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Chapter 8

Endophytic Fungi-Derived Nanoparticles: A Sustainable Way to Alleviate Biotic and Abiotic Stress in Plants

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Abstract: Endophytic fungi play a crucial role in plant health by promoting growth and providing resistance against biotic and abiotic stresses. Recent advancements in nanotechnology have highlighted the potential of fungal-derived nanoparticles (NPs) as sustainable alternatives to conventional agrochemicals. These nanoparticles, synthesized through eco-friendly biological processes, exhibit potent antimicrobial, antioxidant and stress-mitigating properties. Fungal-derived silver (AgNPs), zinc oxide (ZnO NPs), copper (CuNPs) and silicon (SiNPs) nanoparticles have been shown to enhance plant defense mechanisms, improve nutrient uptake and mitigate the effects of drought, salinity and pathogen attacks. The mechanisms underlying their effectiveness include the induction of systemic resistance, modulation of defense-related enzymes and generation of reactive oxygen species (ROS). Additionally, fungal-derived NPs contribute to soil health by reducing chemical residues and improving microbial diversity. This book chapter explores the synthesis, properties and applications of endophytic fungi-derived nanoparticles in sustainable agriculture, emphasizing their potential to replace synthetic fertilizers and pesticides. Future research should focus on optimizing large-scale production and assessing their environmental safety for commercial applications.

Keywords: Endophytic fungi, Nanoparticles, Biotic stress, Abiotic stress, Plant defence mechanisms.

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1 Introduction

Agriculture faces a dual challenge of increasing food production while minimizing environmental impact. Various stress factors, including biotic (pathogens, pests) and abiotic (drought, salinity, heavy metals) stresses, significantly reduce crop yield and threaten global food security (Yadav *et al.,* 2023). Conventional agricultural practices often rely on chemical pesticides and fertilizers, which contribute to environmental pollution, soil degradation and the emergence of resistant pathogens (Yadav *et al.,* 2018). To address these challenges, sustainable approaches such as nanotechnology are being explored for enhancing plant resilience and productivity.

Endophytic fungi microorganisms that live symbiotically within plant tissues without causing harm have emerged as valuable bioresources in plant protection and stress mitigation (Yadav *et al.,* 2023). These fungi produce various bioactive compounds, including antimicrobial peptides, phytohormones and secondary metabolites, that enhance plant growth and defense responses (Kumar *et al.,* 2017). Recent advancements in nanotechnology have enabled the biosynthesis of nanoparticles (NPs) using endophytic fungi, offering an eco-friendly alternative to chemically synthesized nanomaterials (Singh *et al.,* 2021). Fungal-mediated nanoparticle synthesis is a green, cost-effective process that eliminates toxic reagents and provides controlled particle size and stability, making it suitable for agricultural applications (Gezaf *et al.*, 2022). Endophytic fungi-derived nanoparticles (EF-NPs) exhibit remarkable antimicrobial, antioxidant and growth-promoting properties, making them highly effective in mitigating both biotic and abiotic stresses. Studies have demonstrated that silver nanoparticles (AgNPs) synthesized by endophytic fungi exhibit potent antifungal and antibacterial activity against plant pathogens such as *Fusarium oxysporum* and *Xanthomonas oryzae*, reducing disease incidence in crops (Meera *et al.,* 2025). Similarly, fungal-derived silicon (SiNPs) and zinc oxide (ZnO NPs) nanoparticles enhance drought and salinity tolerance by regulating osmotic balance, improving root architecture and modulating stress-responsive gene expression (Alharbi *et al.,* 2022).

Furthermore, EF-NPs play a crucial role in heavy metal detoxification by chelating toxic metals, scavenging reactive oxygen species (ROS) and enhancing antioxidant enzyme activity, thereby protecting plants from heavy metal-induced stress (Pattnaik *et al.,* 2018). The ability of fungal nanoparticles to improve plant resistance to multiple stress factors highlights their potential as a sustainable alternative to conventional agrochemicals. However, challenges such as large-scale production, stability and regulatory considerations must be addressed for their widespread application in agriculture (Salvadori, 2023). This chapter explores the mechanisms and applications of endophytic fungi-derived nanoparticles in mitigating biotic and abiotic stress in plants, emphasizing their role in sustainable agriculture. By integrating nanobiotechnology with microbial symbiosis, EF-NPs offer a promising approach to enhancing crop productivity while reducing environmental impact.

2 Endophytic Fungi: A Natural Source for Nanoparticle Synthesis

Endophytic fungi are microorganisms that live symbiotically within plant tissues without causing any apparent disease symptoms. These fungi play crucial roles in plant growth promotion, stress tolerance and disease resistance by producing bioactive secondary metabolites, including antimicrobial compounds, phytohormones and enzymes (Kumar *et al.*, 2017). Many endophytic fungi, such as *Aspergillus, Fusarium*, *Penicillium* and *Trichoderma*, have been shown to possess the ability to biosynthesize nanoparticles through biological reduction mechanisms (Singh *et al.*, 2021) as shown in Table 1.

The biosynthesis of nanoparticles by endophytic fungi involves enzymatic reduction, protein-mediated synthesis and secondary metabolite-mediated transformation of metal ions into nanoparticles. This method provides several advantages over chemical and physical synthesis, including sustainability, non-toxicity and controlled size and shape of nanoparticles (Gezaf *et al.*, 2022).

Table 1. Endophytic Fungi: A Natural Bioreactor for Nanoparticle Synthesis

Endophytic Fungi	Nanoparticles Synthesized	Properties	Applications in Plant Stress Mitigation	References
Alternaria alternata	Silicon (SiNPs)	Osmoprotectant, drought resistance	Enhances water retention, mitigates salinity stress	Alharbi *et al.*, 2022
Aspergillus niger	Silver (AgNPs)	Antimicrobial, antioxidant, ROS scavenging	Controls fungal pathogens (*Fusarium*, *Alternaria*), enhances stress tolerance	Meera *et al.*, 2025
Beauveria bassiana	Copper (CuNPs)	Antifungal, insecticidal	Controls insect pests, boosts plant immunity	Qayyum *et al.*, 2015
Colletotrichum gloeosporioides	Selenium (SeNPs)	Antioxidant, stress signaling	Enhances plant defense mechanisms, mitigates heavy metal stress	Pattnaik *et al.*, 2018
Fusarium oxysporum	Zinc oxide (ZnO NPs)	UV protection, antimicrobial, enzyme activation	Improves drought resistance, reduces pathogen infection	Gezaf *et al.*, 2023

Penicillium chrysogenum	Gold (AuNPs)	Antibacterial, enhances nutrient uptake	Boosts plant growth, mitigates salinity stress	Yadav *et al.*, 2023
Trichoderma harzianum	Iron oxide (Fe_3O_4 NPs)	Enhances photosynthesis, ROS scavenging	Induces systemic resistance, improves drought tolerance	Kumar *et al.*, 2024

3 Biotic Stress Mitigation by Fungal-Derived Nanoparticles

Biotic stress significantly impacts crop yield and food security (Yadav *et al.*, 2023). Traditional pest control methods, including chemical pesticides and fungicides, have led to environmental pollution, soil degradation and resistance in target organisms (Yadav *et al.*, 2018). In contrast, nanotechnology offers an eco-friendly, sustainable alternative by utilizing fungal-derived nanoparticles (NPs) for plant protection as shown in Table 2. Endophytic fungi possess the unique ability to synthesize bioactive nanoparticles, such as silver (AgNPs), gold (AuNPs), zinc oxide (ZnO NPs) and copper (CuNPs). These NPs exhibit antimicrobial, antifungal and insecticidal properties, enhancing plant immunity and reducing biotic stress. Additionally, fungal-derived nanoparticles activate plant defense mechanisms by inducing systemic resistance (Singh *et al.*, 2021).

Table 2. Biotic Stress Mitigation by Fungal-Derived Nanoparticles

Nanoparticles	**Endophytic Fungi**	**Target Pathogen/Pest**	**Mode of Action**	**References**
Silver (AgNPs)	*Aspergillus niger*	*Fusarium oxysporum, Xanthomonas oryzae*	Disrupts microbial cell membranes, inhibits growth	Hulikere *et al.*, 2019
Zinc Oxide (ZnO NPs)	*Fusarium oxysporum*	*Pseudomonas syringae, Rhizoctonia solani*	Inhibits biofilm formation, induces ROS production	Kumar *et al.*, 2017
Copper (CuNPs)	*Beauveria bassiana*	*Helicoverpa armigera (insect pest)*	Disrupts exoskeleton, affects metabolism	Qayyum *et al.*, 2015
Silicon (SiNPs)	*Alternaria alternata*	Various fungal and bacterial pathogens	Enhances systemic resistance, activates defense enzymes	Alharbi *et al.*, 2022
Iron Oxide (Fe_3O_4 NPs)	*Trichoderma harzianum*	*Spodoptera litura* (insect pest)	Affects nervous system, leads to mortality	Gezaf *et al.*, 2022

3.1 Antimicrobial Properties

Engineered functional nanoparticles (EF-NPs), such as silver (AgNPs), gold (AuNPs), and zinc oxide (ZnO NPs), exhibit strong antimicrobial properties against plant pathogens through multiple mechanisms. AgNPs disrupt microbial cell membranes, causing leakage of intracellular components, ultimately leading to cell death (Meera *et al.*, 2025). Additionally, EF-NPs interact with microbial proteins and enzymes, inhibiting essential metabolic processes and rendering pathogens inactive (Sandhu *et al.*, 2017). Another key mode of action involves the generation of reactive oxygen species (ROS), which induce oxidative stress in microbial cells, damaging cellular structures and preventing their proliferation (Anjum *et al.*, 2023). These antimicrobial properties make EF-NPs highly effective in protecting seeds and seedlings from infections, contributing to improved plant health and crop productivity.

3.2 Insecticidal Activity

Fungal-derived nanoparticles have also shown insecticidal properties against agricultural pests. Beauveria bassiana-derived AgNPs, for example, have been effective against *Helicoverpa armigera*, a major pest in cotton crops (Qayyum *et al.*, 2015). The nanoparticles act by disrupting the exoskeleton, interfering with molting and inhibiting enzymatic activity crucial for insect survival.

3.3 Induction of Plant Defense Mechanisms

Plants possess sophisticated defense mechanisms against biotic and abiotic stresses. These mechanisms include the activation of systemic acquired resistance (SAR), induced systemic resistance (ISR) and enhanced production of defense-related enzymes and secondary metabolites (Yadav *et al.*, 2023). The use of fungal-derived nanoparticles (NPs) has emerged as a novel approach to enhance these defense responses, offering a sustainable alternative to chemical pesticides and fertilizers (Yadav *et al.*, 2018). Fungal-derived nanoparticles, such as silver (AgNPs), silicon (SiNPs) and iron oxide (Fe_3O_4 NPs), can act as elicitors, triggering defense responses in plants. These nanoparticles modulate signalling pathways, enhance reactive oxygen species (ROS) production and boost antioxidant activity, leading to improved plant immunity (Kumar *et al.*, 2017).

4 Abiotic Stress Mitigation by Fungal-Derived Nanoparticles

Abiotic stress, including drought, salinity, extreme temperatures and heavy metal toxicity, significantly affects plant growth and agricultural productivity. Recent advances in nanotechnology have demonstrated that fungal-derived nanoparticles (NPs) offer promising solutions for enhancing plant resilience to such stresses (Singh *et al.*, 2021) as depicted in Table 3. These nanoparticles, synthesized by fungi, exhibit unique physicochemical properties that improve plant stress tolerance and overall agricultural sustainability (Adeleke *et al.,* 2022).

Table 3. Types of Fungal-Derived Nanoparticles and their Applications

Type of Nanoparticle	**Endophytic Fungi**	**Application in Stress Mitigation**	**Reference**
Gold Nanoparticles (AuNPs)	*Penicillium spp.*	Regulates stress-related gene expression	Anjum *et al.,* 2023
Iron Oxide Nanoparticles (Fe_3O_4 NPs)	*Aspergillus niger*	Enhances nutrient uptake and water retention	Rai *et al.,* 2022
Selenium Nanoparticles (SeNPs)	*Fusarium oxysporum*	Aids in heavy metal detoxification	Meera *et al.,* 2025
Silica Nanoparticles (SiO_2 NPs)	*Trichoderma harzianum*	Increases drought and salt tolerance	Singh *et al.,* 2021
Silver Nanoparticles (AgNPs)	*Aspergillus niger*	Enhances stress resistance and antioxidant activity	Goutam *et al.,* 2021
Zinc Oxide Nanoparticles (ZnO NPs)	*Fusarium oxysporum*	Improves plant growth under salinity and drought stress	Anjum *et al.,* 2023

4.1 Drought and Salinity Stress

Drought and salinity are major abiotic stress factors that significantly reduce plant growth, productivity and survival. Endophytic fungi, which colonize plant tissues without causing harm, have emerged as promising biological agents for enhancing plant resilience to these stresses (Rodriguez *et al.,* 2008). These fungi improve plant stress tolerance through multiple mechanisms, including the production of osmoprotectants, enhancement of antioxidant defense, modulation of stress-related gene expression and improvement of water and nutrient uptake (Azad *et al.,* 2016).

Endophytic fungi contribute to plant health by establishing symbiotic relationships that enhance stress tolerance. Some endophytes are known to improve root architecture, facilitating better water absorption under drought conditions. Additionally, fungal associations help in regulating ionic balance in plants exposed to saline environments, reducing the toxic effects of excessive sodium and chloride ions (Xu *et al.*, 2024).

Various endophytic fungi, including *Piriformospora indica*, *Trichoderma harzianum*, *Fusarium* spp. and *Serendipita indica*, have demonstrated their potential in increasing stress resilience in different plant species. These fungi are capable of modulating plant metabolism, thereby improving their ability to withstand extreme environmental conditions (Das *et al.*, 2022).

4.2 Heavy Metal Stress

Heavy metal contamination in soil and water poses a significant threat to plant health and agricultural productivity. The accumulation of toxic metals such as lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg) adversely affects plant growth, metabolic functions and yield. Endophytic fungi-derived nanoparticles (NPs) have emerged as an eco-friendly and effective solution to mitigate heavy metal stress in plants (Singh *et al.*, 2021). These bioengineered nanoparticles enhance plant tolerance to heavy metals and improve soil remediation efforts (Sonawane *et al.*, 2022).

Several fungal species, including *Aspergillus niger, Fusarium oxysporum, Trichoderma harzianum* and *Penicillium chrysogenum*, have been explored for their ability to synthesize nanoparticles that help in reducing heavy metal toxicity. Silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO NPs) have been found to assist in alleviating cadmium and arsenic toxicity, improving plant growth under stress conditions. Similarly, iron oxide nanoparticles (Fe_3O_4 NPs) enhance metal uptake and immobilization, preventing their harmful effects on plant cells (Goutam *et al.*, 2021). Selenium nanoparticles (SeNPs) and gold nanoparticles (AuNPs) have also been reported to mitigate oxidative stress induced by heavy metals, promoting overall plant resilience (Meera *et al.*, 2025).

5 Applications in Sustainable Agriculture

5.1 Biopesticides and Biofungicide: The development of nanoparticle-based biopesticides offers an eco-friendly alternative to chemical pesticides. EF-NPs have been incorporated into formulations for controlling fungal, bacterial and insect pests (Yadav *et al.*, 2018).

5.2 Soil Remediation: Fungal-derived nanoparticles play a crucial role in soil remediation by degrading organic pollutants, immobilizing heavy metals and enhancing soil microbial health (Chavan *et al.*, 2019).

5.3 Nanofertilizers: EF-NPs improve nutrient delivery to plants by providing slow and controlled release of essential minerals such as nitrogen, phosphorus and potassium (NPK), enhancing soil fertility and crop productivity (Kumar *et al.*, 2017).

6 Future Perspectives and Challenges

Endophytic fungi-derived nanoparticles hold great promise for sustainable agriculture and environmental management. These bio-nanoparticles can enhance plant stress tolerance, improve soil health and contribute to eco-friendly bioremediation. In the future, their integration with modern agricultural techniques, such as nanofertilizers and nano-based pesticides, could lead to more efficient and sustainable crop production. Additionally, their potential use in soil and water detoxification could help mitigate pollution and heavy metal contamination. Advances in fungal biotechnology and genetic engineering may also enable the controlled synthesis of nanoparticles with tailored properties for specific applications. Despite their potential, several challenges must be addressed before their widespread adoption. One of the primary concerns is standardization, as variations in fungal strains and synthesis methods can affect the quality and consistency of nanoparticles. Limited field studies mean that their effectiveness in real-world conditions remains uncertain, necessitating large-scale trials. There is also a need to thoroughly assess their environmental impact and long-term effects on soil microbes and plant systems to ensure their safety. Public perception and regulatory challenges may further hinder commercialization, making it essential to establish guidelines for their responsible use.

Overall, while endophytic fungi-derived nanoparticles offer exciting possibilities, more research is required to optimize their production, assess their long-term impact and develop clear regulatory frameworks. Addressing these challenges will be crucial for their successful application in agriculture and environmental sustainability.

Conclusions

Endophytic fungi-derived nanoparticles represent a promising, sustainable approach to mitigating biotic and abiotic stresses in plants. Their biocompatibility, eco-friendliness and multifunctional properties make them a viable alternative to conventional agricultural inputs. Continued research and technological advancements in this field will pave the way for innovative nanobiotechnological applications in sustainable agriculture.

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