Environment and Ecology 43 (4A) : 1282—1289, October—December 2025
Article DOI: https://doi.org/10.60151/envec/IMQQ6032
ISSN: 0970-0420 (Print), ISSN: 3049-3625 (Online)

Integrating Endophytic Fungi and Nanoscience : Emerging Strategies for Crop Stress Management

Gulam Ahmad Siddique, Swati Dwivedi, Vidya Singh, Jay Hind Nishad, Deepak Kumar Singh

Received 17 November 2025, Accepted 25 December 2025, Published on 30 December 2025

ABSTRACT

Biosynthesis of nanoparticles (NPs) has recently been recognised as an effective tool, contrary to chemically derived NPs, for controlling plant abiotic and biotic stress, and crop improvement. In this regard, endophytic fungi have tremendous scope and importance for producing biogenic NPs of various sizes, shapes, and characteristics. Due enhanced bioavailability, biological activity, and higher metal tolerance of endophytic fungi make them highly efficient. NPs derived from endophytic fungi show remarkable antimicrobial properties and growth-promoting activities, while also strengthening systemic resistance in crop plants to enhance their defence against pathogens. Endophytic fungal-derived nano-fertilizers and nano-pesticides offer a promising and sustainable alternative to traditional agrochemicals in crop stress management. The present review focuses on the synthesis of NPs from endophytic fungi and their potential role in crop stress management, influencing crop growth and productivity.

Keywords Endophytes, Nano-fertilizers, Antimicrobial, Nano-pesticides, Metallic nanoparticles.

INTRODUCTION

The term “nanotechnology” was coined by Taniguchi in 1974 to explain the synthesis and use of nano-size particles for the first time (Khan and Rizvi 2014). Nanotechnology represents a significant development in the contemporary science of manipulating matter at the nano scale (1 to 100 nm), and this has revolutionized various sectors with its applications in agriculture, medicine, engineering, chemistry, physics and environmental science (Singh *et al.* 2024). However, one of the latest advancements in the utilization of nanotechnology is in the agricultural and food sectors (Fadiji *et al.* 2022). The synthesis of NPs by conventional methods like physical and chemical, which can be hazardous to the environment, like killing off advantageous microbes, lowering their numbers and activity and polluting and degrading the soil (Ottoni *et al.* 2020), is being superseded by biological processes (Uzair *et al.* 2020). Numerous

Gulam Ahmad Siddique[1], Swati Dwivedi[2], Vidya Singh[3], Jay Hind Nishad[4], Deepak Kumar Singh[5]*

[1,2]PhD Research Scholar [3,5]Assistant Professor, [4]Senior Technical Assistant

[1,2,5]Laboratory of Microbiology and Metabolomics, Department of Botany, A.N.D. Kisan P.G. College, Babhnan (Affiliated to R.M.L. Avadh University, Ayodhya), Gonda, India

[3]Department of Botany, S.S.S Vishram Singh, Govt. P.G. College, Chunar (Affiliated to M.G. Kashi Vidyapeeth, University, Varanasi), Mirzapur, India

[4]Department of Biotechnology, National Agri-Food and Biomanufacturing Institute (NABI), Ministry of Science and Technology (Government of India), Mohali, Punjab, India

Email: bhudeepaksingh@gmail.com
*Corresponding author

biological sources, such as algae, plants, bacteria and fungi are used to build NPs (Singh *et al.* 2024, Shah *et al.* 2025). Endophytic fungi are microorganisms that inhabit inside the healthy plant tissues in a mutualistic relationship without causing any infectious characteristics and are found in all plants (Bhunjun *et al.* 2024, Kharwar 2024). Numerous investigations have examined the importance of endophytic fungi and their contribution to human health (Qin *et al.* 2023). Modern advancements have made it feasible to use endophytic fungi for the building of NPs, facilitating a justifiable choice over chemically synthesized nanoparticle (Hassan *et al.* 2024). The capacity of endophytic fungal NPs to enhance plant resilience to various stressors underscores their potential as a sustainable substitute for conventional agrochemicals (Yadav and Anand 2025). A huge number of enzymes and secondary metabolites are released by endophytic fungi, crucial for the balancing and synthesis of NPs (Govindappa *et al*. 2020, Kharwar 2024). This review paper examines the applications of NPs derived from endophytic fungi in the management of crops and their potential environmental hazards.

Recent trends in nanoparticles synthesis

According to Mostafazade synthesizing metal NPs can be approached in three broad ways: Physical, chemical, and biological methods (Mostafazade *et al.* 2024). The creation of metal NPs through physical means is a top-down style of fabrication, while the use of chemicals and biology are categorized under bottom-up approaches (Wu *et al.* 2019, Messaoudi and Bendahou 2020). Physical processes, such as the use of radiation, pressure, and elevated temperature, can inflict extreme harm to living organisms (Kumari *et al.* 2023). However, chemical processes use harmful chemical substances, require high energy and produce harmful waste that cause a significant environmental risk when exploited in environmental applications (Mazari *et al.* 2021). Besides them, biological methods hold the most promise for producing NPs, which leads to the production of non-toxic and environmentally friendly NPs (Uzair *et al.* 2020). The various methods of physical, chemical and biological approaches are shown in Fig. 1.

Microorganisms and nanoparticles

The production of non-toxic, pure and environmentally friendly methods for NPs production will be the result of using the natural production systems using organisms such as plants, algae, fungi and bacteria (Nayantara and Kaur 2018). It is well known that

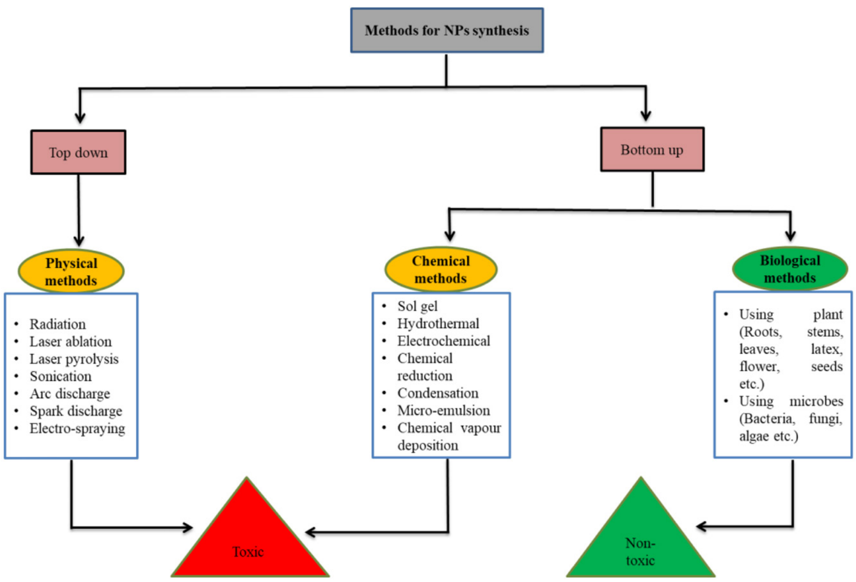

Fig. 1. Different approaches for NPs synthesis.

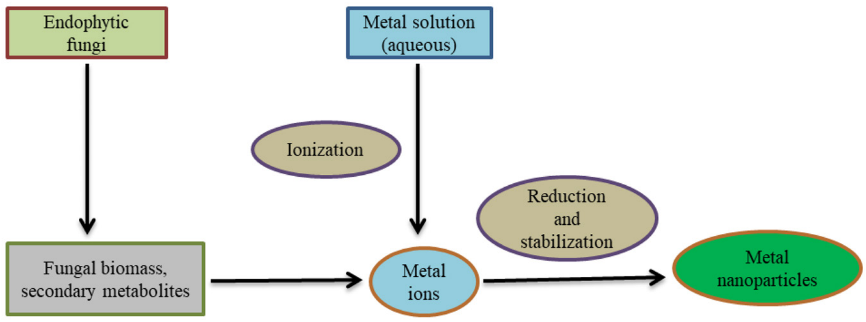

Fig. 2. Summary of synthesis of NPs using endophytic fungi.

plants serve as a reservoir for significant microorganisms that have received greater attention due to their capacity to produce enzymes and secondary metabolites (Adeleke and Babalola 2021). Many researchers have explored the use of bacteria, actinobacteria, fungi, yeast, microalgae, and viruses for synthesizing desired NPs (Salem and Fouda 2021).

Endophytic fungi as a potential NPs source

When compared to using bacteria, plants, and other organisms, the synthesis of endophytic fungal NPs offers several significant interests (Khandel and Shahi 2018). Their rapid growth makes scaling up easy (Mishra *et al.* 2017), they can with stand changes in growth factors like temperature, pH, and salinity in the culture conditions to synthesise uniform NPs, and they are feasibly isolated from plants (Kharkwal *et al.* 2024). Endophytic fungi exhibit the most favorable biological tools for NPs biosynthesis when compared to other microorganisms (Gezaf *et al.* 2022). They also produce a variety of enzymes and metabolites that contribute to the formation of NPs (Kumar *et al.* 2021, Nassar *et al.* 2023). The enzymes and secondary metabolites that fungi secrete aid in balancing the produced NPs and regulating their size and shape

Table 1. List of endophytic fungi, derived NPs and their major role.

Sl. No.	Endophytic fungi	NPs	Major role	References
1	*Aspergillus niger*	Silver NPs	Enhances stress resistance and antioxidant activity	Goutam *et al.* (2021)
2	*Trichoderma harzianum*	Silica NPs	Enhances salt and drought tolerance	Singh *et al.* (2021)
3	*Aspergillus niger*	Iron oxide NPs	Increases water retention and nutrient uptake	Rai *et al.* (2022)
4	*Alternaria alternata*	Silicon NPs	Alleviate salinity stress and increases water retention	Alharbi *et al.* (2022)
5	*Penicillium chrysogenum*	Gold NPs	Increases nutrient uptake, alleviate salinity stress and antibacterial activity	Yadav *et al.* (2023)
6	*Xylaria arbuscula*	Zinc oxide NPs	Shows antibacterial, antifungal and antioxidant activity	Nehru *et al.* (2023)
7	*Colletotrichum fructicola* KL19	Selenium NPs	Enhances plant growth into Cd contaminated soil	Wu *et al.* (2024)
8	*Fusarium crustosum* EP-1	Magnesium oxide NPs	Enhanced various growth parameters, including chlorophyll content, carotenoids level as well as proline concentration	Amin *et al.* (2024)
9	*Chaetomium globosum*	Silver NPs	Shows antifungal, antibacterial and antioxidant activities in crop protection	Sun *et al.* (2025)
10	*Aspergillus awamori*	β-glucan NPs	Enhanced plant growth and prevent wilt disease	Ramalingam and Appu (2025)

(Kharwar 2024). An overview of the biogenic synthesis of NPs from the biomass of endophytic fungi and their secondary metabolites is shown in Fig. 2.

Application of endophytic fungi-derived NPs in crop management

For reducing the use of more toxic agrochemicals, NPs obtained from fungi find applications in agriculture (Kharwar 2024). These NPs exhibit activity against biotic stresses, acting as nano-pesticides and nano-fungicides properties as well as tolerance against various abiotic stresses, including water scarcity, high temperature, heavy metals (HMs) toxicity and salinity (Table 1) (Mubeen *et al.* 2023, Kharwar 2024, Yadav and Anand 2025).

Endophytic fungal derived NPs in mitigation of abiotic stresses

The growth of plants and agricultural productivity are greatly impacted by abiotic stresses, including water scarcity, salinity, temperature extremes and HM toxicity. Recent developments in nanotechnology have revealed that fungal-derived NPs are promising alternatives for increasing plant tolerance to such stresses (Singh *et al.* 2021, Nishad *et al.* 2019). Through a variety of processes, including as the synthesis of osmoprotectants, improvement of antioxidant defence, control of stress-related gene expression, improvement of water and nutrient uptake, endophytic fungi increase the plant tolerance (Azad and Kaminskyj 2016, Yadav and Anand 2025).

Nano-fertilizers

The constantly growing human population is causing pressure to meet the constantly growing requirements for the agricultural sector (Zulfiqar *et al.* 2019). In general, chemical fertilizers used to increase the productivity of agricultural crops have a serious environmental and ecological impact (Pirzadah *et al.* 2020). Nanotechnology produces small sized NPs having unique characteristics which can provide an exceptional opportunity to produce a source of plant supplements (Yadav and Anand 2025). Nitrogen, phosphorus, potassium, magnesium, sulfur and calcium are different macronutrients whereas zinc, copper, boron, iron and manganese are different micronutrients encapsulated with NPs, reducing their overall requirements and improving crop productivity (Zulfiqar *et al.* 2019, Hassan *et al.* 2020).

Improvement of soil health and nutrient uptake

By hastening the decomposition of the soil organic matter, fungal NPs can replenish the soil with organic compounds and humus, increasing soil fertility and ultimately crop output. Fungal NPs can chelate with nutrients, converting them into more soluble forms that plants can easily absorb through their roots (Kumar *et al.* 2023). Furthermore, endophytic fungal connections lessen the harmful impacts of excess sodium and chloride ions by ionic equilibrium in plants exposed to a saline environment (Xu *et al.* 2024).

Heavy metal stress

Crops nutritional value and related ecological factors are also impacted by the presence of HMs in the soil. Crop species, soil physico-chemical properties, and HM types, all affect the crop growth and development (Chaplygin *et al.* 2021). According to reports, the endophytic fungus *Fusarium oxysporum*-derived selenium nanoparticles (SeNPs) aid in the detoxification of HMs and support plant growth in stressful environments (Meera *et al.* 2025). By breaking down pollutants, fungal NPs can help restore contaminated soil from HMs and other dangerous contaminants (Dhanapal *et al.* 2024).

Drought tolerance

One of the main abiotic stressors that lowers crop productivity and growth is tolerance to drought. By increasing the production of secondary metabolites, using NPs from endophytic fungi is an encouraging synergistic strategy to increase crop resilience against drought (Shelke *et al.* 2023). It is reported that Silica nanoparticles (SiO_2NPs) can improve plant biomass, leaf area index, and chlorophyll content, thereby mitigating the effects of drought stress (Mahmoud *et al.* 2023).

Endophytic fungal derived NPs in mitigation of biotic stresses

Crop yields, nutritional value and food security are greatly impacted by biotic stresses (bacteria, fungi, pests). Conventional approaches to biotic stress management, such as the use of chemical fungicides, bactericides and pesticides, have resulted in soil degradation, contamination of the environment and organism resistance (Yadav *et al.* 2023). Instead, developing fields of nanotechnology offers an eco-friendly, sustainable alternative by using endophytic fungi to NPs formation for reducing plant biotic stresses through antibacterial, antifungal and pesticidal activity (Mubeen *et al.* 2023, Yadav and Anand 2025).

Nano-pesticides and nano-fungicides

Effective management of pests and diseases greatly affects agricultural production by increasing the amount of agricultural productivity (Ghormade *et al.* 2011). Silver nanoparticles (AgNPs) and Iron nanoparticles (FeNPs) proved the potential to control arthropod pests, such as spider mites, maize earworms and aphids, as well as controlling insect pests and diseases management (Malik *et al.* 2024). Furthermore, tomato and cucumber wilt disease caused by *Fusarium* species is effectively controlled by utilizing Copper nanoparticles (CuNPs) (Al-Qaissi *et al.* 2024, Li and Liu 2024). Nano-fungicides, nano-pesticides, and nano-herbicides are significantly used in agriculture for effective control and management of pests and diseases, minimizing dependence on chemical pesticides and fungicides (Mubeen *et al.* 2023).

Induction of systemic resistance

Plants have complex defence mechanisms against stresses, like systemic acquired resistance (SAR) and enhanced systemic resistance (ISR), which coordinate long-term immunity throughout the plant to combat future pathogenic attacks (Kharwar 2024). Endophytic fungal-derived NPs have emerged as a novel approach to enhancing these defence mechanisms by improving the production of reactive oxygen species (ROS) and boosting antioxidant properties, which have been the subject of several studies (Yadav *et al.* 2023, Yadav and Anand 2025).

Challenges and future perspectives

The fungal-based NPs' future is bright, as they may be used in various industries, involving health and agriculture. The functions of NPs were investigated in this review to indicate their various potential uses in the sector of agriculture. In agriculture, these NPs can boost plant biotic and abiotic stresses, enhance soil health and productivity of crops. These detections improve the prospects that endophytic fungi could supersede pesticides and synthetic fertilizers in an eco-friendly approach. In addition, their potential utilization in soil and water recovery could help reduce pollution and HMs impurities. By applying genetic engineering, leading to the progression of fungal strains with different characteristics and activities, the expansion of fungal-based NPs innovation bears the potential to disclose new directions for fungal genomics exploration and synthetic biology. Moreover, integrating fungal-based NPs with other nanomaterials and innovations can generate hybrid systems that have mutual qualities, increasing their use in different fields. Regardless of their potential, various drawbacks have also been revealed by researchers. The main limits with fungal-mediated NPs synthesis are uniformity and standardisation, as differences in fungal strains and synthesis methods can influence the quality and reliability of NPs. Commercialisation may be hampered by public perception and legal interference, so standards for their use must be established. A more thorough investigation is required to prove their safety, a detailed evaluation of their effects on the environment and long-term effects on ecosystem stability, soil microbes, dependability, biocompatibility, and ecological impact and plant health, to confirm their effectiveness in the real world. Currently, researchers are using genetic engineering and optimisation of several criteria to address these issues. To reach their full potential, interdisciplinary collaborations between researchers—such as environmental scientists, mycologists, and nanotechnologists—will also be essential to advance fungal-based NPs to the forefront of nanotechnology and spur important scientific and industrial breakthroughs by increasing their efficacy and adaptability.

CONCLUSION

NPs offer eco-friendly, cost-effective, and non-toxic substitutes for other traditional methods. NPs made from endophytic fungi have been utilized more and more in recent studies due to their potential and environmental friendliness in crop management. It has been demonstrated that NPs made from endophytic fungi increase crop yield, nutritional value, and plant defence against biotic and abiotic stresses. Future research should attentive on acquiring a deeper knowledge of how different NPs cooperate with plants and plant pathogens to reduce biotic and abiotic stresses. Future research should also be centred on improving large-scale production and evaluating its environmental protection for commercial application.

ACKNOWLEDGMENT

We gratefully acknowledge the support of our institution for providing access to research facilities and literature resources essential for the completion of this work.

REFERENCES

Adeleke, B. S., & Babalola, O. O. (2021). Pharmacological potential of fungal endophytes associated with medicinal plants: A review. *Journal of Fungi*, 7 (2), 147. https://doi.org/10.3390/jof7020147

Alharbi, K., Rashwan, E., Mohamed, H. H., Awadalla, A., Omara, A. E. D., Hafez, E. M., & Alshaal, T. (2022). Application of silica nanoparticles in combination with two bacterial strains improves the growth, antioxidant capacity and production of barley irrigated with saline water in salt-affected soil. *Plants*, 11 (15), 2026. https://doi.org/10.3390/plants11152026

Al-Qaissi, A. R., Fouzi, S. H., & AL-Baytay, A. J. (2024). Characterization of biologically synthesized copper nanoparticles by Aspergillus carbonarius and evaluation of their activity in reducing the pathogenic stress of tomatoes infected with *Fusarium oxysporum*. *Tikrit Journal for Agricultural Sciences*, 24 (2), 161—177. https://doi.org/10.25130/tjas.24.2.12

Amin, M. A., Abu-Elsaoud, A. M., Nowwar, A. I., Abdel wahab, A. T., Awad, M. A., Hassan, S. E., Boufahja, F., Fouda, A., & Elkelish, A. (2024). Green synthesis of magnesium oxide nanoparticles using endophytic strain to improve the growth, metabolic activities, yield traits and phenolic compounds content of *Nigella sativa* L. Green Processing and Synthesis, 13 (1), 20230215. https://doi.org/10.1515/gps-2023-0215

Azad, K., & Kaminskyj, S. (2016). A fungal endophyte strategy for mitigating the effect of salt and drought stress on plant growth. *Symbiosis*, 68, 73—78. https://doi.org/10.1007/s13199-015-0370-y

Bhunjun, C. S., Phukhamsakda, C., Hyde, K. D., McKenzie E. H. C., Saxena, R. K., & Li, Q. (2024). Do all fungi have ancestors with endophytic lifestyles ? *Fungal Diversity* 125, 73—98. https://doi.org/10.1007/s13225-023-00516-5

Chaplygin, V. A., Minkina, T. M., Mandzhieva, S. S., Nazarenko, O. G., Zimulina, I. V., Bauer, T. V., Litvinov, Y. A., & Rajput, V. (2021). Heavy metals in agricultural crops of Rostov region through the example of soft wheat (*Triticum aestivum)*. IOP Conference Series: *Earth and Environmental Science*, 624, 012204. https://doi.org/10.1088/1755-1315/624/1/012204

Dhanapal, A. R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024). Nanotechnology approaches for the remediation of agricultural polluted soils. *ACS Omega*, 9 (12), 13522—13533. https://doi.org/10.1021/acsomega.3c09776

Fadiji, A. E., Mthiyane, D. M. N., Onwudiwe, D. C., & Babalola, O. O. (2022). Harnessing the known and unknown impact of nanotechnology on enhancing food security and reducing ing postharvest losses: Constraints and future prospects. *Agronomy*, 12, 1657. https://doi.org/10.3390/agronomy12071657

Gezaf, S. A., Hamedo, H. A., Ibrahim, A. A., & Mossa, M. I. (2022). Mycosynthesis of silver nanoparticles by endophytic fungi: Mechanism, characterization techniques and their applications. *Microbial Biosystems*, 7 (2), 48—65. https://doi.org/10.21608/mb.2023.185718.1066

Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances,* 29 (6), 792—803. https://doi.org/10.1016/j.biotechadv.2011.06.007

Goutam, J., Sharma, J., Singh, R., & Sharma, D. (2021). Fungal-mediated bioremediation of heavy metal-polluted environment. *Microbial Rejuvenation of Polluted Environment*, 2, 51—76. https://doi.org/10.1007/978-981-15-7455-9_3

Govindappa, M., Lavanya, M., Aishwarya, P., Pai, K., Lunked, P., Hemashekhar, B., Arpitha, B. M., Ramachandra, Y. L., & Raghavendra, V. B. (2020). Synthesis and characterization of endophytic fungi, *Cladosporium perangustum* mediated silver nanoparticles and their antioxidant, anticancer and nano-toxicological study. *BioNanoScience,* 10, 928—941. https://doi.org/10.1007/s12668-020-00719-z

Hassan, M. U., Aamer, M., Chattha, M. U., Haiying, T., Shahzad, B., Barbanti, L., Nawaj, M., Rasheed, A., Afzal, A., Liu, Y., & Guoqin, H. (2020). The critical role of zinc in plants facing the drought stress. *Agriculture,* 10 (9), 396. https://doi.org/10.3390/agriculture10090396

Hassan, S., Karaila, G. K., Singh, P., Meenatchi, R., Ven kateswaaran, A. S., Ahmed, T., Bansal, S., Kamalraj, R., Kiran, G. S., & Selvin, J. (2024). Implications of fungal nanotechnology for sustainable agriculture- applications and future perspectives. *Biocatalysis and Agricultural Biotech nology*, 57, 103—110. https://doi.org/10.1016/j.bcab.2024.103110

Khan, M. R., & Rizvi, T. F. (2014). Nanotechnology: Scope and application in plant disease management. *Plant Patholology Journal*, 13 (3), 214—231. https://doi.org/10.3923/ppj.2014.214.231

Khandel, P., & Shahi, S. K. (2018). Mycogenic nanoparticles and their bio-prospective applications: current status and

future challenges. *Journal of Nanostructure in Chemistry*, 8 (4), 369—391.
https://doi.org/10.1007/s40097-018-0285-2

Kharkwal, A. C., Joshi, H., Shandilya, C., Dabral, S., Kumar, N., & Varma, A. (2024). Isolation and characterization of a newly discovered plant growth-promoting endophytic fungal strain from the genus *Talaromyces*. *Scientific Reports*, 14, 6022.
https://doi.org/10.1038/s41598-024-54687-5

Kharwar, R. N. (2024). A research journey from epiphytic to endophytic fungi: insights into ecology, diversity and biotechnological potential. *Kavaka*, 60 (12—29).
https://doi.org/10.36460/Kavaka/60/sp/2024/12-29

Kumar, N., Samota, S. R., Venkatesh, K., & Tripathi, S. C. (2023). Global trends in use of nano-fertilizers for crop production: Advantages and constraints- a review. *Soil and Tillage Research*, 228, 105645.
https://doi.org/10.1016/j.still.2023.105645

Kumar, V., Ahluwalia, V., Saran, S., Kumar, J., Patel, A. K., & Singhania, R. R. (2021). Recent developments on solid-state fermentation for production of microbial secondary metabolites: challenges and solutions. *Bioresource Technology*, 323, 124566.
https://doi.org/10.1016/j.biortech.2020.124566

Kumari, S., Raturi, S., Kulshrestha, S., Chauhan, K., Dhingra, S., András, K., Thu, K., Khargotra, R., & Singh, T. (2023). A comprehensive review on various techniques used for synthesizing nanoparticles. *Journal of Materials Research and Technology*, 27, 1739—1763.
https://doi.org/10.1016/j.jmrt.2023.09.291

Li, X., & Liu, J. (2024). Soil amendments with nanoparticles control cucumber wilt caused by *Fusarium oxysporium*. *South African Journal of Botany*, 168, 384—393.
https://doi.org/10.1016/j.sajb.2024.03.034

Mahmoud, A. W. M., Rashad, H. M., Esmail, S. E. A., Alsa madany, H., & Abdeldaym, E. A. (2023). Application of silicon, zinc, and zeolite nanoparticles- a tool to enhance drought stress tolerance in coriander plants for better growth performance and productivity. *Plants*, 12 (15), 28—38.
https://doi.org/10.3390/plants12152838

Malik, M. A., Wani, A. H., Bhat, M. Y., Siddiqui, S., Alamri, S. A. M., & Alrumman, S. A. (2024). Fungal-mediated syn thesis of silver nanoparticles: A novel strategy for plant disease management. *Frontiers in Microbiology*, 15, 1399331.
https://doi.org/10.3389/fmicb.2024.1399331

Mazari, S. A., Ali, E., Abro, R., Khan, F. S. A., Ahmed, I., Ahmed, M., Nizamuddin, S., Siddiqui, T. H., Hossain, N., Mubarak, N. M., & Shah, A. (2021). Nanomaterials: applications, waste-handling, environmental toxicities, and future challenges- a review. *Journal of Environmental Chemical Engineering*, 9 (2), 105028.
https://doi.org/10.1016/j.jece.2021.105028

Meera, C. R., Zaynitdinova, L., & Great, U. (2025). Sustainable production of nanoparticles from fungi and their agricultural applications. In Nano-microbiology for Sustain able Development (pp. 71-103). Cham: Springer Nature Switzerland.
https://doi.org/10.1007/978-3-031-78845-1_4

Messaoudi, O., & Bendahou, M. (2020). Biological synthesis of nanoparticles using endophytic microorganisms: Current development. Nanotechnology and the Environment London, UK: Intechopen.
https://doi.org/10.5772/intechopen.93734

Mishra, V. K., Passari, A. K., Chandra, P., Leo, V. V., Kumar, B., Uthandi, S., Thankappan, S., Gupta, V. K., & Singh, B. P. (2017). Determination and production of antimicrobial compounds by *Aspergillus clavatonanicus* strain MJ31, an endophytic fungus from *Mirabilis jalapa* L. using UPLC-ESI-MS/MS and TD-GC-MS analysis. *PLoS One* 12, e0186234.
https://doi.org/10.1371/journal.pone.0186234

Mostafazade, R., Arabi, L., Tazik, Z., Akaberi, M., & Bazzaz, B. S. F. (2024). Fungal endophytes: treasure trove for green synthesis of metallic nanoparticles and their biological applications. *Biocatalysis and Agricultural Biotechnology*, 60, 103—307.
https://doi.org/10.1016/j.bcab.2024.103307

Mubeen, I., Mfarrej, M. F. B., Razaq, Z., Iqbal, S., Naqvi, S. A. H., Hakim, F., Mosa, W. F. A., Moustafa, M., Fang, Y., & Li, B. (2023). Nanopesticides in comparison with agrochemicals: outlook and future prospects for sustainable agriculture. *Plant Physiology and Biochemistry,* 198, 107670.
https://doi.org/10.1016/j.plaphy.2023.107670

Nassar, A. R. A., Atta, H. M., Abdel-Rahman, M. A., El Naghy, W. S., & Fouda, A. (2023). Myco-synthesized copper oxide nanoparticles using harnessing metabolites of endophytic fungal strain Aspergillus terreus: An insight into antibacterial, anti-Candida, biocompatibility, anticancer, and antioxidant activities. *BMC Complementary Medicine and Therapies,* 23, 261.
https://doi.org/10.1186/s12906-023-04056-y

Nayantara., & Kaur, P. (2018). Biosynthesis of nanoparticles using eco-friendly factories and their role in plant pathoge nicity, a review. *Biotechnology Research and Innovation*, 2 (1), 63—73.
https://doi.org/10.1016/j.biori.2018.09.003

Nehru, L., Kandasamy, G. D., Sekar, V., Alshehri, M. A., Panneerselvam, C, Alasmari, A., & Kathirvel, P, (2023). Green synthesis of ZnO-NPs using endophytic fungal extract of *Xylaria arbuscula* from *Blumea axillaris* and its biological applications. Artificial Cells, *Nanomedicine and Biotechnology*, 51 (1), 318—333.
https://doi.org/10.1080/21691401.2023.2232654

Nishad, J. H., Singh, A., Gautam, V. S., Kumar, D., Kumar, J., & Kharwar, R. N. (2019). Endophytic fungi: A cryptic fountainhead for biodiversity, functional metabolites, host stress tolerance, and myco-mediated nanoparticles (Nps) syn thesis. *Endophytes and Secondary Metabolites* (pp. 541—569). Springer, Cham.

Ottoni, C. A., Lima Neto, M. C., Leo, P., Ortolan, B. D., Barbieri, E., & De Souza, A. O. (2020). Environmental impact of biogenic silver nanoparticles in soil and aquatic organisms. *Chemosphere*, 239, 124698.
https://doi.org/10.1016/j.chemosphere.2019.124698

Pirzadah, B., Pirzadah, T. B., Jan, A., & Hakeem, K. R. (2020). Nanofertilizers: A way forward for green economy. *Nanobiotechnology in Agriculture Cham*, Switzerland: Springer. 99—112.
https://doi.org/10.1007/978-3-030-39978-8_5

Qin, X., Xu, J., An, X., Yang, J., Wang, Y., Dou, M., Wang, M., & Huang, J., & Fu, Y. (2023). Insight of endophytic fungi promoting the growth and development of woody plants. *Critical Reviews in Biotechnology*, 44 (1), 78—99. https://doi.org/10.1080/07388551.2022.2129579

Rai, P., Singh, V. P., Sharma, S., Tripathi, D. K., & Sharma, S. (2022). Iron oxide nanoparticles impart cross tolerance to arsenate stress in rice roots through involvement of nitric oxide. *Environmental Pollution,* 307, 119320. https://doi.org/10.1016/j.envpol.2022.119320

Ramalingam, P., & Appu, M. (2025). Aspergillus-derived β-glucan nanoparticles: a dual strategy for Fusarium wilt management and tomato plant growth enhancement. *Frontiers in Plant Science,* 16, 1611582. https://doi.org/10.3389/fpls.2025.1611582

Salem, S. S., & Fouda, A. (2021). Green synthesis of metallic nanoparticles and their prospective biotechnological applications: An overview. *Biological Trace Element Research*, 199, 344370.

Shah, S. T, Sari, I. P., Yanto, D. H. Y, Chowdhury, Z. Z., Bashir, M. N., Badruddin, I. A., Hussien, M., & Lee, J. S. (2025). Nature's nanofactories: biogenic synthesis of metal nanoparticles for sustainable technologies. *Green Chemistry Letters and Reviews*, 18 (1), 2448171. https://doi.org/10.1080/17518253.2024.2448171

Shelke, D. B., Islam, N. F., Chambhare, M.R., Sonawane, H.B., Patowary, R., Prasad, R., & Sarma, H. (2023). Enhancing secondary metabolites and alleviating environmental stress in crops with mycogenic nanoparticles: a comprehensive review. *Biocatalysis and Agricultural Biotechnology*, 52, 102805. https://doi.org/10.1016/j.bcab.2023.102805

Singh, A. V., Shelar, A., Rai, M., Laux, P., Thakur, M., Dosnkyi, I., Santomauro, G., Singh, A. K., Luch, S., Patil, R., & Bill, J. (2024). Hormonization risks and rewards: nano-QSAR for agricul tural nanomaterials. *Journal of agricultural & Food Chemistry*, 72 (6), 2835—2852. https://doi.org/10.1021/acs.jafc.3c06466

Singh, S., Kapoor, D., Khasnabis, S., Singh, J., & Ramamurthy, P. C. (2021). Mechanism and kinetics of adsorption and removal of heavy metals from wastewater using nanomaterials. *Environmental Chemistry Letters*, 19, 2351—2381. https://doi.org/10.1007/s10311-021-01196-w

Sun, D., Chen, R., Lei, L., & Zhang, F. (2025). Green synthesis of silver nanoparticles from the endophytic fungus Panax notoginseng and their antioxidant and antibacterial activities and effects on cherry tomato preservation. *International Journal of Food Microbiology*, 431, 111083. https://doi.org/10.1016/j.ijfoodmicro.2025.111083

Uzair, B., Liaqat, A., Iqbal, H., Menaa, B., Razzaq, A., Thiripuranathar, G., Fatima Rana, N., & Menaa, F. (2020). Green and cost-effective synthesis of metallic nanoparticles by algae: Safe methods for translational medicine. *Bioengineering*, 7 (4), 129. https://doi.org/10.3390/bioengineering7040129

Wu, K., Su, D., Liu, J., Saha, R., & Wang, J. P. (2019). Magnetic nanoparticles in nanomedicine: A review of recent advances. *Nanotechnology*, 30, 502003. https://doi.org/10.1088/1361-6528/ab4241

Wu, Y., Huang, S., Tian, W., Yang, S., Shen, W., & Dong, J. (2024). Endophytic Colletotrichum fructicola KL19 and its derived SeNPs mitigate Cd-stress-associated damages in *Spinacia oleracea* L. *Plants,* 13 (17), 2359. https://doi.org/10.3390/plants13172359

Xu, L., He, J., Meng, Y., Zheng, Y., Lu, B., Zhang, J., & Zhou, Y. (2024). Enhancing drought resistance in *Pinus tabuliformis* seedlings through root symbiotic fungi in oculation. *Frontiers in Plant Science*, 15, 1446437. https://doi.org/10.3389/fpls.2024.1446437

Yadav, S. A., Suvathika, G., Alghuthaymi, M. A., & Abd-El salam, K. A. (2023). Fungal-derived nanoparticles for the control of plant pathogens and pests. *Fungal Cell Factories for Sustainable Nanomaterials Productions and Agricultural Applications*, 755—784. https://doi.org/10.1016/B978-0-323-99922-9.00009-X

Yadav, U., & Anand, V. (2025). Endophytic fungi-derived nanoparticles: a sustainable approach to mitigating biotic and abiotic stress in Plants. In *Eco-Friendly Nanotechnology*: *Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet*, (pp, 106—115). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_8

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. *Plant Science*, 289, 110270. https://doi.org/10.1016/j.plantsci.2019.110270