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Endophytic Nanoparticle: An Emerging Frontier in Biomedical, Agricultural, and Environmental Applications

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ABSTRACT

Endophytic microorganisms that colonize plant tissues without causing harm serve as sustainable bio-factories for the green synthesis of metallic and metal-oxide nanoparticles. This review provides an integrated synthesis of endophytic diversity, biosynthetic mechanisms, and cross-sector applications, addressing the fragmentation in previous reports. Fungal endophytes particularly *Aspergillus* and *Penicillium* species and bacterial genera such as *Bacillus* and *Streptomyces* mediate nanoparticle formation, including silver, gold, zinc oxide, copper oxide, and selenium, through NADH-dependent reductase activity and metabolite-based bio-capping involving polyphenols, terpenoids, and alkaloids. Recent studies highlight *Talaromyces funiculosus* derived silver nanoparticles showing strong antibacterial zones (26 mm) and *Penicillium verhagenii*-produced selenium nanoparticles exhibiting selective anticancer cytotoxicity (IC_{50} = 225–283 μg/mL) while sparing normal cells. We further discuss extracellular versus intracellular synthesis routes, correlations between synthesis parameters and particle size, morphology, and stability, and summarize biomedical, agricultural, and environmental applications using quantitative activity metrics. Statistical optimization tools including Taguchi and response-surface methodologies are emphasized for enhancing reproducibility and scalability. Finally, future directions involving metabolic engineering, OSMAC strategies to activate silent biosynthetic clusters, and omics-guided optimization are outlined. By linking mechanistic insights with translational outcomes, this review establishes endophyte-mediated nanotechnology as a scalable, eco-efficient platform addressing antimicrobial resistance, cancer therapy, food security, and environmental remediation.

INTRODUCTION

Nanotechnology has revolutionized modern science and industry by enabling the manipulation of matter at the nanoscale, where materials exhibit unique physical, chemical, and biological properties. Among these innovations, metallic nanoparticles (MNPs) have attracted particular attention for their distinctive optical, electronic, antimicrobial, and catalytic behaviors that differ markedly from those of their bulk counterparts. These features have expanded the scope of nanotechnology into diverse fields such as medicine, agriculture, food processing, and environmental management, where multifunctional performance and precision are increasingly required [1].

Despite their promise, conventional nanoparticle synthesis methods face substantial limitations. Physical approaches such as high-energy ball milling and thermal evaporation require costly equipment, elevated temperatures, and high energy inputs. Chemical routes including sol–gel processing, microemulsion techniques, and chemical reduction enable large-scale production but often depend on toxic solvents, hazardous reducing agents, and stabilizers, which generate harmful by-products and compromise environmental safety [2]. Moreover, nanoparticles produced via these methods may exhibit poor biocompatibility, limiting their suitability for biomedical or agricultural use. These drawbacks have intensified global efforts toward eco-friendly "green synthesis" strategies that rely on biological systems for safer and more sustainable nanoparticle fabrication [3].

Biological synthesis represents a promising alternative because it utilizes naturally occurring reducing and capping agents in living organisms. A wide array of biological entities including plants, algae, actinomycetes, yeasts, fungi, and bacteria can convert metal salts into nanoparticles through their intrinsic metabolic processes. Such biosynthetic systems operate under mild conditions, eliminate toxic reagents, and produce nanoparticles coated with biomolecules that enhance stability and compatibility for downstream applications [4,5]. Within this paradigm, endophytic microorganisms have emerged as particularly powerful bio-factories for nanoparticle synthesis.

Endophytes are bacteria or fungi that reside asymptomatically within healthy plant tissues, forming mutualistic relationships that influence plant metabolism and resilience. They are nearly ubiquitous across plant species and produce a rich spectrum of secondary metabolites such as alkaloids, terpenoids, phenolics, peptides, and enzymes that contribute to host defense and stress tolerance [6]. These same metabolites can serve as natural reducing and stabilizing agents, mediating the transformation of metal ions into nanostructures without external chemical inputs [7].

Among endophytes, fungal species have gained prominence due to their ease of cultivation, high biomass yield, and secretion of extracellular enzymes (e.g., reductases, oxidases) that drive nanoparticle nucleation and stabilization. *Aspergillus*, *Penicillium*, *Fusarium*, and *Cladosporium* species have been widely reported for the biosynthesis of silver and gold nanoparticles exhibiting potent antimicrobial and anticancer properties [8]. Bacterial endophytes, though less extensively studied, have also demonstrated remarkable potential; species such as *Bacillus cereus* and *Cytobacillus firmus* synthesize antimicrobial silver nanoparticles via enzymatic reduction [9].

Compared with physical or chemical methods, the biogenic route offers several distinct advantages. Nanoparticles formed through endophyte-mediated processes are typically more stable due to natural bio-capping, exhibit superior biocompatibility, and can be produced at lower cost with minimal environmental impact [10]. These attributes make them attractive for diverse

applications. In biomedicine, they display antimicrobial, anticancer, antioxidant, and anti- inflammatory properties. In agriculture, they act as nano-fertilizers and eco-friendly biopesticides that enhance nutrient uptake and crop resistance. In environmental and industrial contexts, they facilitate pollutant degradation, wastewater treatment, and the fabrication of antimicrobial textiles and catalysts [11–13].

Previous reviews on endophyte-mediated nanoparticle synthesis have remained fragmented, often limited to specific metals or single application areas. A unified framework linking endophyte selection, enzymatic and metabolite-driven reduction, tunable culture conditions, and quantitative bioactivity outcomes is still lacking. Recent advances such as the discovery of selective anticancer selenium nanoparticles from *Penicillium verhagenii*, OSMAC-based yield enhancement, and dual-functional bimetallic systems underscore the need for integrated analysis. This review fills that gap by comparing fungal and bacterial endophytes across yield and synthesis kinetics, mapping key metabolites to stabilization roles, and outlining strategies for optimization, scale-up, and safety validation. By bridging mechanistic insights with translational applications, it provides a coherent framework for advancing endophyte-based sustainable nanotechnology across biomedical, agricultural, and environmental domains.

Endophytic Sources for Nanoparticle Synthesis

Fungal Endophytes

Fungal endophytes are among the most widely studied microbial systems for nanoparticle biosynthesis due to their ease of cultivation, ability to generate abundant biomass, and secretion of extracellular metabolites that act as natural reducing and stabilizing agents. Genera such as *Aspergillus*, *Penicillium*, *Fusarium*, *Cladosporium*, *Trichoderma*, and *Chaetomium* have been consistently reported as promising sources for nanoparticle production [3–8].

Figure 1. Morphological features of *Aspergillus* species isolated as endophytic fungi (adapted from Atallah et al. [3]).

One representative study involved *Penicillium oxalicum*, an endophyte isolated from *Litsea* leaves, which

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synthesized spherical silver nanoparticles (AgNPs) with an average size of ~52 nm. The fungal culture filtrate contained proteins and metabolites that reduced silver nitrate into nanoparticles and simultaneously acted as capping agents. These AgNPs exhibited antibacterial and cytotoxic activity against cancer cells, demonstrating their biomedical potential [5]. Similarly,

Aspergillus niger and *A. flavus* isolates produced AgNPs in the 5–50 nm range, showing a distinct surface plasmon resonance (SPR) peak at 420–430 nm and strong antimicrobial efficacy [6].

Fungal endophytes also produce nanoparticles beyond silver. *Chaetomium globosum* generated gold nanoparticles (AuNPs) with anti-inflammatory properties, while *Cladosporium* species synthesized AuNPs exhibiting broad-spectrum antibacterial and antifungal activity [8]. Other studies demonstrated endophytic production of zinc oxide (ZnO), copper oxide (CuO), manganese oxide (MnO), and selenium nanoparticles (SeNPs), each with distinctive biomedical or agricultural applications [7,10–12]. The endophytic fungus *Penicillium verhagenii* fabricated selenium nanoparticles with potent antimicrobial, antioxidant, and anticancer effects [16]. Likewise, *Trichoderma virens* synthesized bimetal oxide nanoparticles (CuO/TiO_2) exhibiting strong microbiocidal activity against bacterial pathogens [12].

Marine endophytic fungi have recently gained attention as sources of novel nanomaterials. Isolates from the Gulf of Mannar produced AgNPs with high antibacterial efficacy [13], while exposure of marine fungi to hypo-osmotic stress improved nanoparticle yield and stability, emphasizing how environmental adaptation can be leveraged to optimize biosynthesis [15]. These findings underscore the versatility of fungal endophytes, whose metabolic diversity supports the synthesis of nanoparticles with wide-ranging sizes, morphologies, and applications.

Bacterial Endophytes

Although less explored than fungi, bacterial endophytes are increasingly recognized as efficient nanoparticle synthesizers. They often display faster growth, require simpler culture media, and can produce nanoparticles more rapidly. Members of the genera *Bacillus*, *Cytobacillus*, and *Streptomyces* are among the most frequently reported bacterial endophytes capable of nanoparticle biosynthesis [4,7,9].

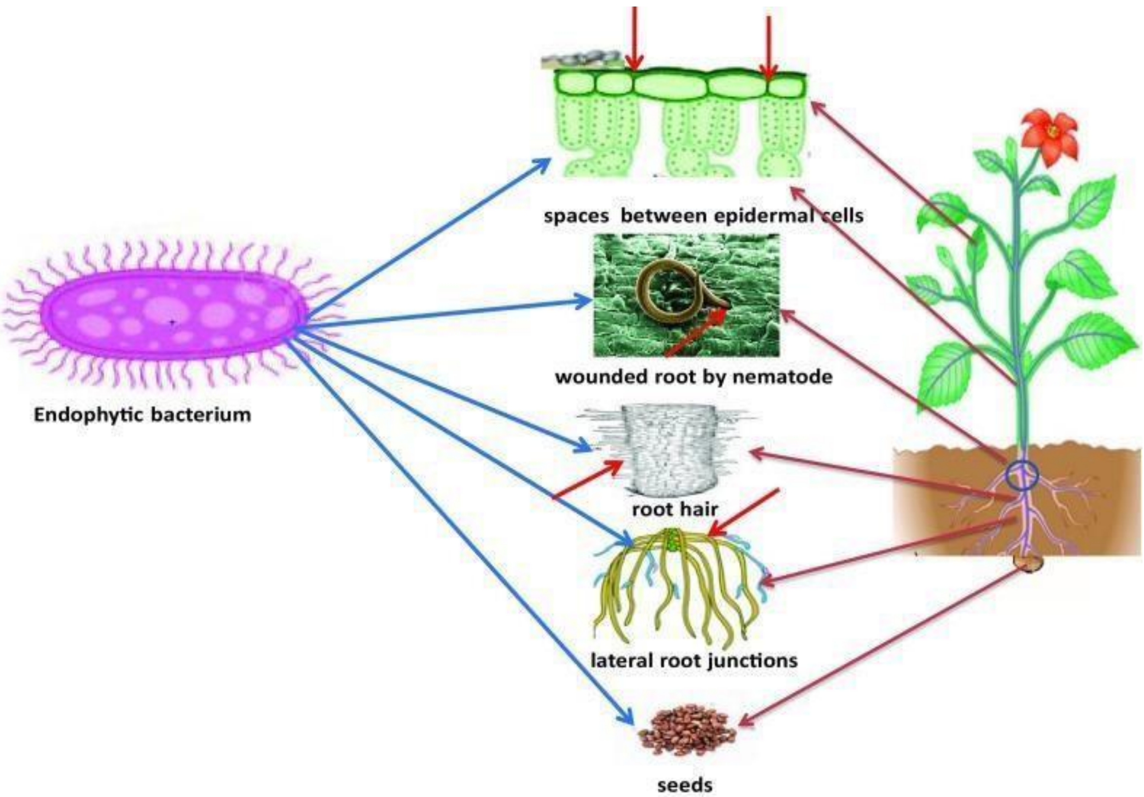

Figure 2. Representative bacterial endophytes implicated in nanoparticle biosynthesis.

For instance, *Bacillus cereus* isolated from *Garcinia xanthochymus* produced AgNPs through extracellular enzymatic reduction of silver nitrate. The resulting nanoparticles were confirmed via ultraviolet–visible (UV–Vis) spectroscopy, X-ray diffraction (XRD), and electron microscopy, exhibiting potent antibacterial activity against both Gram-positive and Gram-negative bacteria [4]. Similarly, *Cytobacillus firmus* from the bark of *Terminalia arjuna* synthesized spherical AgNPs (10–30 nm) with strong antimicrobial properties, as characterized by UV–Vis, XRD, transmission electron microscopy (TEM), and energy-dispersive X-ray (EDX) analyses [9].

Actinobacteria, particularly *Streptomyces* species, are also efficient nanoparticle producers. *Streptomyces antimycoticus* synthesized AgNPs that were incorporated into textile fibers, producing durable antimicrobial fabrics that retained activity after repeated washing [10]. This highlights the translational potential of bacterial endophyte-derived nanoparticles for industrial applications.

Compared with fungi, bacterial endophytes generally produce smaller nanoparticles under shorter incubation times, reflecting their rapid metabolism. Fungal systems, however, often yield greater quantities and a broader diversity of metabolites that enhance stability and multifunctionality. Together, fungal and bacterial endophytes represent complementary biogenic platforms, each offering distinct advantages for biomedical, agricultural, and environmental applications.

Endophyte Type	**Representative Species**	**Nanoparticle Type**	**Average Size (nm)**	**Primary Application**	**Reference**
Fungal	*Aspergillus niger*, *Penicillium oxalicum*, *Cladosporium sp.*, *Trichoderma virens*	Ag, Au, Se, CuO/TiO_2	5–60	Antimicrobial, anticancer, anti-inflammatory	[5–13,16]
Bacterial	*Bacillus cereus*, *Cytobacillus firmus*, *Streptomyces antimycoticus*	Ag, CuO	10–30	Antibacterial, textile coatings, environmental	[4,7,9,10]

Table 1. Comparative summary of fungal and bacterial endophyte-mediated nanoparticle synthesis.

Mechanism of Endophyte-Mediated Nanoparticle Synthesis

Endophytic microorganisms synthesize nanoparticles through a biological bottom-up process, in which metal ions are enzymatically reduced to their elemental state and nucleate into stable nanostructures. Unlike top-down physical fragmentation methods, this biosynthetic route relies on the intrinsic metabolic and enzymatic machinery of microbes, enabling atom-by-atom or cluster- by-cluster assembly of nanoparticles under mild, environmentally benign conditions [16,17]. The resulting nanomaterials are naturally coated with proteins, polysaccharides, and other metabolites that act as bio-capping agents, providing exceptional stability and biocompatibility [18–20].

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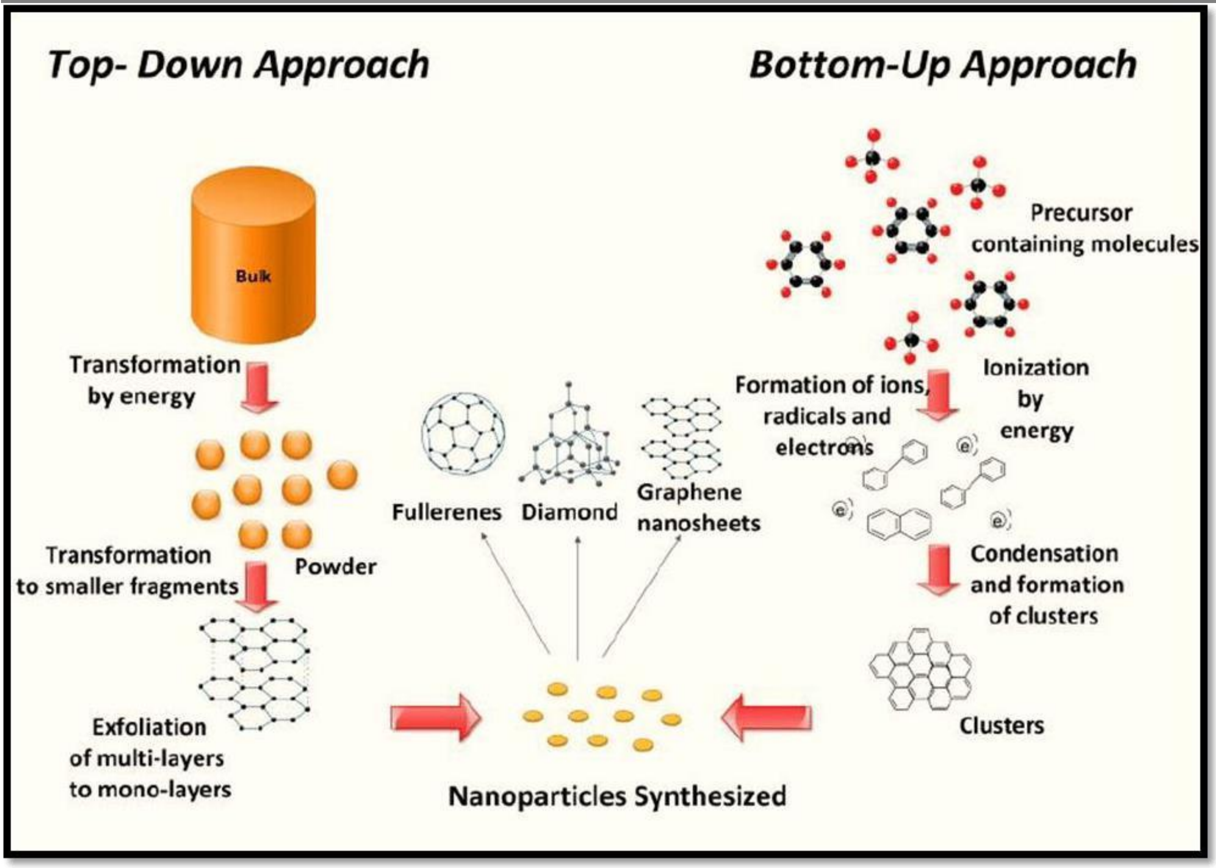

Figure 3. Conceptual illustration of top-down and bottom-up approaches for nanoparticle synthesis, highlighting enzymatic reduction and metabolite capping in endophytic systems (adapted from Álvarez-Chimal et al. [17]).

Extracellular Biosynthesis

Extracellular synthesis is the most frequently reported route of endophyte-mediated nanoparticle production. In this mechanism, culture filtrates rich in secreted enzymes and metabolites are mixed with metal-salt precursors, initiating ion reduction in the extracellular medium[17]. A key enzyme, NADH-dependent nitrate reductase, transfers electrons from reduced cofactors to the metal ions, following the reaction:

$$NADH + H^+ \rightarrow NAD^+ + 2\square^- + 2\square^+$$

These electrons reduce metal cations (for example, Ag^+ or Au^{3+}) to their zero-valent state, driving nucleation and growth of nanoparticles. Simultaneously, small biomolecules such as phenolics, flavonoids, terpenoids, and alkaloids act as both reducing and stabilizing agents, maintaining nanoparticle uniformity and preventing aggregation [19,20]. A classic example is *Fusarium oxysporum*, which produces protein- and amine-capped silver nanoparticles that are easily recoverable from the culture medium [21]. Because extracellular synthesis eliminates the need to disrupt biomass, it is highly suitable for scalable and reproducible production.

Figure 4. Mechanism of Fungi mediated silver nanoparticles (AgNPs)

Intracellular Biosynthesis

In some endophytic systems, nanoparticle formation occurs within microbial cells. Metal ions first adsorb functional groups such as carboxyl, hydroxyl, and amino residues on the cell wall surface [18]. After internalization, these ions are reduced by cytoplasmic enzymes and redox-active metabolites, forming nucleation centers inside the cell matrix [22]. Proteins, peptides, and polysaccharides stabilize the nascent nanoparticles, while reducing sugars for example, glucose and fructose can directly donate electrons to accelerate nucleation [19]. Although intracellular nanoparticles require cell disruption or sonication for recovery, they often exhibit superior stability and biological activity due to the presence of natural biomolecular coatings [20].

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

Role of Secondary Metabolites

Secondary metabolites play a central role in endophyte-mediated nanoparticle synthesis. Polyphenols and alkaloids function as electron donors for metal-ion reduction, terpenoids provide hydrophobic interactions that enhance stabilization, and proteins or amino acids contribute functional groups (–OH, $–NH_2$, –COOH) that cap the nanoparticle surface [19,20]. For instance, in *Penicillium verhagenii*, intracellular metabolites simultaneously reduced selenite (SeO_3^{2-}) to elemental selenium (Se^0) and stabilized the resulting SeNPs, generating highly stable and bioactive particles with antimicrobial and anticancer activity [16].

Environmental and Cultural Factors

The size, shape, and yield of biogenic nanoparticles are profoundly influenced by environmental and culture parameters.

pH: Neutral to slightly alkaline conditions (pH 6.5–8.5) enhance enzymatic activity, whereas excessively alkaline pH (>9) may accelerate reduction but increase aggregation risk [17].

Temperature: Moderate ranges (25–37 °C) support enzyme stability and efficient reduction, while higher temperatures denature proteins and lower yields [18].

Precursor concentration: Optimal metal-ion concentrations typically 1–5 mM for $AgNO_3$ or 0.5– 1 mM for $HAuCl_4$ favor uniform nucleation; excessive levels cause polydispersity [18].

Incubation time: Reaction durations between 12 and 72 hours are common; prolonged incubation often leads to larger or aggregated particles.

Fine-tuning these parameters allows precise control over nanoparticle morphology and functionality. Ultimately, the interplay between enzymatic reduction, metabolite-driven stabilization, and environmental modulation governs the physicochemical properties and bioactivity of endophyte-derived nanoparticles [19,20].

Characterization and Optimization of Biogenic Nanoparticles

A critical step in validating endophyte-mediated nanoparticle formation is comprehensive characterization, which establishes structural, morphological, and functional attributes. Because nanoparticle size, shape, and surface chemistry dictate their physicochemical behavior and biological activity, detailed analysis is essential to correlate synthesis conditions with application potential [22–24].

Ultraviolet–Visible (UV–Vis) Spectroscopy

UV–Vis spectroscopy is typically the first analytical tool employed to monitor nanoparticle formation. Metallic nanoparticles exhibit a surface plasmon resonance (SPR) band, arising from the collective oscillation of conduction electrons in resonance with incident light. The appearance of this absorption peak confirms nanoparticle synthesis and provides an initial estimate of size and monodispersity. Silver nanoparticles usually show maxima between 400–430 nm, whereas gold nanoparticles exhibit peaks near 520–540 nm [22]. Red or blue shifts in the SPR band indicate changes in particle size, morphology, or aggregation, making UV–Vis spectroscopy a rapid and non-destructive screening method.

X-ray Diffraction (XRD)

XRD analysis reveals the crystalline structure and phase purity of nanoparticles. Biogenic silver, gold, and zinc-oxide nanoparticles often exhibit diffraction peaks corresponding to face-centered cubic (fcc) lattices [23].

The Debye–Scherrer equation is used to calculate average crystallite size from the full width at half maximum (FWHM) of major peaks. XRD thus confirms the crystalline nature of the product and distinguishes pure metallic forms from mixed or oxide phases that may arise during biosynthesis

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Electron Microscopy (TEM and SEM) with EDX

Transmission electron microscopy (TEM) provides high-resolution imaging of nanoparticle morphology, lattice fringes, and core–shell architecture, whereas scanning electron microscopy (SEM) visualizes surface topology and particle distribution. When combined with energy-dispersive X-ray spectroscopy (EDX), these techniques verify elemental composition. For example, strong Ag or Au signals in the EDX spectrum validate successful formation of metallic cores synthesized by endophytic systems [24]. Together, TEM/SEM–EDX provides definitive evidence of particle uniformity and purity.

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR analysis identifies functional groups on nanoparticle surfaces, revealing the biomolecules responsible for metal-ion reduction and subsequent stabilization. Absorption bands corresponding to hydroxyl (–OH), amine (–NH_2), carboxyl (–COOH), and sulfhydryl (–SH) groups are frequently observed in endophyte-derived nanoparticles [25].

These signatures originate from proteins, polysaccharides, and phenolic compounds that serve as both reducing and capping agents. The presence of such bio-capping layers supports enhanced colloidal stability and biocompatibility.

Dynamic Light Scattering (DLS) and Zeta Potential

DLS determines the hydrodynamic diameter of nanoparticles in suspension, typically larger than core sizes measured by TEM due to solvation and surface coatings. Zeta potential measurements assess electrostatic stability; values greater than ±30 mV generally indicate well-dispersed colloids resistant to aggregation [26]. These parameters are particularly crucial for biomedical and agricultural uses, where suspension stability affects bioavailability, cellular uptake, and delivery performance.

Optimization of Biosynthesis Parameters

Optimization of culture and reaction conditions is vital for obtaining nanoparticles with controlled size, shape, and stability. Statistical design tools such as the Taguchi method and Response Surface Methodology (RSM) enable efficient identification of significant factors with minimal experimental runs [27,28]. These factors collectively determine nanoparticle nucleation, growth kinetics, and stability. Proper optimization enhances reproducibility, scalability, and the translational potential of endophyte-mediated nanomaterial production.

Key optimization parameters include:

Parameter	Optimal Range / Condition	Effect on Nanoparticle Properties	Challenges / Notes	References
pH	6–9 (neutral to slightly alkaline)	Enhances enzyme activity and yields smaller, monodisperse particles	Excess alkalinity (>9) increases aggregation	[14,19]
Temperature	25–37 °C	Maintains enzymatic stability; uniform crystal growth	High temperature denatures proteins	[19]
Precursor concentration	1–5 mM ($AgNO_3$); ~1 mM ($HAuCl_4$)	Controls nucleation density; influences size	Excess precursor causes polydispersity	[14]

Incubation time	12–72 h	Longer times increase yield but risk aggregation	Requires balancing reduction and stability	[19]
Statistical tools	Taguchi design; RSM	Identify optimum conditions, improve reproducibility	Requires validated models	[14]
Scale-up	Bioreactor vs. flask culture	Controlled aeration, pH, nutrient delivery	Process engineering needed for consistency	[19]

Table 2. Optimization parameters influencing endophyte-mediated nanoparticle biosynthesis.

Application of Endophyte-Derived Nanoparticles

Endophyte-mediated nanoparticle synthesis has become a pivotal tool at the intersection of biotechnology and sustainability. These biologically fabricated nanoparticles naturally stabilized by microbial proteins, polysaccharides, and secondary metabolites exhibit superior biocompatibility, stability, and multifunctionality. Their applications now span biomedicine, agriculture, and environmental or industrial systems, reflecting their adaptability and ecological relevance.

Biomedical Applications

In medicine, endophyte-derived nanoparticles exhibit broad-spectrum antimicrobial, anticancer, antioxidant, and anti-inflammatory activities, while their biogenic capping layers make them ideal nanocarriers for targeted drug delivery.

Antimicrobial Activity.

Silver nanoparticles (AgNPs) synthesized by *Talaromyces funiculosus* inhibited *Escherichia coli* with inhibition zones up to 26 mm, demonstrating strong bactericidal efficacy [26]. Similarly, *Clonostachys byssicola*–derived AgNPs exhibited potent activity against multidrug-resistant *Pseudomonas aeruginosa* [29,30]. These effects arise from reactive oxygen species (ROS) generation, membrane disruption, inhibition of biofilm formation, and interference with DNA replication [30].

Anticancer Properties.

Selenium nanoparticles (SeNPs) produced by *Penicillium verhagenii* showed selective cytotoxicity toward cancer cells (IC_{50} = 225–283 µg/mL) while sparing normal cells [31]. Gold nanoparticles (AuNPs) synthesized by *Aspergillus flavus* and conjugated with paclitaxel enhanced anticancer efficacy compared with the free drug [32], and AgNPs from *Cladosporium cladosporioides* induced apoptosis in A549 lung carcinoma cells, confirming their therapeutic promise [33].

Antioxidant and Anti-inflammatory Roles.

SeNPs demonstrated robust free-radical scavenging activity, neutralizing up to 86.8% of DPPH radicals [34]. Similarly, AgNPs synthesized by *Coniothyrium chiangmaiense* reduced TNF-α levels while upregulating IL-10 expression, indicating a dual function in oxidative stress mitigation and immune modulation [35].

Nanocarrier and Drug Delivery Systems.

Endophyte-derived nanomaterials are increasingly utilized as delivery vehicles. AgNPs loaded with paclitaxel enhanced drug uptake and cytotoxicity in breast cancer cells [36], while SeNPs encapsulated with

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue X October 2025

phytochemicals improved oral bioavailability and stability under gastrointestinal conditions [37]. These findings highlight their potential in developing next- generation, biologically compatible therapeutic delivery platforms.

Nanoparticle Type	Endophytic Source	Key Stabilizing Metabolites	Primary Bioactivity	Reported Activity	References
AgNPs	*Talaromyces funiculosus*	Proteins, metabolites	Antibacterial	Inhibition zone: 26 mm vs *E. coli*	[26]
SeNPs	*Penicillium verhagenii*	Intracellular metabolites	Anticancer (selective); Antioxidant	IC_{50} = 225-283 µg/mL (cancer cells); DPPH scavenging: 86.8%	[16,31]
AuNPs	*Aspergillus flavus*	Proteins, metabolites	Anticancer (drug carrier)	Enhanced cytotoxicity when conjugated with paclitaxel	[32]
AgNPs	*Cladosporium cladosporioides*	Extracellular proteins	Anticancer (apoptosis)	Induced apoptosis in A549 lung carcinoma cells	[33]
AgNPs	*Coniothyrium chiangmaiense*	Not specified	Anti-inflammatory	TNF-α reduction; IL-10 upregulation	[35]
ZnO NPs	*Aspergillus* sp. SA17	Fungal exudates	Antimicrobial; Anticancer	Demonstrated activity in vitro and in silico	[39]
CuO/TiO_2	*Trichoderma virens*	Fungal metabolites	Microbiocidal	Broad-spectrum bacterial pathogen inhibition	[12]
Ag-CuO (bimetallic)	*Clonostachys rosea*	Fungal biomolecules	Catalytic degradation	Accelerated organic pollutant degradation	[44]

Table 3. Key Bioactive Compounds and Nanoparticle Properties from Endophytic Sources

Note: MIC = Minimum Inhibitory Concentration; IC_{50} = Half-maximal inhibitory concentration; DPPH = 2,2-diphenyl-1-picrylhydrazyl (antioxidant assay).

Agricultural Applications

In agriculture, endophyte-derived nanoparticles offer sustainable alternatives to chemical fertilizers and pesticides. Acting as nano-fertilizers, biostimulants, and biopesticides, they improve plant productivity and resilience while minimizing environmental impact.

Growth Enhancement and Nutrient Uptake.

Carbon quantum dots from *Aspergillus flavus* enhanced biomass accumulation and curcumin content in *Curcuma longa* [38]. Zinc oxide (ZnO) nanoparticles derived from fungal and bacterial endophytes improved photosynthetic efficiency, shoot growth, and abiotic stress tolerance in soybean and tea crops [39].

Biocontrol and Disease Suppression.

AgNPs synthesized by *Bacillus* species effectively inhibited *Magnaporthe oryzae*, the rice blast fungus [40], while ZnO nanoparticles from *Paenibacillus* reduced *Rhizoctonia solani*–induced root rot [41]. These nanoparticles not only suppress pathogens directly but also elicit systemic resistance and strengthen plant immunity.

Abiotic Stress Mitigation.

Copper oxide (CuO) nanoparticles combined with *Trichoderma harzianum* enhanced salt-stress tolerance and controlled soilborne pathogens simultaneously [42]. However, further research

should address phytotoxicity thresholds, soil persistence, and field-scale validation, as most current studies are limited to controlled environments.

Overall, endophyte-derived nanomaterials present a dual ecological advantage supporting plant health while reducing dependence on synthetic agrochemicals.

Environmental and Industrial Applications

In environmental science and industry, endophyte-mediated nanoparticles are emerging as catalysts, adsorbents, and functional materials for pollution control and sustainable manufacturing.

Pollutant Degradation and Wastewater Treatment.

Aspergillus japonicus–derived magnesium oxide (MgO) nanoparticles effectively adsorbed synthetic dyes from wastewater, enabling color and toxin removal [43]. Bimetallic Ag–CuO nanoparticles synthesized by *Clonostachys rosea* accelerated organic pollutant degradation through catalytic oxidation [44]. Furthermore, composites integrating fungal biomass with Fe_3O_4 nanoparticles produced magnetically retrievable catalysts capable of repeated dye removal without loss of efficiency [45].

Industrial Material Innovations.

AgNPs from *Streptomyces laurentii* were integrated into cotton textiles, creating durable antimicrobial fabrics that maintained activity after multiple washes [46]. Similarly, ZnO nanoparticles demonstrated photocatalytic degradation of plastics and microplastics, underscoring their potential for green packaging and environmental remediation [47,48]. Additionally, endophyte-assisted phytoremediation systems have been designed where microbes enhance plant tolerance to nanoparticles such as CuO while facilitating the removal of heavy metals and pollutants from contaminated water and soil [49].

These advancements emphasize the multifunctional versatility of endophyte-derived nanoparticles in creating safer, cleaner, and more sustainable ecosystems.

CONCLUSION

Endophyte-mediated nanoparticle synthesis represents a sustainable alternative to conventional physical and chemical routes, coupling enzymatic reduction with metabolite-based bio-capping to yield colloidally stable, biocompatible nanomaterials under mild conditions. Comparative analyses indicate that fungal endophytes especially *Aspergillus*, *Penicillium*, and *Fusarium* species excel in yield and metabolite diversity, while bacterial genera such as *Bacillus* and *Streptomyces* achieve faster synthesis and smaller particle sizes. Marine- and mangrove-derived endophytes have also been shown to produce diverse bioactive secondary metabolites, including depsidones, polyketides, and nitrogenous compounds, expanding the chemical repertoire available for nanomaterial functionalization [50–52].

To enhance reproducibility and translational potential, future studies should adopt standardized culture and characterization protocols (TEM, DLS, zeta potential, FTIR) and report quantitative bioactivity metrics with defined replicates and appropriate controls. Notably, *Nigrospora* species isolated from mangrove environments have demonstrated potent antioxidant and antimicrobial activity, reinforcing the biotechnological promise of endophytic fungi as nano-biofactories [53].

Omics integration linking genomics, metabolomics, and proteomics will enable identification of key reductases and metabolic pathways for rational strain improvement. Lichen-associated endophytes such as *Apiospora montagnei*further exemplify the structural diversity and metabolic versatility that can be harnessed through integrative biosynthetic studies [54]**.** Complementary synthetic biology tools, including CRISPR-based pathway enhancement and OSMAC strategies to activate silent gene clusters, can further optimize biosynthetic output.

Scale-up efforts must focus on bioreactor process control, aeration, and nutrient management while addressing batch-to-batch variability and product uniformity. Parallel safety evaluations encompassing cytotoxicity, eco-toxicology, and long-term stability will be essential for regulatory readiness. Recent regional investigations into antimicrobial natural products and environmental remediation materials support the broader applicability of biologically inspired nano-systems [55–58].

With unified reporting frameworks and cross-disciplinary collaboration, endophyte-derived nanomaterials can evolve from laboratory systems to scalable green-manufacturing platforms. This convergence of microbiology, nanotechnology, and bioengineering positions endophytic nano-factories as a transformative route toward sustainable solutions in antimicrobial resistance, targeted cancer therapy, agricultural productivity, and environmental remediation.

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