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REVIEW

The role of endophytic fungi on orchid sustainability

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Orchids, renowned for their diverse beauty and medicinal properties, are increasingly threatened by habitat destruction and illegal trade, pushing many species toward extinction. To better understand and conserve these enchanting plants, research into their symbiotic relationship with endophytic fungi has become a focal point. This review paper delves into the multifaceted roles of endophytic fungi in orchids, including seed germination, stress tolerance, secondary metabolite production, nutrient acquisition, and *in vitro* propagation.

Endophytic fungi play a critical role in facilitating orchid seed germination and growth by providing essential nutrients and enhancing stress tolerance. Additionally, these fungi produce bioactive compounds with significant pharmaceutical potential, underscoring their importance in drug discovery. Moreover, endophytic fungi improve nutrient uptake and support micropropagation efforts, thereby contributing to the conservation of orchids. Understanding the intricate interactions between orchids and endophytic fungi is essential for promoting sustainable floriculture, preserving biodiversity, and advancing human well-being.

Keywords: Bioactive compounds, Conservation, Endophytic fungi, Orchids, Seed germination.

INTRODUCTION

The Orchidaceae family is the most diverse among all angiosperms, with an estimated >25,000 species (Gravendeel *et al.* 2004; Niu *et al.* 2017). Orchids are highly prized for their long-lasting and beautiful flowers, which come in various shapes, sizes, colors, scents, and textures. Freshly cut blooms from genera such as *Cymbidium*, *Dendrobium*, *Cattleya*, *Paphiopedilum*, *Phalaenopsis*, *Vanda*, and other captivating orchid species are in high demand in global floriculture markets, admired for their exquisite allure (Khasim *et al.* 2020).

Beyond their aesthetic appeal, orchids possess significant medicinal attributes with promising benefits for human well-being (Hossain, 2011). Virtually every part of the orchid plant, from its roots and foliage to its pseudobulbs, has therapeutic potential, offering remedies for a wide range of ailments, including rheumatism, respiratory conditions, sexual dysfunction, nausea, hemorrhoids, inflammation, viral infections, and even cancer (Gutiérrez, 2010; Subramaniam *et al.* 2013).

However, the floristic and medicinal importance of orchids raises concerns about their continued existence in the wild, as they face threats from illegal trade and habitat destruction. Additionally, climate change has contributed to the decline of orchid populations to some extent (Sathiyadash, 2020).

In natural settings, orchids exhibit limited rates of seed germination and propagation. Upon reaching maturity, orchid pods release millions of powdery seeds dispersed by wind currents to various locations. However, only a tiny fraction of these

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seeds successfully germinate, with the majority failing. Research has shown that germinating orchid seeds depend on fungal mycelium. When in a suitable environment, orchid seedlings establish contact with fungi, which provide essential nutrients needed for germination, compensating for the absence of endosperm in the seeds (Pant *et al*., 2017). This symbiotic relationship evolves, with the fungi persisting as both mycorrhizal and non-mycorrhizal endophytes within the orchid throughout its lifespan (Selosse, 2014; van Der Heijden, 2015).

Endophytes inhabit plant tissues without causing overt harm, forming complex symbiotic relationships that are crucial for plant vitality and proliferation (Brundrett, 2004). In orchids, endophytic fungi play a pivotal role not only in seed germination but also in significantly influencing plant survival and sustainability in natural habitats. Beyond their ecological functions, endophytic fungi are essential for sustainable agricultural practices and pharmaceutical applications. The bioactive compounds synthesized by these fungi exhibit a wide range of pharmacological properties, including antimicrobial, anti-inflammatory, antioxidant, and anti-cancer activities. Harnessing the therapeutic potential of orchid-associated endophytic fungi opens new avenues for drug discovery and highlights the importance of preserving these delicate ecosystems for future generations.

Given these considerations, elucidating the multifaceted roles of endophytic fungi in orchid sustainability is essential for both conservation efforts and biotechnological advancements. This review paper delves into the intricate interactions between orchids and endophytic fungi, highlighting their ecological significance, medicinal potential, and implications for sustainable floriculture and biodiversity conservation. Through a comprehensive understanding and strategic conservation measures, we can work towards ensuring the continued existence and flourishing of these enchanting floral wonders in our natural world.

MULTIFACETED ROLE OF ENDOPHYTIC FUNGI IN ORCHIDS

Endophytic fungi in orchids have recently become an exciting topic of discussion. Initially, research on orchid-endophytic fungi interactions focused primarily on promoting seed germination and growth. However, studies have since expanded into various fields, including pharmaceutical research, revealing that endophytes are a significant resource for scientific investigation.

Endophytes not only aid in seed germination and seedling development but also enhance stress tolerance and resistance to pathogen infections. The secondary metabolites produced by endophytes are crucial for the vigor and health of orchids. Beyond their ecological significance, orchid-associated endophytic fungi offer promising biotechnological applications, with their bioactive compounds providing potential benefits for pharmaceutical and flori-agricultural industries. Understanding and harnessing the role of endophytic fungi in orchid ecosystems enhances our knowledge of plant-microbe interactions and opens avenues for conservation, biotechnological innovation, and sustainable floriculture.

Seed germination and growth

Orchid seed germination relies on fungal assistance due to the absence of endosperm. During the initial protocorm stage, marked by meristematic activity, endophytic fungi play a crucial role in facilitating the formation of leaves and roots, a process documented in various orchid species (Fang *et al*., 2016). The specific fungal associations established during germination often persist throughout its life cycle. However, while these associations are vital for the sustainability of orchids, not all fungal partners contribute equally to seedling development, as evidenced by studies on helleborine orchids (Bidartondo and Read, 2008).

In the case of *Arundina graminifolia*, the bamboo orchid, research has shown that while multiple fungal species can be isolated from advanced seedlings and adult roots, only a subset supports germination beyond the initial imbibition stage (Meng *et al.,* 2019). The conservation of endangered terrestrial orchids in Thailand, such as *Pecteilis gigantea*, depends on endophyte isolates for successful seed germination and protocorm development. This vulnerable terrestrial orchid yielded eight endophytic fungi from its roots. A phylogenetic study using the internal transcribed spacer region of nuclear rDNA identified one isolate as *Fusarium* sp. and seven as belonging to the genus *Epulorhiza*. These fungi demonstrated the highest percentage of symbiotic seed germination (86.2%) and advanced protocorm development (17.8%), highlighting the orchid's dependency on fungal symbionts for early seedling growth (Chutima *et al.,* 2011). Additional examples of endophytes assisting in seed germination are depicted in Table 1.

The successful germination and proliferation of orchids are contingent upon specific fungal associations. In many cases, the fungal association is influenced by the environment where the seeds are lodged. Conversely, fungi that facilitate seed germination may not necessarily contribute to the subsequent growth and development of the orchid plant. For example, a study demonstrated that *Fusarium* sp., isolated from *Dendrobium moniliforme* roots, can promote the growth of *Rhynchostylis retusa* orchids when co-cultured together (Shah *et al*., 2018). Several studies have explored the intricate specificity of orchid-fungus interactions and the complexity of these symbiotic relationships, revealing differential effects among fungal species on orchid seedling development (Rasmussen *et al*., 2015).

Stress tolerance and pathogen resistance

The orchid family, comprising both terrestrial and epiphytic species, faces various abiotic and biotic challenges that influence their growth and development (Novotná, 2018). Fungal endophytes are believed to have a significant impact on plant adaptation to diverse environments. Endophytic fungal genera such as *Colletotrichum*, *Piriformospora*, *Trichoderma*, *Epulorhiza*, and *Botrytis* can withstand abiotic stresses and promote host acclimatization. Stress-related enzymes like peroxidases and superoxide dismutases, produced by fungal endophytes, enable them to survive harsh conditions, while others enhance nutrient and water access (Albores *et al.,* 2005). Reports suggest that endophytic fungi induce stress-related enzymes that increase the chances of plant survival in challenging environments (Verma *et al.,* 2021). For instance, orchids harbouring *Penicillium chrysogenum* and *Rhizoctonia* spp. have demonstrated tolerance to lead contamination, although their growth rates are reduced (Idris *et al.,* 2019). Similarly, endophytic fungi associated with the roots of *Epipactis helleborine* tolerate various heavy metals, including iron, copper, zinc, lead, and cadmium (De Agostini *et al.*, 2020).

Endophytic fungi also play a crucial role in overcoming biotic stress, particularly infection by pathogens. They enhance plant defense against pathogens by producing compounds such as enzymes and siderophores (Shubha and Srinivas, 2017). Studies have shown that specific fungal endophytes isolated from orchids like *Dendrobium devonianum* and *D. thyrsiflorum* exhibit antipathogenic activity against phytopathogenic bacteria and fungi (Xing *et al.,* 2011). Furthermore, endophytic fungi found in *Cymbidium aloifolium* produce siderophores with antibacterial properties that are effective against major phytopathogens. These bioactive endophytes, when adequately formulated, can help crop plants resist other phytopathogens (Chowdappa *et al.*, 2020).

Molecular and pathogenicity studies on endophytic fungi from *Dendrobium nobile* and *D. officinale* revealed that *Trichoderma longibrachiatum* exhibited the least pathogenic effects, while *Colletotrichum tropicicola* was highly pathogenic. These findings highlight the dual role of endophytes in orchids, influencing plant development and disease resistance (Sarsaiya *et al.,* 2020).The research has also demonstrated that colonization by orchid mycorrhizal fungi, particularly *Tulasnella calospora*, induces a systemic resistance in *Bletilla striata* against the necrotrophic pathogen *Dickeya fangzhongdai*. This mechanism, mediated by jasmonate and ethylene pathway regulation, shares similarities with arbuscular mycorrhizal-induced resistance in other plants (Pujasatria *et al.*, 2024).

Endophytic fungi, therefore, play a pivotal role in orchid survival by enhancing tolerance to abiotic stresses such as heavy metal contamination and improving resistance against biotic threats through the production of stress-related enzymes and antimicrobial compounds. Their dual role in plant development and defense mechanisms highlights their potential applications in agriculture and ecological conservation, offering promising avenues for sustainable plant growth and protection.

Secondary metabolite production

The global pursuit of pharmacological breakthroughs from natural resources aims to develop drugs with minimal toxicity and broad-spectrum activity. Plants serve as reservoirs of natural rejuvenating compounds, including herbal-based remedies. Orchids, long utilized in traditional medicinal practices like Ayurveda, are integral to formulations such as 'Ashtawarga' (Shah, 2019). Studies have revealed the essential interaction between fungi and orchids, with fungi potentially serving as sources of potent chemicals that mirror the curative properties of their host plants (Knapp, 2021).

Notably, the endophytic fungal association with the epiphytic orchid *Cymbidium aloifolium* has been harnessed for medicinal purposes based on traditional knowledge (Wary *et al.,* 2022). Active compounds such as gibepyrone A, pyrrolo [1, 2-a] pyrazine-1, 4-dione, hexahydro-3-(2-methylpropyl), and indole acetic acid, all with various biological activities, were obtained from acetate extracts of endophytes isolated from the flower parts of *Dendrobium lindleyi* (Bungtongdee *et al*., 2019). Species like *Chaetomium globosum* and *Colletotrichum gloeosporioides*, associated orchids like *Anoectochilus* and *Ludisia*, have been shown to enhance the biomass of *Anoectochilus roxburghii*, a terrestrial orchid, and induce the biosynthesis and accumulation of active ingredients, including flavonoids, kinsenoside, and polysaccharides (Ye *et al.,* 2020). The orchid-associated fungal species *Daldinia eschscholtzii*, isolated from *Paphiopedilum exul*, was found to produce a wide range of aromatic polyketides, including the new naphthalene derivative daldionin, nodulones B and C, and daldinones F and G, along with eight known compounds (Barnes *et al.,* 2016).

An endophytic fungus identified as *Xylaria* sp., isolated from the surface-sterilized leaf segment of *Anoectochilus setaceus*, yielded helvolic acid, a known antibacterial compound, through bioassay-guided chromatographic fractionation of the laboratory culture (Ratnaweera *et al*., 2014). Among 59 endophytic fungal isolates from *Cymbidium* and *Dendrobium* species, 13.56% exhibited antibacterial activity against *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*, with all isolates showing antifungal activity against pathogenic fungi. Phytochemical investigations have attributed the antibacterial properties of extracts from *Trichoderma asperellum* and *Fusarium incarnatum* to constituents such as alkaloids, flavonoids, phenols, saponins, tannins, and terpenoids (Chua *et al*., 2022). These findings underscore the potential of orchid-derived fungal endophytes as sources of novel antimicrobial agents.

Nutrient acquisition

Orchids rely on an obligate relationship with endophytic fungi to meet their nutritional requirements. These fungi inhabit orchid tissues and facilitate the decomposition of organic matter, replenishing essential nutrients. This process enriches the soil, creating optimal conditions for orchid growth and establishment (Rana *et al*., 2019). Endophytes such as *Trichoderma* sp., *Epulorhiza* sp., and *Botrytis* sp. are associated with *Cattleya skinneri* and aid in acclimatizing to nutrient-poor environments (Albores *et al*., 2005). Endophytic fungi also enhance carbon uptake in orchids, a critical nutrient for plant development and growth (Gennaro *et al.,* 2003; Zimmer *et al.,* 2007). For instance, the *Achlorophyllous epipogium*, a mycoheterotrophic orchid, relies on an endophyte, *Inocybe* sp., a basidiomycetous fungus, to provide a significant amount of carbon to the plant (Roy *et al.,* 2009).

Phosphorus is another essential nutrient for plants, which they can absorb either through their transport systems or via mycorrhizal associations (Li *et al*., 2013). Endophytic fungi, such as *Piriformospora indica*, enhance the surface area for absorption in plants, allowing phosphorus to be taken up more efficiently by root-colonized endophytes (Malla *et al.,* 2004).

Overall, these symbiotic relationships with endophytic fungi significantly contribute to the

Table 1: List of endophytic fungi supporting the seed germination of orchids

Host	Endophytes	Reference
Sprianthes spiralis *Dactylorhiza osmanica*	*Rhizoctonia* sp.	Sazak and Ozdener, 2006
Habenaria macroceratitis	*Epulorhiza* sp.	Stewart and Kane, 2006
Anacamptis pyramidalis, *Ophrys fusca,* *Serapias vomeracea,* *Orchis sancta*	*Fusarium* sp. *Rhizoctonia* sp. *Rhizoctonia* sp. *Papulaspora* sp.	Gezgin and Eltem, 2009
Dendrobium nobile	*Xyalaria* sp.	Yuan *et al.*, 2009
Grammatophyllum speciosum	*Fusarium* sp.	Salifah *et al.*, 2011
Cypripedium reginae	*Fusarium* sp.	Chen *et al.*, 2011
Vanda coerulea	*Rhizoctonia zeae*	Aggarwal *et al.*, 2012
Gastrodia elata	*Mycena* sp.	Park and Lee, 2013
Cymibidium manni	*Epulorhiza* sp	Zi *et al.*, 2014
Cynorkis purpurea	*Tulasnella* sp.	Rafter *et al.*, 2016
Liparis japonica	*Rhizoctonia* sp.	Herrera *et al.*, 2017
Pleurothallis coriacardia	*Ilyonectria* and *Coprinellus* sp.	Maldonado *et al.*, 2020
Phalaenopsis japonica	*Ceratobasidia* sp.	Chamara *et al.*, 2024
Dendrobium moschatum	*Fusarium* sp.	Shah *et al.*, 2025

nutrient acquisition and growth of orchids. The introduction of Arbuscular Mycorrhizal Fungi (AMF) can further improve nutrient uptake, stress tolerance, and soil health, offering a promising approach to sustainable agricultural productivity and ecosystem restoration (Mohan and Joshi, 2024).

In vitro propagation and ecorestoration

Orchids are renowned for their floral beauty and have been valued for both their aesthetic appeal and medicinal properties since ancient times. This high regard has led to increased threats against orchid plants, prompting conservationists to implement measures for the preservation and restoration of natural ecosystems. In these conservation efforts, endophytic fungi play a crucial role.

Orchid micropropagation is primarily achieved through green pod culture. Due to the absence of endosperm in orchid seeds, additional nutrients and hormones are required for successful propagation, which can be costly. Endophytic fungi contribute significantly by providing essential nutrients and growth hormones needed for seed propagation under *in vitro* conditions. Thus, the studies have extended to the utilization of this endophytic association for the propagation of orchid seeds under controlled condition. Notably, *Fusarium* sp. and *Pyrenochaeta* sp. demonstrated significant plant growth-promoting effects, suggesting their potential role in biocontrol and plant-microbe interactions (Chen *et al*., 2010**).** Growth promotion in *Dendrobium* species is enhanced by five endophytic fungi that produce indole-3-acetic acid (IAA), leading to improved nutrient uptake, chlorophyll content, and leaf biomass (Deepthi and Ray, 2019). Additionally, specific endophytes isolated from *D. moniliforme* roots show promise as fungal elicitors for mass orchid propagation, along with compounds that stimulate orchid germination (Shah *et al.,* 2018). The endophytic fungal diversity in *D. loddigesii* were studied, *Fusarium* and *Acremonium* are identified as the dominant genera, with several isolates exhibiting antimicrobial activity.

Research studies have further uncovered the possibility of co-inoculation with endophytic bacteria and fungi to enhance orchid growth. In *Dendrobium catenatum*, the isolated endophytes *Epulorhiza* sp. and *Herbaspirillum* sp. showed synergistic effects on root tip number, additive effects on fresh weight and lateral root number, and tiller development in *in vitro* asymbiotic germinated seedlings compared to single inoculation with *Pyrenochaeta* sp. and *Herbaspirillum* sp. (Wang *et al*., 2016). Additionally, *in vitro* embryo development in *Pleurothallis coriacardia* seeds was significantly enhanced by isolates belonging to the genera *Ilyonectria* and *Coprinellus*, underscoring the potential ecological functions of these endophytic fungi in natural environments (Maldonado *et al*., 2020).

Endophytic fungi isolated from the roots, stems, and leaves of *Vanda cristata* primarily belong to *Ascomycota*, with an unidentified fungus exhibiting the highest efficacy in auxin synthesis and phosphate solubilization. Meanwhile, *Agaricus bisporus* and *Mycoleptodiscus* sp. excelled in ammonia synthesis. When tested on *Cymbidium aloifolium* protocorms, all the fungi demonstrated growth-promoting activity, with the highest growth observed on Murashige and Skoog (MS) medium supplemented with fungal elicitors (Chand *et al*., 2020). Endophytic fungi from *D.longicornu* roots, including dominant species like *Coniochaeta* sp. and *Cladosporium* sp., have been shown to promote growth in *Cymbidium aloifolium* and *D. longicornu*, respectively, when cultured *in vitro* with IAA (Shah *et al.,* 2022).These findings highlight the diverse roles of endophytic fungi and their interactions with bacteria in promoting orchid growth, nutrient acquisition, and stress tolerance, emphasizing their importance in orchid conservation and commercial cultivation.

CONCLUSION

In conclusion, the intricate interactions between orchids and endophytic fungi are vital for orchid sustainability, ecological dynamics, and potential biotechnological applications. Orchids, celebrated for their beauty and environmental significance, depend on endophytic fungi for essential nutrients, stress tolerance, and protection against pathogens. These symbiotic relationships are crucial for seed germination, seedling growth, and overall plant health across diverse ecosystems. Moreover, endophytic fungi hold significant promise for pharmaceutical innovation due to their bioactive compounds, which exhibit a range of pharmacological properties. Understanding and leveraging the role of endophytic fungi in orchid ecosystems are critical for advancing conservation efforts, sustainable floriculture, and biodiversity preservation. Therefore, exploring the complex relationships between orchids and endophytic fungi is essential for enhancing orchid cultivation, promoting environmental stewardship, and improving human well-being.

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DECLARATION

Conflict of Interest. Authors declare no conflict of interest in publishing the article.

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