flowering plant family, consisting of 12 sub-families, 240 genera, and approximately 7,200 recognized species worldwide. The Pogostemon genus has been classified as containing about 80 species, of which approximately 20 are native to India, and most fall within an area of Southeast Asia. P. cablin is a tropical herbaceous plant native to the Philippines that has adapted well to many different climates across Asia, including China and Indonesia, as well as Brazil, Singapore, Seychelles, and West Africa. P. cablin requires the following environmental conditions to achieve optimal growth: temperature between 24°C and 28°C; relative humidity of approximately 75%; annual rainfall of between 2000mm and 3000mm; and altitude from sea level to 1200m(Shukla et al., 2024b). Morphologically, P. cablin is a dicotyledon and has a bushy, herbaceous perennial growth form. The plant's height ranges from 1- 1 ½ m, has a strong upright stem, and produces long oval leaves that average about 10cm x 2cm.

2.9 Importance of Patchouli

Pogostemon cablin (Linn.) Backer (patchouli) is a medicinal herb of great significance in traditional Asian medicine systems like Traditional Chinese Medicine (TCM) and Ayurveda(Malakar & Mandal, 2024). Ethnobotanical studies show P. cablin dry leaves have long been used to treat a range of health issues, including digestive disorders, nausea, loss of appetite, and use of leaf poultices for wound healing. Pharmacological studies have shown P. cablin may have beneficial effects as an antipyretic agent, analgesic agent, and anti-inflammatory agent(Sharma et al., 2024). The phytochemicals found in the leaves can aid in regulating inflammatory cell signaling pathways, and they are commonly used in clinical aromatherapy sessions for the treatment of patients suffering from stress and anxiety. Recent laboratory studies have also revealed many different types of bioactive compounds in the leaves of P. cablin that demonstrate antibacterial activity against resistant bacteria such as Staphylococcus aureus and Escherichia coli (E. coli)(S. K. Pandey et al., 2021). Furthermore, the extracts from the leaves of P. cablin have demonstrated antioxidant activity by neutralizing reactive oxygen species (ROS), thereby helping to reduce the oxidative stress experienced by cells. Patchouli is a very important industrial cash crop to the world economy. The complex sesquiterpenoids and natural non-volatile metabolites found in patchouli cannot be produced by economical chemical means and therefore, continued reliance will be placed on the exportation of patchouli from plantations in countries such as Indonesia, India, and China(A. Kumar et al., 2024). The growing demand for organic and plant-based products has considerably increased the market value of patchouli. In addition to the economic importance of patchouli as a cash crop, patchouli farming also plays an important role in the socio-economic structure of rural agricultural economies in tropical areas by providing many employment opportunities and contributing to agrarian infrastructure development(de Souza et al., 2020).

Studies are currently being performed in the pharmaceutical industry using extracts from the patchouli leaf and its isolated compounds such as flavonoids and glycosides to develop new antibacterial agents and dermal agents for chronic

diseases such as acne and eczema. Patchouli extracts are also being used in the development of environmentally friendly botanical larvicides to control mosquitoes(Carvalho, 2017).

In the cosmetic and fragrance industry, both the raw and processed materials from the patchouli leaf are utilized in many high-end personal care products, acting as a natural fixative to help retain the scent longer. In the field of food technology, derivatives from P. cablin are used to develop natural flavoring agents that can provide unique herbal flavors and serve as natural bio-preservatives against food-borne pathogens(Rahim Pouran et al., 2015). Patchouli is used for its medicinal and economic values, but its cultivation also aids sustainable agricultural methods. The plant serves as a viable alternative to standard cereal crops (used for human food) and thus promotes diversification of agricultural operations. The plant's secondary metabolites have insecticidal & nematicidal properties which facilitate the use of the plant in crop rotation systems and/or intercropping systems (the growing of two or more crops together in the same field)(Kamilaris & Prenafeta-Boldú, 2018). This reduces reliance on synthetic pesticides and enhances ecological balance in farming systems.

CONCLUSION

Endophytes represent significant organisms, which can significantly improve and boost patchouli growth, development, and performance. Beneficial endophytic bacteria and fungi not only contribute to the plant growth; they do this through different mechanisms, for example, nutrient solubilization, nitrogen fixation, synthesis of phytohormones, synthesis of siderophores, and stimulation of root and shoot growth. Their ability to stimulate antioxidant protection and increase resistance to drought, salinity, pathogens, and environmental pressures proves once again all the advantages of using endophytes in sustainable patchouli cultivation. Endophytes are also able to influence secondary metabolic pathways linked to the production of highly effective essential oils and other bioactive compounds. Thus, endophytes can improve the quality and quantity of patchouli oil. However, their efficiency may depend either on some unique microbial strain features, plant genotype, place of cultivation, or soil conditions. Thus, systematic screening and characterization of the most efficient strains of endophytes is complex. Further investigations should be focused on the study of plant-endophytes interactions on molecular and biochemical levels.

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