



Revolutionizing Sustainable Agriculture: Harnessing Macrofungi and Bacterial Systems for Eco-Friendly Silver Nanoparticle Synthesis and Enhanced Plant Growth

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ABSTRACT

Nanotechnology offers transformative potential in modern agriculture, providing sustainable alternatives to conventional agrochemicals. This review examines the synthesis, characterization, and applications of silver nanoparticles (AgNPs), emphasizing biologically mediated "green synthesis" via fungi and bacteria. These eco-friendly approaches exploit microbial reductive enzymes, such as nitrate reductase and oxidoreductases, to convert silver ions (Ag^+) into nanoparticles, avoiding the environmental and energetic drawbacks of chemical and physical methods. AgNPs exhibit strong antimicrobial activity through membrane disruption, reactive oxygen species (ROS) generation, and enzyme inhibition, making them effective against phytopathogens. Additionally, they promote seed germination, root elongation, and modulate phytohormone pathways, benefits attributed to their high surface-area-to-volume ratio and tunable physicochemical properties. Both intracellular and extracellular biosynthetic routes are discussed, with evaluation of their scalability, stability, and yield. Characterization techniques, including UV-vis spectroscopy, SEM, XRD, FTIR, and AFM, provide insights into size (5–100 nm), shape, crystallinity, and dispersity, key factors influencing efficacy. In soil systems, AgNPs function as nanopesticides and nanofertilizers, enhancing nutrient bioavailability and reducing agrochemical runoff. Advances focus on optimizing microbial strains (e.g., *Bacillus subtilis*, *Aspergillus niger*), controlling zeta potential, and surface functionalization for targeted applications. Challenges such as phytotoxicity, bioaccumulation, and regulatory concerns persist. By integrating over 50 studies, this review underscores AgNPs' potential to support resilient, resource-efficient farming while highlighting the need for standardized protocols, long-term field assessments, and comprehensive safety evaluations to realize nanotechnology's full agricultural promise.

INTRODUCTION

Global food security, environmental sustainability, and the harmful effects of chemical fertilizers and pesticides have emerged as pressing concerns in modern agriculture [1]. Conventional farming practices, which rely heavily on synthetic agrochemicals, degrade soil health, pollute water resources, reduce biodiversity, and contribute significantly to climate change [2]. Thereupon different kinds of sustainable policies such as organic agriculture, biofertilizer and precision agriculture are being launched to optimize the use of the resources while minimizing the consequences to the environment [3]. The rising requirements for inexpensive and harmless solutions triggered the development of nanotechnology as a fresh scientific field with the vast possibilities of application in

agriculture [4]. Nanotechnology is applicable to crop protection products by working with materials at a scale of 100 nm or less toward controlled nutrient release and plant health. Nanomaterials, such as ceramics, polymers, quantum dots, metal oxides, and magnetic materials have been utilized effectively for improving seed germination, increasing plant growth and preventing losses of nutrients during fertilization, to ensure sustainable agricultural productivity.

The self-assembly of nanoparticles reported in fungi and bacteria towards green synthesis is emerging as an attractive eco-friendly alternative to the conventional chemical synthesis [5]. In biosynthetic route, the mitosis that occurs among the microorganisms is borrowed to reduce the metal shear ions to nanoparticulate forms and

the products are characterized to have enhanced stability, size uniformity and biocompatibility [6]. Fungi such as *Fusarium oxysporum* and *Aspergillus niger* produce and secrete high quantities of both extracellular enzymes and metabolites that mediate the reduction of metal ions; secreted proteins can also act as capping agents to ensure particle stabilization. In addition, the bacteria such as *Bacillus subtilis* and *Escherichia coli* are rapid synthesizers, which are amenable to mass production. As a successful newly synthesized biological material, silver nanoparticles (AgNPs) exhibit excellent antimicrobial activity for host plant disease control and crop health improvement, and mitigate contamination to the environment by chemical pesticides [7].

Considering these known benefits, the present study missed to investigate the incorporation of nanotechnology and, in particular, biosynthesized silver nanoparticles into agronomically sustainable ecosystems. Focus is now on exploring fungus- and bacteria-associated synthesis networks for their potential to generate stable nanoparticles, environmentally benign in formulation, analysis of their antimicrobial activity against stalk and shoot pathogens as well as role in improved crop yield, nutrient utilization and tolerability/stress [8]. Furthermore, the green synthesis has overcome the toxicity and energy issues because of scale issues and causes by the chemical synthesis generating the concept of green chemistry. Hybridized biopolymer-metal nanoparticle-based materials thus lead to efficient ultra-specific solutions for plant cultivation, disease management and nutrient delivery, which would otherwise act as a guarantee for nourishing the burgeoning population meanwhile reducing the ecological footprint of modern agriculture [9].

Novelty of the Study

- Dual-function AgNPs – Combines antimicrobial activity with enhancement of plant growth and phytohormone modulation, integrating nanopesticide and nanofertilizer roles.
- Macrofungi + Bacterial Green Synthesis – Employs eco-friendly microbial routes, leveraging fungal and bacterial enzymes for sustainable AgNP production.
- Intracellular vs Extracellular Insights – Compares synthesis pathways for stability, yield, and scalability, guiding targeted agricultural applications.
- Soil- and Field-Relevant Applications – Connects nanoparticle characteristics (size, shape, zeta potential) to practical effects in soil systems, promoting safe, resource-efficient farming.

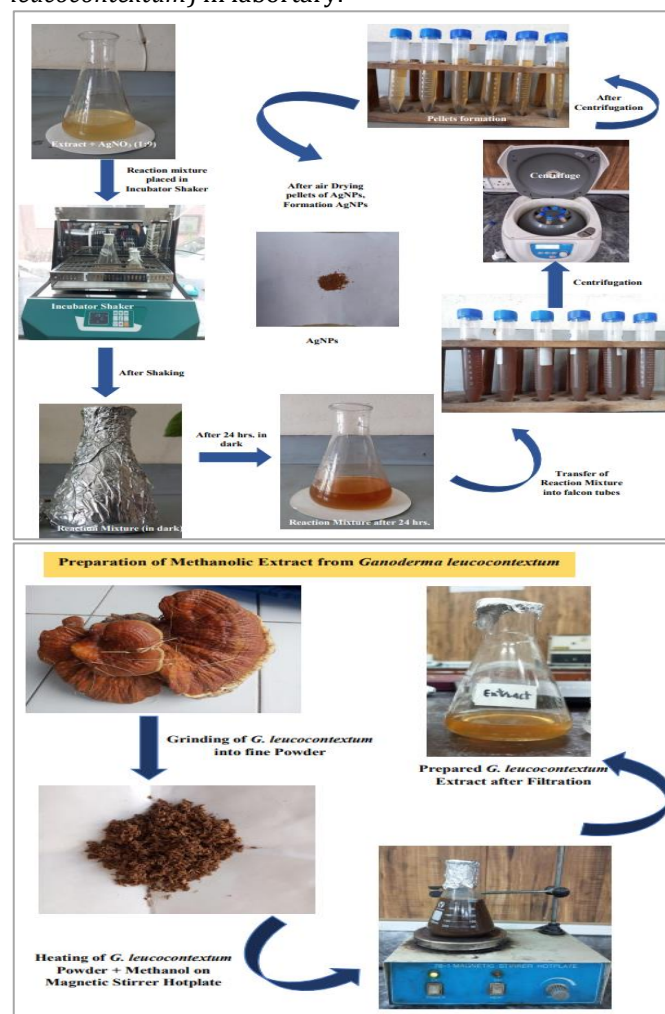
Why Fungi Are a Preferred Choice for Nanoparticle Synthesis?

Macrofungi, primarily from the Basidiomycota phylum and a few Ascomycota species, include about 14,000 globally distributed varieties, with 350 consumed for nutritional and medicinal purposes [10]. Cultivated species such as *Agaricus bisporus*, *Lentinula edodes*, and *Pleurotus* spp. are valued for their rich vitamins, proteins, fibers, and essential minerals, serving food, medical, and cosmetic industries. Their secretion of bioactive

compounds including enzymes, antioxidants, and antimicrobial agents enhances soil health, suppresses pathogens, and improves nutrient availability, making them ideal candidates for green silver nanoparticle (AgNP) synthesis. Leveraging these metabolites as natural reducing and capping agents enables eco-friendly, efficient, and cost-effective AgNP production with strong antimicrobial activity, promoting both pathogen control and plant growth. This dual benefit supports sustainable agriculture by boosting yields, reducing chemical inputs, and improving overall soil and plant health, as illustrated in Figure 1 with *Ganoderma leucocontextum*-mediated AgNP biogenesis.

Figure 1

Synthesis of nanoparticles using Fungus (*Ganoderma leucocontextum*) in laboratory.



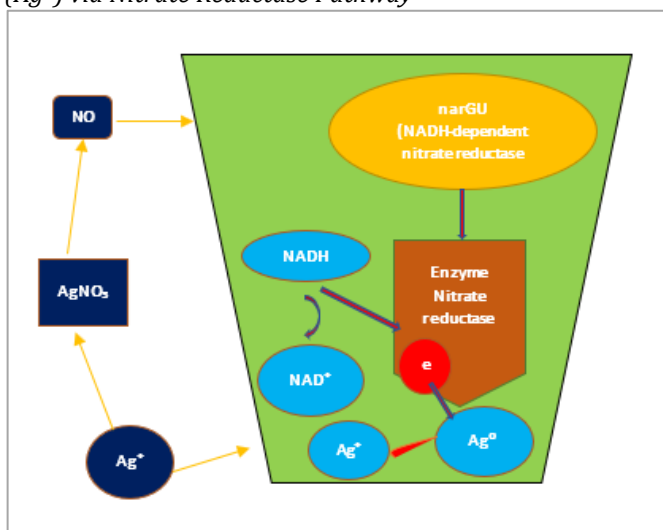
Biological Mechanisms Underlying AgNP Synthesis by Macrofungi

Macrofungi have the ability to produce silver nanoparticles (AgNPs) by the reduction of silver ions (Ag^+) to metallic silver (Ag) with the use of fungal metabolites such as proteins, enzymes, and other bioactive substances that simultaneously serve as both reducing and capping agents [11]. One of the important enzymes that is responsible for this process is nitrate reductase, which provides electrons to silver ions to produce AgNPs using NADH as the electron donor [12]. In the first step, Ag^+ ions are immobilized at the fungal cell surface where they are

nucleated into nanoparticles by nitrate reductase and related proteins (Figure 2). The use of fungal extract is able to create protective protein film by the containment of amino acids, polysaccharides, vitamins, and enzymes provided by the fungal extract which simultaneously maximize the reduction of the substrates, thereby preventing nanoparticle aggregation. Synthesis can be intracellular leading to larger size particles inside cells or extracellular for free cell filtrates, the latter is more scalable and quite often leads to more uniform nanoparticles of less size [13].

Figure 2

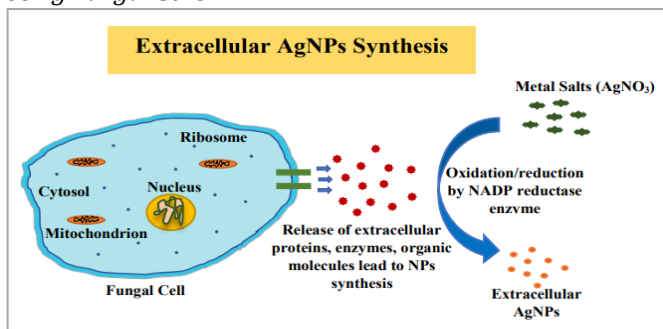
Enzymatic Reduction of Silver Ions (Ag^+) to Metallic Silver (Ag^0) via Nitrate Reductase Pathway



The morphology, size, and stability of biosynthesized AgNPs depend on the fungal species and the biomolecules present in their fruiting bodies or mycelia. Species such as *Agaricus bisporus*, *Calocybe indica*, *Ganoderma neo-japonicum*, and *Pleurotus sajor-caju* produce nanoparticles with distinct morphologies due to variations in protein- and enzyme-mediated nucleation. Extracellular biosynthesis (Figure 3) is particularly advantageous for large-scale production due to its simplicity and efficiency, while intracellular synthesis provides a confined environment for nucleation. Stability is strongly influenced by amino and other functional groups on capping proteins, which maintain dispersion over extended storage periods, as shown in *Trichoderma asperellum* and *Fusarium semitectum*, where nanoparticles exhibited no aggregation after six months [14], [15], [16].

Figure 3

Extracellular Biosynthesis of Silver Nanoparticles (AgNPs) Using Fungal Cells

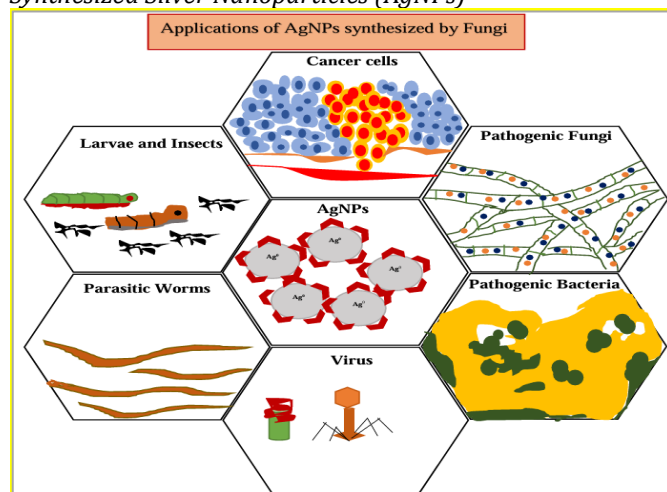


Advantages and challenges of using fungi.

Fungi provide an eco-friendly platform for nanoparticle (NP) synthesis due to their diverse bioactive metabolites, including polysaccharides, phenolic compounds, proteins, terpenoids, and enzymes, which aid in NP reduction, stabilization, and surface functionalization [16], [17]. Enzymes like laccase facilitate NP synthesis under mild conditions, and efficiency can be enhanced by stimuli such as UV or gamma irradiation [12]. *Ganoderma* species, in particular, produce nanoparticles with antioxidant, antibacterial, anti-inflammatory, and anticancer properties. In agriculture, fungal-mediated silver nanoparticles (AgNPs) improve crop yields, early disease detection, pest management, and the development of eco-friendly nanofertilizers and nanopesticides, leveraging fungi's natural reducing and stabilizing capabilities for sustainable nanotechnology [18]. These uses are complemented by green practices and exploit the natural reducing and stabilizing properties of fungi as a potential biologic source for scale-up production green nanomaterials (Figure 4).

Figure 4

Antimicrobial and Therapeutic Applications of Fungi-Synthesized Silver Nanoparticles (AgNPs)



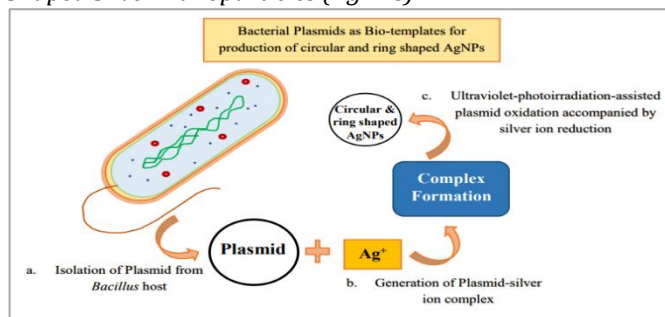
Role of different bacterial strains in AgNPs production

Bacteria and other microorganisms are proposed as a suitable synthesized nanoparticle (NP) producer, using the same guidance, useful and troublesome at the same time. Among these, the particular interest has been attracted by the electron absorption/electrosynthesis of metal ions, such as during the biosynthesis of silver nanoparticles (AgNPs) in bacteria. However, such methodology is not devoid of its difficulties when it comes to culture contamination, size restriction of nanoparticles and time-consuming steps [19]. Bacteria represent one of the most promising entities for the production of nanoparticles due to their intrinsic capability to reduce heavy metal ions in very demanding conditions of a high metal ion concentration. For instance, commandant bacteria including *stutzeri Pseudomonas* and *Pseudomonas aeruginosa* have been found to have protection mechanisms that provide them with resistance in terms of death and growth by exposure to toxic strong metals focus [20]. One of the first works on this subject by Klaus et al.

[21] has successfully firmly achieved the synthesis of silver nanoparticles with definable morphologies and compositions using the bacterium *Pseudomonas stutzeri*. This was one of the pioneering reports demonstrating usage of microorganisms in aggressiveness of AgNPs production. Use of bacterial plasmids as bio-templates for the preparation of circular and ring-shaped AgNPs by plasmid oxidizing and $\text{Ag}^+ / 2$ groups reducing reaction (Fig. 5).

Figure 5

Bacterial Plasmid-Mediated Synthesis of Circular and Ring-Shaped Silver Nanoparticles (AgNPs)



Other bacterial species have also been studied, also for nanoparticle synthesis. For example, Shivaji et al. [77] have employed culture supernatants of psychrophilic bacteria, whereas Nanda and Sravanan, [22] have employed *Staphylococcus aureus* for synthesis of silver nanoparticles. Moreover, Kalimuthu et al. [6] prepared silver NPs from the biomass of *Bacillus licheniformis* and achieved NPs of size 40 to 50 nm stabilized through nitrate enzymes. A new method of Saifuddin et al. [23] was a combination of culture suspension of *Bacillus subtilis* and the microwave irradiation in the water to synthesize monodisperse AgNPs with the size range from 5-50 nm. The results demonstrate that how heating conditions applied to the nanoparticles were more homogeneous with microwaves and shorter reaction times in addition to a reduction in aggregation (aggregation) with improved particle homogeneity.

Bacterial cell-cycle and mechanisms for regulating nanoparticle biosynthesis.

One of the dynamics of such microbial/(metal)/metalloid associations is the genetic and biochemical evolution of resistance mechanisms that enable the survival of the microbes in these altered environments [24]. Extracellular binding and complexation, precipitation, intracellular deposition, thiol-containing metal complexes, change in redox status of metal ions, efflux pumping and absence of specific metal transport systems are the mechanisms leading to AgNPs synthesis in bacteria systems [25]. These interactions are necessary in order to maintain the metal in a resistant and homeostatic state when forming nanoparticles. Species of *Acinetobacter baumannii*, *Enterobacter cloacae*, *Escherichia coli*, *Pseudomonas stutzeri*, etc., have shown silver ion resistance. Reduction of Ag^+ by NAD(P)H-dependent reductases and nitrate reductase is implicated as a central bioprocess. For example, Nitrate reductase can be used for this purpose by *Bacillus subtilis*, while *Pseudomonas aeruginosa* shows the same reduction activity in cell free extracts [26]. In

Enterobacteriaceae it was demonstrated that nitrate reduction and, hence, AgNP synthesis can be inhibited by piperidones. Other than yeasts, besides the endogenous and exogenous mechanism, the pathways are also present as in the case of *Lactobacillus* species where sugars are elaborated efficiently for biosynthesis of AgNPs.

Some physicochemical mechanisms were associated with bacterial AgNP biosynthesis that include but not limited to: reaction rate kinetics, enzyme function, thermodynamics, photocatalysis, and host biology. However, time is crucial as the formation of AgNPs has been reported to be hours at controlled conditions and several days [27] respectively. There is heterogeneity in the action of temperature for Ag^+ reduction on Ag when a moderate heating rate is used which shows superactivity at low temperature, while high temperature favours the denaturation of enzymes, causing a reduction of yield, especially for CFEs. Silver nitrate (AgNO_3) is used in most cases as Ag^+ source, synthesizing at a typical starting concentration of ~ 1 mM, however violating the optimum pH resulted in a substantial decrease in synthesis efficiency, with reduced nanoparticle yield and quality [28]. All of these chemical, biological and environmental conditions are responsible for determining the size, efficiency and stability of the AgNPs formed in bacterial systems.

Comparison of Bacterial and Fungal Systems for Nanoparticle Synthesis

Bacterial and fungal systems are biological platforms for nanoparticle (NP) synthesis, each with unique strengths and limitations. Bacteria can rapidly produce nanoparticles of various shapes including spheres, rods, and triangles via intracellular and extracellular routes, using enzymes like nitrate reductase and hydrogenase, as well as cell wall functional groups [29]. However, bacterial systems often yield low amounts of nanoparticles, face stability issues, and are sensitive to extreme pH, temperature, and metal ion concentrations, limiting their use under harsh conditions.

Fungal systems, in contrast, offer larger biomass and higher secretion of reductases and phytochelatins, promoting extracellular NP formation. Fungal proteins act as capping agents, stabilizing nanoparticles and controlling their size and morphology [30]. They produce more homogeneous, stable nanoparticles and tolerate environmental stresses better than bacteria. These features, combined with mature extracellular secretion systems, make fungi particularly suitable for industrial-scale, high-yield, and high-throughput nanoparticle production under varying conditions.

Physicochemical Characterization of Silver Nanoparticles

Broad range of physicochemical techniques have been used to provide rich characterization details for synthesized silver nanoparticles (AgNPs). Some of the most commonly used methods are Fourier Transform Infrared (FTIR) spectroscopy, Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Atomic Force Microscopy (AFM) and UV-Visible (UV-Vis) spectroscopy, Zetasizer analysis. Neutron scattering and x-ray diffraction are complementary and give information about

nanoparticle structure, stability, morphology and surface chemistry.

UV-Visible Spectroscopy

Ultra Violet-Visible (UV-Visible) Spectroscopy is one of the most essential tools for primary characterization, synthesis monitoring and stability analysis of Silver nanoparticles (AgNPs). It is a fast and reliable technique for analyzing colloidal suspensions and is well applicable to AgNPs for their strong optical properties. This technique utilizes matrix plasmon spectroscopy (MPS), a technique utilizing surface plasmon resonance (SPR), a physical effect that occurs when free electrons on the surface of a nanoparticle resonate with incident light. Silver SPR peaks are usually in the visible (410 to 430 nm) and are dependent upon nanoparticle size, geometry and medium environment. For instance, Tripathi et al. [31], have reported SPR peaks around 420 nm during the process of synthesis of AgNP with bacterial pellet confirming the nanoparticle formation. Spherical AgNPs usually exhibit single SPR band, whereas anisotropic or cylindrical AgNPs exhibit multiple peaks owing to a range of oscillation frequencies.

Zeta Potential

Zeta potential is an indication of the surface charge of nanoparticles and therefore a critical factor in the determination of colloidal stability. PZPS and polydispersions above +30 mV or below -30 mV are usually associated with stable dispersions due to strong electrostatic repulsion while values close to zero are considered indicative of instability and a tendency to flocculate. Barabadi et al. [32] found the zeta potential of AgNPs is -23 mV, indicating moderate stability. In biologically synthesized AgNPs, stability is nearly always the result of a combination of electrostatic repulsion and steric effects. Unique mechanisms like steric stabilization exist as a result of the adsorption to nanoparticles surface of biomolecules like proteins and enzymes produced by surrounding fungi covering the nanoparticles surface, protecting them from the aggregation.

X-ray Diffraction (XRD)

XRD is a non-destructive analysis technique which is employed to estimate crystal characteristics from diffraction patterns acquired in response to X-rays interfering with crystal lattices. Furthermore, the recorded results of XRD experiments in the AgNP studies are generally recorded in the 20-80deg (2 θ) within a structure of face-centred cubic (FCC) structure of silver at positions 38.19, 44.46, 64.63, and 77.34 corresponding to the orientation planes (111), (200), (220), and (311), respectively. For example, Poudel et al. [33] sent FCC silver nanoparticles synthesized by *Gaingerelum lucidum* extracts for XRD validation, and the results obtained corresponded to the JCPDS file number: 87-0717. The Debye-Scherrer relation is most commonly used to estimate average crystallite size from peak-broadening.

Fourier Transform Infrared Spectroscopy (FTIR)

Functional groups and biomolecules present in AgNP synthesis and stabilization were determined by FTIR. It works by measuring absorption of infrared light to produce a fingerprint of the molecule that can show

chemical bonds contained within. This method is able to verify biomolecules such as proteins, amines or hydroxyl groups that reduce and stabilize silver nanoparticles. Abdel-Hadi et al. [34] were able to use FTIR on AgNPs synthesized by *Fusarium oxysporum* and showed peaks at 1522.63 cm⁻¹ (amide group from proteins) and 3329.89 cm⁻¹ (hydroxyl groups from quinones), who reported that the proteins encapsulated the nanoparticles.

Scanning Electron Microscopy (SEM)

SEM allows for high-resolution nanoparticle morphological, size distribution and agglomeration images. Combined with energy-dispersive X-ray spectral analysis (EDX) it also gives information on elemental composition. Field emission SEM (FESEM) provides higher resolution by rastering a spot that gives improved resolution. Feroze et al. [35] produced spherical-shaped AgNPs by the use of fungi, where SEM validated the sizes in the range of 60-80 nm. Compared to thermionic emission sources, field emitters' brightness and stability are higher without thermal drift.

Atomic Force Microscopy (AFM)

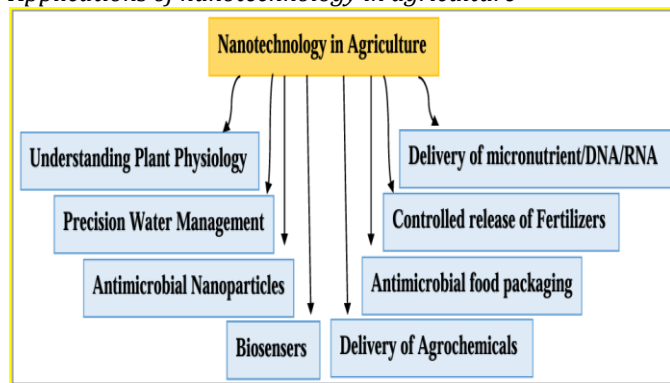
AFM can detect nanoparticles in high resolution without the use of an incident beam allowing imaging under nearly physiologic conditions. A sharp probe probes the surface of the sample, interacting with the material through sharp pico-newton scale forces. Jaloot et al. [36] produced 2D and 3D AFM image of AgNPs, and studied roughness parameters including root mean square and surface area ratio. Results showed that the majority of the particles were ≤ 85 nm, in close agreement with Owaid et al. [37].

Genetic Innovations in Nanoparticle Biosynthesis: Towards Eco-Friendly Solutions.

Advances in genetic engineering have enhanced nanoparticle (NP) production by enabling precise, efficient, and environmentally friendly biosynthesis, addressing limitations of conventional methods and public concerns over biosafety. Genetically modified organisms, such as recombinant *Escherichia coli* co-expressing phytochelatin synthase and metallothioneins, can produce diverse NPs, while silver-resistant strains with the CusCFBA system catalyze periplasmic silver NP formation via Cytochrome-C, highlighting its essential role [38]. In plants, genetic modifications including expressing the silicatein gene LoSilA1 in *Nicotiana tabacum* to enhance silver NP production up to threefold, producing spherical NPs (~12–80 nm) with high precision and sustainability, making transgenic plants effective green biofactories for nanoparticle synthesis [39].

Applications in Sustainable Plant Growth Enhancement

In contrast to the utility of silver nanoparticles (AgNPs) in the medical and pharmaceutical industries, their role in seed germination, root growth, and biomass formation in agricultural sciences, which is a relatively new research area, and has attracted a great deal of attention. Figure 6 shows that the revolution in agriculture is coming from nanotechnology in the form of precision in the delivery of nutrients, controlled delivery of fertilizers and refreshed approaches to produce sustainable farming.

Figure 6*Applications of nanotechnology in agriculture*

Positive Effects of AgNPs on Seed Germination and Growth

Seed germination is a very important stage of plant development which has a direct influence on the crop quality [39]. Certain AgNPs have been found to increase seed germination due to their adsorption on seed coats with increased water absorption, better starch metabolism, and rapid germination. As a result, AgNPs are used for nano-priming or surface treatment of old rice seed before sowing to enhance grain germination and seedling quality. One of the main goals of the priming techniques using AgNPs is the enhancement of the expression of the aquaporin genes which further helps for the diffusion of water and hydrogen peroxide (H_2O_2) into the seeds. This methodology proved to be enormously effective in primary enhancement of seedling development as evident from germinating rice seeds primed with photosynthesized AgNPs more successfully in transformation rates in expansion with better vigor than traditional hydropriming, $AgNO_3$ priming and the control unprimed seeds [40]. Furthermore, AgNP nano-priming was found to positively influence α -amylase activity to encourage higher soluble carbohydrate content leading to further augmentation of seedling growth.

Si Sable et al, [41] showed the positive results of the extracellular synthesis of AgNPs (using *Bacillus Subtilis* Spizizenni), for penisetum glaucum (Bajra) seeds. These AgNPs were found to germinate seed within three days after being applied at the concentration of 1 mM. Statistical analysis showed that both the plumule and radicle length showed a significant increase over the corresponding values for control seeds, underlining the phytostimulatory nature of AgNPs with respect to early plant development.

Potential Negative Effects of AgNPs on Plant Growth

While AgNPs broadly are plant growth-promoting agents, some quantities are known to cause toxicity on the plants. Mazumdar and Ahmed [42] showed the cytotoxicity of high concentrations of AgNPs (1000-1600 $\mu g/mL$) in *Brassica campestris* *Oryza sativa*, and *Vigna radiata*. Concentrations of 4500 and 6000 $\mu g/mL$ were inhibitory to root development, causing root length reductions of 1% and 0.5% of the control with *Oryza sativa* and *Brassica campestris*, respectively; a similar effect was obtained with *Vigna radiata* roots. Moreover, El-Temseh et al. [43] reported that AgNPs inhibition of *L. perenne* (germination percentage reduction) was remarkably significant at 10-20 mg/L.

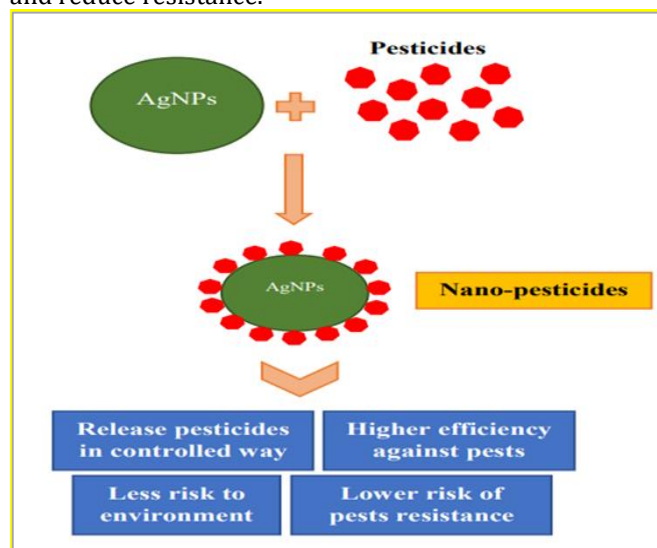
AgNPs as pest management agent

AgNPs have become a promising tool for pest management, as it represents a safe, non-toxic and effective control strategy to reduce pest populations. As a pest control agent, AgNPs not only disperse to insects, but also affect the development and physiology of the insects. On the other hand, using multifunctional nanoparticles they provide an effective particle-specific delivery of active compounds in a targeted manner to target organisms. Agrochemicals at the nanoscale, including nano-pesticides, nano-formulation, nano-fertilizers and nano-sensors, have transformed previous conventional approaches of farming techniques to more efficient and purpose-oriented methods.

Protein-free nanobased pesticides (Corresponding to non-organic based agro-nanotechnologies, like AgNPs) have been investigated for use in pest control, particularly for storage applications. Plant-based nanoparticles are also of great importance in controlling pests in grain stores for a greener solution compared with the conventional control techniques [44]. Apart from their direct toxicity to insects, AgNPs are also employed as carriers for agrochemicals to allow their precise transport directly to their targets, in this way increasing the efficiency of pest control. As can be seen from Fig. 7, AgNPs are incorporated with pesticides to form nano-pesticides for controlled release and improved specific pest activity to minimize environmental hazards.

Figure 7

Silver nanoparticles integrate with pesticides, creating AgNP-based nano-pesticides that enhance pest control and reduce resistance.



AgNPs as a nano fertilizer

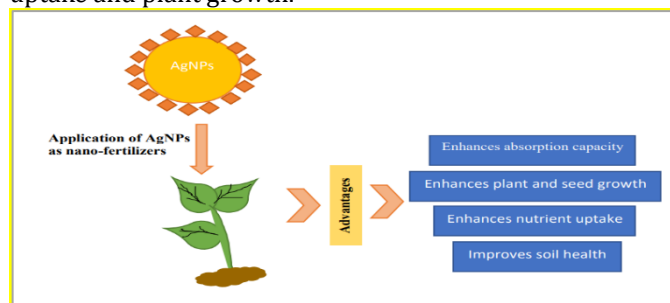
AgNPs (silver nanoparticles) uptake as nano fertilizer has attracted much attention because of its potential to improve plant nutrient supply. AgNPs can be used as highly efficient nanofertilizer, which would facilitate slow and specific release of nutrients, decreasing nutrient loss and increasing nutrient absorption from the soil [45]. This slow-release system ensures that no excess fertilizer is fed, which is a widespread reason behind polluting the environment in conventional farming methods. Figure 8 illustrates AgNP nano fertilizers' superior role in higher

nutrient absorption, promoting plant growth, and improving soil health for lower agricultural production costs.

AgNPs as an eco-friendly substitute with a number of uses in agriculture. For instance, an onion extract (ofertilizer) fabricated from onion extracts showing potential for crop growth (tomato and brinjals) was found effective in the synthesis of nano fertilizers. Besides the enhancement in plant growth due to using receptors for plant's intrinsic growth response, these nano-biofertilizers are also of considerable importance in controlling farm management costs and barring the stretching of unrequired use of chemical fertilizers. The result of this is a considerably lower pollution of the environment, making AgNPs an environmentally friendly alternative for modern farming.

Figure 8

The use of AgNPs as nano-fertilizer enhances nutrient uptake and plant growth.



Nanomaterial Properties and Feedstock: Laboratory plant/nanoparticle interactions (phytotoxicity of nanomaterials)

Nanoparticles, due to their small size, large surface area, and inherent catalytic reactivity, can chemically and mechanically interact with plants, influencing both beneficial and adverse effects on growth and metabolism [46]. Phytotoxicity research, guided by standards like the U.S. EPA Guide 123, often measures seed germination and root elongation to assess plant responses, but these tests may not capture the diverse effects across species or nanoparticle types [76]. Toxicity is highly species-dependent and complex, involving mechanisms such as nanoparticle penetration into the symplast, aggregation in the apoplast causing mechanical damage, and induction of oxidative stress through excessive reactive oxygen species (ROS).

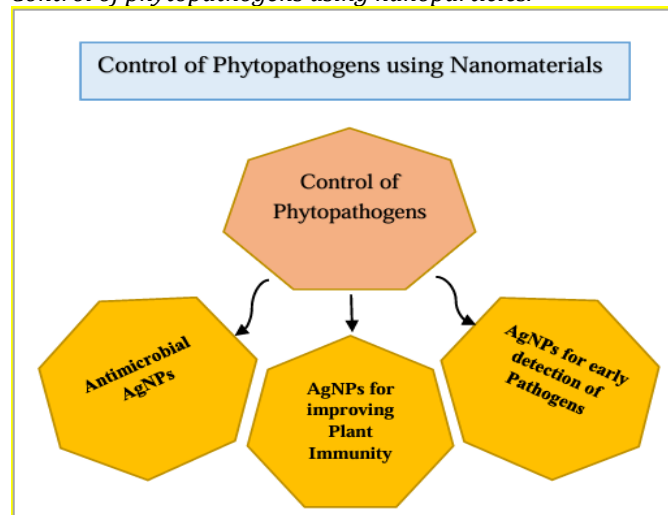
Role in Plant Disease Management

Silver nanoparticles (AgNPs) have recently become a promising technology for plant disease management because of their potent antimicrobial activity. Notably, their role in controlling different types of plant pathogens,

especially the fungal diseases, has attracted major attention in recent years. AgNPs provide a broad array of beneficial antifungal and antimicrobial activity, which can be useful as a chemical control for soil- and foliar-plant pathogens. Figure 9 shows that Nanomaterials, especially AgNPs, could be applied for strengthening plant immunity and offering early pathogen perception to manage phytopathogen efficiently for better crop health.

Figure 9

Control of phytopathogens using nanoparticles.



Sharon et al. [47] reported the dual role of silver nanoparticles as a plant growth stimulator and excellent antifungal agent. They established the efficacy of the AgNPs not only against *Sphaerotheca pannosa* var. *rosae* (causative agent of powdery mildew in roses), but also against *Bipolaris sorokiniana* (spot blotch of wheat) and *Magnaporthe grisea* (causative agent of blast disease in rice). Of these, rice blast pathogen was identified as possessing a significant susceptibility to silver nanoparticle treatment, indicating AgNPs' higher efficiency on some fungal species.

In addition to foliar pathogens, AgNPs have exhibited good utility against soil-borne pathogens. Kaman and Dutta [48] were able to show the fungicidal effect of mycogenically synthesized AgNPs, particularly that of *Trichoderma asperellum*, against the key soil-borne pathogens, such as *Fusarium oxysporum*, *Rhizoctonia solani*, *Sclerotinia sclerotiorum* and *Sclerotium rolfsii*. They claimed the effective inhibition of pathogens at a concentration of 100 ppm AgNPs for controlling root and vascular diseases, which are among the most troublesome of crop diseases. Table 1 gives a comprehensive list of pathogens associated with some diseases and also describes the possible role(s) of silver nanoparticles in their treatment and management.

Table 1

Application of silver nanoparticles (AgNPs) against phytopathogens

Nanomaterial	Pathogen Category	Pathogenic Organism	Target Disease/Infection	Affected Crops/Hosts	Application of AgNPs	Source
Silver Nanoparticles (AgNPs)	Fungi	<i>Colletotrichum gloeosporioides</i>	Anthraxnose	Apples, avocados, mangoes	Fungicidal coating for post-harvest fruit preservation	[49]
	Fungi	<i>Fusarium graminearum</i> , <i>F. oxysporum</i>	Wheat head blight, tomato wilt	Wheat, tomatoes	Seed treatment and soil	[50]

				amendment to reduce fungal load	
Fungi	<i>Alternaria alternata</i>	Leaf spots, fruit rot	Citrus, vegetables	Nano-fungicide sprays for foliar protection	[51]
Nematodes	<i>Meloidogyne</i> spp.	Root-knot nematode	Bermudagrass	Nematicidal root dip or soil drench	[52]
Bacteria	<i>Xanthomonas axonopodis</i> pv. <i>punicae</i>	Bacterial blight	Pomegranate	Antibacterial nano-coating for leaves and stems	[53]
Fungi	<i>Botrytis cinerea</i>	Gray mold	Strawberries, grapes	Edible nano-coatings to extend shelf-life	[54]
Pests	<i>Eobania vermiculata</i> (snail)	Crop damage	General agriculture	Pest-repellent nano-particles in soil or foliar sprays	[55]
Fungi	<i>Rhizoctonia solani</i>	Root rot	Soybeans, potatoes	Seed priming with AgNPs to enhance disease resistance	[56]
Fungi	<i>Bipolaris sorokiniana</i>	Spot blotch	Wheat	Foliar spray to suppress fungal growth	[57]
Fungi	<i>Sclerotinia sclerotiorum</i>	White mold	Oilseeds, legumes	Combined with biocontrol agents for synergistic effects	[58]

AgNPs mode of action and their efficacy against various plant pathogens will enable their use as an effective additive to integrated pest & disease management strategies in agriculture. Overall, silver nanoparticles can be an effective tool and will probably play an important role in controlling fungal plant diseases and to the sustainable development of agriculture by minimizing the use of conventional chemical fungicides. Their broad-spectrum and ability to act on both foliar and soil pathogens that accumulate show their value for improving crop protection and production.

Antibacterial potential

Nanoparticle's antibacterial activity is widely described because of a broad spectrum of the antibacterial effect against both Gram-positive and Gram-negative bacteria. Dridi et al. [59] yielded high antibacterial activities of metal nanoparticles from several bacterial species, including *Serratia marcescens*, *Escherichia coli*, *Micrococcus luteus*, *Staphylococcus aureus* and *Klebsiella pneumoniae*. This shows that they improve the anti-microbe skills against wide variety of bacterial pathogens, and this after all proves the capability of such materials in the antibacterial applications. Furthermore, Sardella et al. [60] highlighted the multi-functional capabilities of metal nanoparticles with potential applications in food packaging, water disinfection and air coating. All these technologies are relevant for the regulation of the bacterial contamination in several industries and public health environments.

Antibacterial mechanism of AgNPs

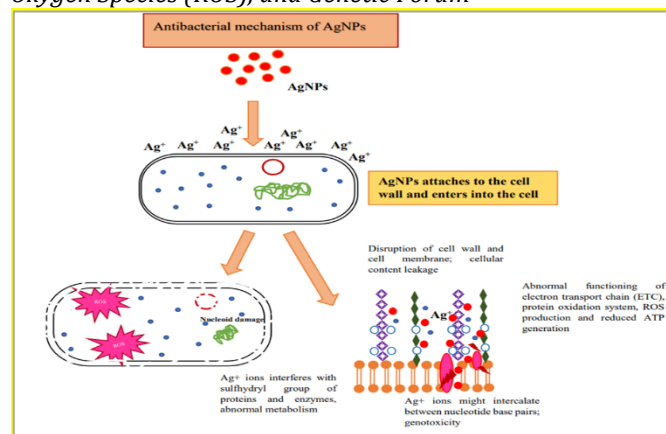
The bactericide ability of silver nanoparticles (AgNPs) comprises both bacteriostatic and bactericidal effects with the ability to control the bacterial populations with multiple mechanisms. AgNPs have good inhibitory effect against the bacteria. Among them, the main mechanism is the aggregation of AgNPs at the bacterial cell membrane resulting in the formation of III by perforation of the membrane. This type of disruption induces a loss of permeability of cells and eventually leads to the death of the bacteria. Abd-Elsalam and Prasad [61] further put

forward five major theories that explain the antibacterial mechanism of AgNPs:

Silver nanoparticles (AgNPs) exert antibacterial effects through multiple mechanisms. They release silver ions that bind to sulfur-containing proteins in bacterial membranes, compromising membrane integrity and increasing permeability. These ions can penetrate cells, causing DNA damage and inhibiting bacterial division. AgNPs also disrupt the electron transport chain, leading to loss of membrane potential and impaired metabolism, while generating reactive oxygen species (ROS) that induce oxidative damage to cellular components. Additionally, they interfere with bacterial nutrient uptake, hindering growth and reproduction. Together, these actions result in effective bacterial cell death.

Figure 10

Antibacterial Activity of Silver Nanoparticles (AgNPs) Through Cell Wall Destruction, the Generation of Reactive Oxygen Species (ROS), and Genetic Forum



Antifungal potential

The antifungal activity of biosynthesized nanoparticles (NPs) has been widely investigated and shown their potential action to fight fungal pathogen. Fernandez, et al. [62] reported the antifungal activity of biosynthesized silver nanoparticles (Ag NP) against *Cryptococcus laurentii* and *Rhodotorula glutinis*, showing the possibility of fungal

inhibition by these agents. Also, Yassin et al. [63] demonstrated the efficacy of Ag NPs (150 ppm) that showed a substantial inhibition in growth of *Fusarium chlamydosporum* and *Aspergillus flavus* by about 50%. Al-Otibi et al. [64] also supported the antifungal activity of Ag NPs and this was found to be 88.6% in lowering the growth of mycelium against *Helminthosporium rostratum* species. Moreover, they emphasized that the leaf extract of *Malva parviflora* had high efficiency against *Fusarium solani* (65.3%) indicating the possibility of designing new fungicide with the combination of AgNPs with botanical extracts.

Moreover, the antifungal ability of copper oxide nanoparticles (CuO NPs) also has been investigated. Devi et al. [65] reported the tremendous antifungal activity of CuO NPs against *Aspergillus niger* and *Mucor piriformis*. Their scavenging capacity of free radicals, along with its small size, provided improved antifungal activities. This completely synergistic action further reinforces the relevant role of nanoparticles' characteristics to enhance antifungal activity.

Soil health and sustainability

Silver nanoparticles (AgNPs) have attracted interest in relation to their impacts on soil health and sustainability given their antimicrobial activity by interacting with the soil system. Soil health is important for nutrient cycling, organic matter decomposition and ecosystem balance, all are dependent on active soil microbial communities [66]. In the traditionally complex soil matrix, AgNPs interact with various constituents, and their properties (e.g., size, surface chemistry, aggregation, dissolution rate, surface area) are affected by soil conditions which accordingly influence their stability, transformation, transport and (potential) toxicity. Presence of these interactions defines the environmental fate of AgNPs and its long-term impact on soil sustainability. Besides, AgNPs may cause an improvement in root health as demonstrated in Mehta et al. [67] where it was found that, besides promoting higher seed germination and root production number, the application of nanoparticles also causes an increase in plant growth. AgNPs and its benefits: These nanoparticles stimulate root exudation and enhance plant-microbe interactions, as evidenced by an AgNP-enhanced response (growth parameters) in the experiments with Fenugreek (*Trigonella foenum-graecum* L.) by upregulating genes associated with abscisic acid (ABA) and indole-3-acetic acid (IAA) [68].

Comparative analysis with chemically synthesized nanoparticles

The various synthesis methods from physical to chemical and eco-friendly green methods for metal nanoparticle synthesis has been investigated in recent years. Conventional chemical and physical methods with high energy requirements and the generation of hazardous by-products, along with the requirement of cumbersome equipment for their execution have been becoming less favored [69]. Physical processes such as aerosolization, ultraviolet irradiation, thermal decomposition, etc. often work under sustained temperature and pressure [69] and green methods use organic or ecologically sustainable reducing agents that are low on energy consumption and

are free from hazardous chemicals. Polyphenols and proteins are effective green synthesizers of metal ions into nanoparticles and produce a better nanomaterial when compared to the chemical synthesis [70].

Though chemical synthesis is the mostly employed technique, it's dependent on toxic catalysts plus stabilizers that contaminate the environmental surroundings and produce poisonous waste. Biological synthesis is a sustainable technique and it uses plant-based materials, microorganisms, bacterial metabolites, enzymes to lower metal ions without harmful side effects. In both techniques, the role of reducing agents is highly effective on the size, morphology, and dispersal of nanoparticles. The chemical agents like oleyl, amine, hydrazine, and sodium borohydride are efficient but toxic [71] whereas green synthesis replaces such reagents with harmless actors like amino acids, vitamins, proteins, polysaccharides, and flavonoids [72]. The green approach has to be highlighted as a promising strategy for the biobased synthesis of high quality, environmental friendly nanoparticles with limited environmental footprint.

Challenges

Regardless of these advantages, the synthesis of fungal NPs is challenging mainly due to the control of the NP size, shape, and surface function. The stability and the efficiency of AgNPs biosynthesis are not generally consistent. Further, they need aseptic culture conditions to prevent contamination of sample and NPs obtained by this technique can vary in terms of size, complicating their use [73]. Furthermore, myco-synthesis is a more time-consuming process; it may often exceed five days, lessening the efficiency of rapid production [74]. The NP crystallization can also become an obstacle in the downstream processes and jeopardize the aim of easy or cheap production routes.

There have been a number of attempts to overcome these problems. The fungal cultures have been altered, using parts of the fungus (biomass vs. biomass filtrates) for optimization of the NPs size and yield. It has been reported that smaller AgNPs in the range 1.5-20 nm, which could be desirable for some applications, were obtained by extracting the biomass from the reaction medium [75]. Additionally, optimization of several parameters such as biomass concentration, incubation time, temperature and silver nitrate concentration was found to be well for NP size and properties control.

CONCLUSION AND FUTURE PERSPECTIVE

Agro-synthesized silver nanoparticles (AgNPs) using macrofungi and bacteria represent a promising eco-friendly tool for advancing agricultural technologies. This green approach leverages natural organisms as agents for nanoparticle synthesis, reducing costs and supporting sustainable plant growth. The study highlights the role of macrofungi and bacteria in converting silver ions into nanoparticles, with physicochemical analyses confirming their stability, morphology, and size. These characteristics directly contribute to significant antimicrobial activity, with potential applications in both medical and environmental sectors. In agriculture, biosynthesized AgNPs show strong potential as bio-fertilizers and bio-pesticides. They enhance nutrient uptake, promote plant

growth, and improve disease management by targeting phytopathogens. At the molecular level, research is focusing on identifying the genes and enzymes involved in nanoparticle synthesis by fungi, enabling better control over size, shape, and crystallinity. This molecular understanding is expected to overcome current challenges and support large-scale, cost-effective production of nanoparticles with tailored properties. Looking ahead, further exploration is needed to expand applications in

sustainable crop management and environmental health. In particular, more knowledge is required about plant gene-nanoparticle interactions, including the role of sugars and other molecules produced during green synthesis. With continued research, biosynthesized silver nanoparticles could emerge as a key innovation in sustainable agriculture, balancing productivity with environmental responsibility.

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