

## NANO-FUNGICIDES: SYNTHESIS AND EFFICACY OF GREEN-SYNTHESIZED SILVER NANOPARTICLES (AGNPS) FOR THE TARGETED MANAGEMENT OF CEREAL SMUT PATHOGENS

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### Abstract

The cereal crops wheat, barley, and maize are the foundation of global food security, and these are targeted by seed- and flower-infecting smut and bunt pathogens such as *Ustilago tritici*, *Ustilago nuda*, *Ustilago hordei*, *Ustilago maydis* and several species belonging to the genus *Tilletia*. These biotrophic fungi are responsible for replacing the normal kernel of grain with masses of dark teliospores resulting in 30–34% yield loss during serious epidemics and reduction of market value as well as seed viability. Synthetic conventional fungicides are effective, but select for resistance, are toxic to non-target organisms and environment, leave residues of chemicals and are financially unsustainable for smallholder farmers. This review is focused on green synthesized AgNPs as a potential sustainable and multitarget nano fungicide for specific management of cereal smut. Botanical extracts and microbial derivatives contain polyphenols, flavonoids, alkaloids, protein, and biosurfactants that act as reducing  $Ag^+$  to  $Ag^0$ , as well as capping and stabilizing agent during the synthesis process of NPs which are generally spherical and 10–50 nm with surface plasmon resonance between 420 to 450 nm. These green AgNPs exhibit % mycelial growth inhibition from 77 to 100, inhibit teliospore germination and amressorium formation at  $12.5-50 \mu g \cdot mL^{-1}$  and their multisite mode of action includes cell wall degradation, ergosterol depletion, cell membrane disruption, reactive oxygen species burst, lipid peroxidation, enzymatic inactivation, DNA damage and cAMP signaling suppression, which contribute to limiting the development of resistance. So, seed nanoprimer and chitosan-silver nanocomposite coatings enable the targeted delivery, sustained release of ions and also provide additional physiological advantages such as improved germination, activation of antioxidants, and absorption of micronutrients. Selective toxicity to ergosterol-containing fungal membranes rather than phytosterol-containing plant membranes coupled with good ecotoxicological profiles also indicate biosafety. Nevertheless, dose standardization, surveillance of environmental

*fate, silver accumulation levels, and regulatory issues need to be addressed for commercial use.*

## 1. INTRODUCTION

Cereal crops such as wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and maize (*Zea mays*) are the key contributors to the global food security, providing the majority of daily caloric and protein intake worldwide. Yet global cereal yields were and still are being continuously depressed by the biotic factors, especially specialized phytopathogenic fungi, more so biotroph and hemibiotroph members from the orders Ustilaginales and Tilletiales (Jabran et al., 2024). Smut and bunt fungi like *Ustilago tritici* (loose smut of wheat), *Ustilago nuda* (loose smut of barley), *Ustilago hordei* (covered smut of barley), *Ustilago maydis* (corn smut), *Tilletia* species (Karnal bunt caused by *T. indica* and kernel smut by *T. barclayana*) cause massive financial loss in global agriculture (Fatima et al., 2025). These are mainly seed borne or floral infecting species. Teliospores, either airborne or on seed, germinate and infect the developing floral ovary at anthesis, proceeding to systemic, biotrophic infection in the reproductive tissue of hosts. Healthy grain kernels are replaced by dark, powdery fungal teliospores, resulting in yield losses between 30 and 34% during severe epidemics, as well as reduction of market quality and seed germinability (Debnath et al., 2025).

Control of cereal smuts has traditionally been based on the use of synthetic fungicide seed treatments and, in some cases, multiple applications of chemicals to the foliage. While synthetic fungicides are able to suppress the pathogens at a base level, the continual and extensive use of them, poses major agronomical, ecological and socio-economical problems. Continuous application of single-site fungicides enhances the selection of resistant fungal populations, and eventually results in the failure of disease control in certain areas (Fatima et al., 2025). In addition, conventional synthetic formulations generally have non-target environmental effects, causing chemical residues

in the soils, contaminating water bodies, and harming beneficial soil microorganisms. From a financial point of view, subsistence and small-scale farmers in the developing world often cannot buy the costly commercial fungicides that would protect their staple crops from repeated attack by smut fungi and similar limp (Desnath VI, 2025). As a solution to these sustainability barriers, agricultural nanotechnology has modified nano-fungicides as a more focused approach in sustainable crop protection. Nano-sized engineered materials that have 1 to 100 nm at least in one dimension have unique physiochemical properties such as high surface area to volume ratios, good penetration into tissues, and high reactivity compared to their bulk chemical counterparts. Among all the kinds of metallic nanomaterials, AgNPs are exceptional since they possess a potent broad-spectrum antimicrobial activity (Abd-Elsalam, 2024).

Instead of using toxic chemical reductants (such as sodium borohydride) and requiring high energy consumption as in physical and chemical production of nanoparticles, green synthesis is preferred in bio-nanotechnology route. Green synthesis exploits biological materials such as plant extracts, seed exudates and microbial metabolites as reducing, capping and stabilizing agents, thereby converting ionic silver ( $\text{Ag}^+$ ) into elemental silver nanoparticles ( $\text{Ag}^0$ ) (Abd-Elsalam, 2023). Multi-target nano-fungicides are the green-synthesized AgNPs and these can break down fungal cell membranes, cause intracellular oxidative stress and modulate significant gene expression networks. In this review, we consolidate the recent advancements in the biological synthetic routes of green AgNPs and their structural aspects, assess their antifungal potential against the predominant cereal smuts, describe their multi-site modes of action, discuss advanced modes of application such as seed nanoprimering and biopolymer nanocomposites,

and highlight host biosafety and ecotoxicological issues (Abd-Elsalam, 2021).

## 2. Phytochemical and Microbial Synthesis Mechanics of Green AgNPs

In green synthesis, the clean waste product is water and therefore the process is cost-effective and environmentally friendly when compared to the traditional physical and chemical methods, which

involve hazardous chemicals as reducing agents and produces toxic waste (Iravani, 2011). Biogenic synthesis: Various biological systems including plant extracts (obtained from leaves, seeds, fruits, or stems) and microorganisms (bacterial fermentation broths and fungal extracts) are employed for the production of stable silver nanoparticles (Mikhailova, 2024).

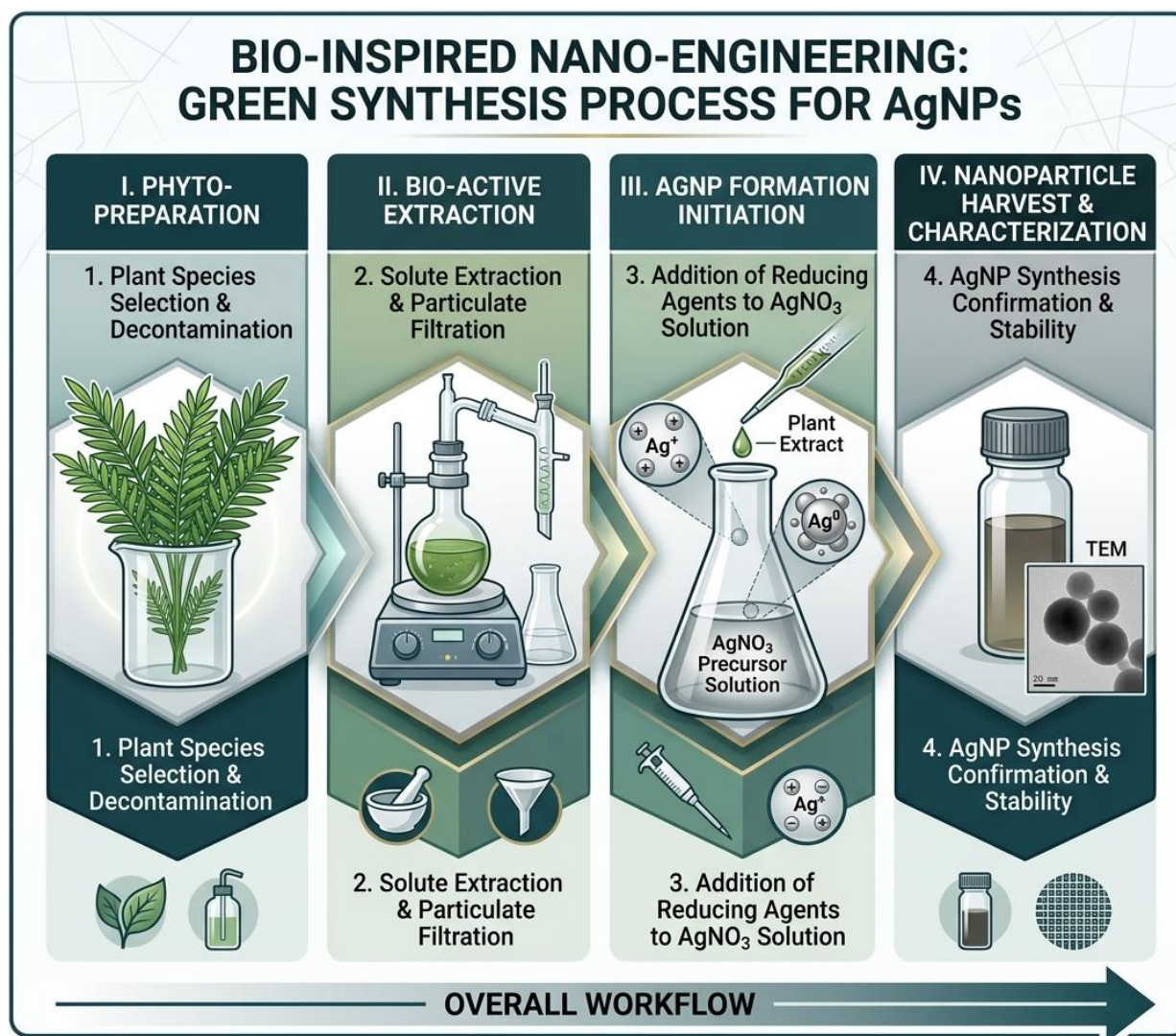


**Fig 1. Schematic for Green Synthesis**

Figure 1: Schematic Overview of the Four-Phase Green Synthesis and Characterization Workflow for Silver Nanoparticles (AgNPs)

### 2.1 Biological Reduction Pathways and Biomolecular Capping

The underlying principle enabling green synthesis is the biochemical reduction of monovalent silver ions ( $\text{Ag}^+$ ) usually in the form of silver nitrate ( $[\text{AgNO}_3]$ ) to zero-valent metallic nanoclusters ( $\text{Ag}^0$ ) by biomolecules followed by biomolecular capping along with stabilization. In plant based synthesis, aqueous plant extracts provide a complex matrix of secondary metabolites, such as polyphenols, flavonoids, terpenoids, alkaloids and soluble proteins (Vorkapić et al., 2026). These act as phytochemicals molecules and have an electron donating potential to reduce  $\text{Ag}^+$  to  $\text{Ag}^0$  and complex with growing nanoparticles. This biomolecular capping layer induces steric and electrostatic repulsions, which inhibits particle agglomeration and sustain the colloidal stability for long-term. Various plant extracts have been proven to be effective in the formation of AgNPs such as *Datura metel*, *Allium sativum*, *Moringa oleifera*, *Prosopis juliflora*, *Acalypha indica*, *Argemone mexicana*, *Solanum nigrum*, *Catunaregam spinosa* and *Cicer arietinum* (Thakur et al., 2026).

The microbial and fermentation-based routes are equally potent for the preparation of AgNPs. Bacterial fermentation extracts (RFE) of *Pseudomonas aeruginosa* R64 containing phenazine and quinoline derivatives mediate an ultra fast reduction of  $\text{Ag}^+$  and simultaneously capping the formed nanoparticles with organic functional groups (Rabiee, 2025). In the same way, phytopathogenic fungi can be used for green synthesis; for example, the corn smut pathogen *Ustilago maydis* secretes extracellular amino acids and biosurfactants that reduce silver ions and stabilize the resulting colloidal AgNPs. The use of fungal biomass or extracts has potential for the process scale-up, as fungi produce a lot of extracellular enzymes and proteins which can increase the synthesis yields and improve the nanoparticle colloidal stability (Le Ngoc, 2026).

### 2.2

### Characterization Techniques and Reaction Kinetics

The green-synthesized AgNPs should be accurately characterized to know their size, shape, surface charge, and crystal structure, as all these parameters are controlled on the biological activity and fate of nanoparticles in the environment. The synthesis of metallic AgNPs is consistently tracked with the help of UV-Visible spectroscopy which shows a well defined SPR absorption peak generally around 420 nm to 450 nm as a consequence of the collective vibration of the free conduction electrons (Mukasyan & Shuck, 2017). The structural evolution followed by size distributions in the dry state by utilizing TEM (Transmission Electron Microscopy) and Field Emission scanning Electron Microscopy (FESEM) confirms that the bioorganic compound based AgNPs are spherical or quasi spherical in shape with core diameters between 15 and 50 nm (Donahue et al., 2022).

Dynamic Light Scattering (DLS) analysis is used to determine the hydrodynamic particle size in aqueous suspensions; DLS values are always higher compared to those obtained from TEM since DLS measurements consider not only the metallic silver core but also the surrounding biomolecular hydration layer. Surface charge and colloidal stability are measured by Zeta Potential (Dunn et al., 1999). A negative zeta potential value (e.g.  $-10.75 \pm 0.84$  mV) indicates the presence of strong electrostatic repulsive forces between the particles which prevent their aggregation in an aqueous medium. Reaction kinetics, size and yield of nanoparticles are significantly affected by the reaction condition including pH value, concentration of biological extract, temperature and exposure to light. Alkaline pH conditions (pH 9 to 11) favor deglycosylation of phytochemical active groups, and result in faster rate of reduction, and smaller and well-dispersed NPs. Furthermore, exposure to sunlight or focused light acts as a photo-catalytic accelerator, significantly shortening reaction times and improving particle uniformity (Lu et al., 2019).

Table 1: Green Synthesis Vectors, Capping Biomolecules, and Characterization Profiles of Biosynthesized AgNPs

| Biological Synthesis Source       | Source Category        | Capping and Reducing Agents       | Core Size Range (nm) | Morphology and SPR Peak           |
|-----------------------------------|------------------------|-----------------------------------|----------------------|-----------------------------------|
| <i>Pseudomonas aeruginosa</i> R64 | Bacterial Fermentation | Phenazine & quinoline derivatives | 19.24 nm             | Spherical; SPR $\approx$ 420 nm   |
| <i>Ustilago maydis</i>            | Fungal Extract         | Amino acids & biosurfactants      | 153 – 256 nm         | Quasi-spherical; SPR 420 – 450 nm |
| <i>Datura metel</i>               | Plant Leaf Extract     | Polyphenols & alkaloids           | 15 – 50 nm           | Crystalline, spherical            |
| <i>Solanum nigrum</i>             | Plant Leaf Extract     | Flavonoids & saponins             | < 100 nm             | Spherical                         |
| <i>Cicer arietinum</i>            | Plant Leaf Extract     | Phenolic compounds & proteins     | 10 – 50 nm           | Spherical to quasi-spherical      |
| <i>Catunaregam spinosa</i>        | Plant Fruit Extract    | Tannins & glycosides              | Nanoscale (< 50 nm)  | Spherical                         |

### 3. Antifungal Efficacy Against Cereal Smut and Bunt Pathogens

Green-synthesized AgNPs demonstrate significant, dose-dependent antifungal activity against a broad spectrum of phytopathogenic fungi, including major cereal smut and bunt pathogens belonging to the genera *Ustilago* and *Tilletia* (Mahapatra et al., 2022).

#### 3.1 Quantitative Mycelial and Colony Growth Suppression

Green AgNPs inhibit fungal radial growth and reduce biomass accumulation in vitro in poison food and microdilution assays. Biosynthesized AgNPs from bacterial fermentation broths (RFE-AgNPs) at a concentration of  $20 \mu\text{g} \cdot \text{mL}^{-1}$  result in 77% inhibition of colony growth of target fungal pathogens. Likewise, plant-derived AgNPs (e.g., those synthesized using *Datura metel* leaf extract) show complete (100%) mycelial growth inhibition of fungal targets at  $100 \mu\text{g} \cdot \text{mL}^{-1}$  (Yalage et al., 2020).

Green AgNPs are incorporated into composite biopolymer matrices (e.g., chitosan-silver nanocomposites (Ch-AgNPs)) to improve their antifungal activity. Optimized Ch-AgNP formulations (especially L10 and DP4) at  $1.0 \text{ mg} \cdot \text{mL}^{-1}$

$[\text{mL}]^{-1}$  inhibit mycelial growth by 84% to 92%. Pure silver-nanochitosan composites at  $0.5 \text{ mg} \cdot \text{mL}^{-1}$  cause 100% mycelial growth termination, outperforming individual components due to additive structural and biochemical effects (Kjeldgaard et al., 2022).

#### 3.2 Spore Germination and Appressorium Development Inhibition

The control of cereal smut pathogens relies on stopping spore germination and early development of infective structures prior to host infection. Cereal smuts e.g. *Ustilago tritici* and *Tilletia indica* infect the host plant at anthesis or early seedling stage through specialized infection structures (Hegde & Kolattukudy, 1997).

Green AgNPs inhibit this early developmental change. In the concentration range  $12.5\text{--}50 \mu\text{g} \cdot \text{mL}^{-1}$ , biogenic AgNPs inhibit teliospore and conidial germination, they induce germ tube growth arrest and prevent appressorium formation. The direct interaction of silver nanoparticles/ions with the surface of fungal spores has been demonstrated to prevent spore penetration into host plant tissues, hindering biotrophic colonization prior to the manifestation of smut on cereal spikes (Barilli et al., 2016).

Table 2: Comparative Antifungal Performance Metrics of Green-Synthesized AgNPs and Bio-Nanocomposites

| AgNP Formulation / Source        | Target Fungal Pathogen            | Applied Concentration                                                       | Measured Antifungal Efficacy     | Primary Mechanism / Inhibitory Effect        |
|----------------------------------|-----------------------------------|-----------------------------------------------------------------------------|----------------------------------|----------------------------------------------|
| RFE-AgNPs (P. aeruginosa)        | Magnaporthe oryzae / cereal fungi | 20 $\mu\text{g} \cdot \text{mL}^{-1}$                                       | 77% colony growth inhibition     | Blocks conidia germination & appressoria     |
| Chitosan-AgNPs (L10 formulation) | Fusarium spp. / Wheat pathogens   | 1.0 $\text{mg} \cdot \text{mL}^{-1}$                                        | 92% mycelial growth inhibition   | Synergistic cell wall & membrane degradation |
| Chitosan-AgNPs (DP4 formulation) | Fusarium spp. / Wheat pathogens   | 1.0 $\text{mg} \cdot \text{mL}^{-1}$                                        | 84% mycelial growth inhibition   | Disruption of hyphal integrity               |
| Pure Silver Nanochitosan (Ag-NC) | Cereal fungal pathogens           | 0.5 $\text{mg} \cdot \text{mL}^{-1}$                                        | 100% mycelial growth termination | Complete arrest of hyphal expansion          |
| Datura metel AgNPs               | Phytopathogenic fungi             | 100 $\mu\text{g} \cdot \text{mL}^{-1}$                                      | 100% mycelial growth inhibition  | Complete growth suppression                  |
| Acalypha indica AgNPs            | Agronomic fungal pathogens        | 15 $\text{mg} \cdot \text{L}^{-1}$ (15 $\mu\text{g} \cdot \text{mL}^{-1}$ ) | Broad-spectrum inhibition        | Spore & germ tube destruction                |

#### 4. Multi-Targeted Mode of Action and Intracellular Disruptions

The strong antifungal effect of the green AgNPs befalls a multi-directional process where physical, biochemical and genetic pathways of the fungal cells are at the same disrupted (Derbalah et al., 2020). This multi-target action can lessen the chance of the fungus to develop single gene resistance (Yang et al., 2026).

The suppression of the pathogens is begun early with the physical attraction between green AgNPs and the external fungal cell wall. Biomolecules in the nanoparticle capping facilitate electrostatic interaction with the polymers of fungal cell wall. AgNPs, once attached, destroy cell wall molecules by reducing the production of essential structural molecules such as chitin and ergosterol (Chand et al., 2024). At the same time AgNPs also modulate the plasma membrane phospholipids by altering the phosphatidylcholine (PC) to phosphatidylethanolamine (PE) ratio. This lipid dysregulation affects membrane fluidity, structural organization, and selective permeability. Electron microscopy studies demonstrate (Han et al., 2025)

significant pitting of the surface of the treated fungal hyphae, marked shrinkage, collapse of the ultrastructure, and extensive disruption of the cell wall.

After digestion of the cell wall, intracellular production of reactive oxygen species (ROS) including superoxide radicals ( $\text{O}^-_2$ ), hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), and hydroxyl radicals ( $[\text{OH}]^\cdot$ ) as one of the triggers of cytotoxicity. Isolated green AgNPs seem to disrupt electron transport when they come into contact at the interface of fungal membrane bound respiratory chains, leading to an outburst of intracellular ROS (Benaim & Paniz-Mondolfi, 2024). Too much ROS produces a devastating oxidative stress leading to lipid peroxidation of polyunsaturated fatty acids in fungal cell membrane. Biochemical analyses of malondialdehyde (MDA), a quantitative indicator of lipid peroxidation, demonstrate a drastic increase up to 77.77% upon nanoparticle treatment. This leads to membrane disruption, with the formation of micropores that give rise to

an unregulated loss of intracellular ions, sugars and proteins (Singh et al., 2026).

Inside the fungal cytoplasm after endocytosis or membrane pores, AgNPs release silver ions ( $\text{Ag}^+$ ) by oxidative dissolution. The released  $\text{Ag}^+$  ions possess a strong chemical affinity towards the  $-\text{SH}$  (sulfhydryl group) and thiol groups of certain functional fungal enzymes and structural proteins (Wen et al., 2024). Essential disulfide bonds ( $-\text{S}-\text{S}-$ ) reduction by  $\text{Ag}^+$  covalent binding to sulfhydryl groups leads to tertiary protein denaturation and a subsequent loss of activities of major constituent enzymes. Concurrently, endocytosed AgNPs and  $\text{Ag}^+$  ions penetrate the nuclear membrane to bind to nucleic acids directly. Silver ions intercalate between the base pairs of fungal DNA, interfering with the

hydrogen bonding of base pairs, resulting in chromatin condensation, nuclear fragmentation, and double strand DNA breaks (Herranz-López et al., 2017).

In terms of biochemistry, the biogenic AgNPs interfere with key metabolic and signaling pathways at the systemic level. Transcriptome and metabolome data demonstrate that biosynthesized AgNPs modulate lipid and glycogen metabolism and inhibit cyclic adenosine monophosphate (cAMP) signaling. Signaling through cAMP controls fungal morphogenesis, hyphal growth, conidiation, and appressorium development, and perturbation of this signaling pathway inhibits the smut pathogens' development of viable infection structures, thereby suppressing their ability to invade host plant tissues (Zhang et al., 2025).

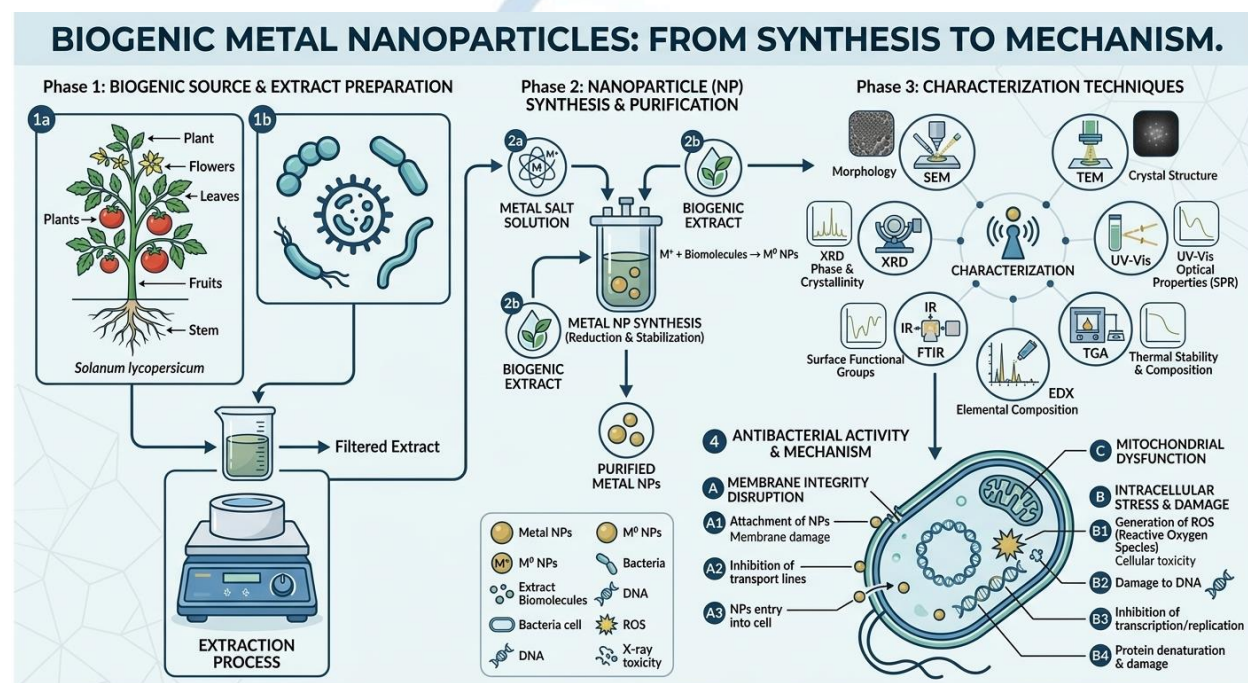


Figure 2: Comprehensive Schematic of Biogenic Metal Nanoparticle Synthesis, Characterization Techniques, and Multi-Targeted Antifungal Mechanisms

## 5. Agronomic Application Strategies: Seed Nanopriming and Nanocomposites

To effectively control seed-borne smut and bunt pathogens under field conditions, green AgNP formulations must be applied using delivery methods that ensure uniform grain coverage,

direct contact with dormant pathogen structures, and sustained active life (Shukla et al., 2019).

### 5.1 Mechanics and Physiological Benefits of Seed Nanopriming

Seed nanopriming is an advanced pre-sowing seed treatment technology in which cereal grains are

soaked in aqueous nano-fungicide suspensions under controlled temperature and duration conditions. This process allows controlled seed hydration without triggering radicle emergence (Imtiaz et al., 2023).

Because smut pathogens such as *Ustilago tritici* inhabit seed embryos or seed coats, nanopriming delivers AgNPs directly to internal and surface infection sites. Nanoparticles smaller than 100 nm cross the seed coat (testa) through natural micro-capillaries and intercellular spaces, penetrating deep into embryonic tissues to eliminate dormant biotrophic hyphae (Nile et al., 2022).

Beyond pathogen control, seed nanopriming enhances crop physiological performance:

- Nanopriming accelerates seed metabolic activity, speeds up seed coat rupture, reduces dormancy, and promotes rapid, uniform seedling emergence under variable field conditions.
- Pre-sowing nanopriming activates seed antioxidant enzyme systems (including superoxide dismutase, peroxidase, and catalase) and triggers Systemic Acquired Resistance (SAR) pathways, priming young plants against secondary infections (Shelar et al., 2021).
- Nanopriming enhances the uptake and accumulation of essential micronutrients (such as zinc, iron, and selenium) within germinating grains, promoting early root elongation, increasing seedling biomass, and raising final grain quality (Kandhol et al., 2022).

## 5.2 Chitosan-Silver Nanocomposite Coatings

Natural biopolymer matrices, such as chitosan, can be used to encapsulate green AgNPs, resulting in stable nanocomposite seed coatings. Chitosan creates a biodegradable and nontoxic film that uniformly coats the surface of the grain providing a physical protective barrier (Canama et al., 2023).

Chitosan-silver nanocomposites (Ch-AgNPs) modulate the release of active Ag<sup>+</sup> ions, enabling a sustained antifungal protection during early seedling growth. In addition, the chitosan matrix possesses a complementary antifungal activity by interacting with fungal cell membranes and aside from binding it also removes ergosterol, leading

to synergism with AgNPs. Additionally, seeds with a film coating exhibit better flowability when sown mechanically and generate less dust while being transported and handled (Alhussaini & Alyahya, 2026).

## 5.3 Foliar Application and Integrated Disease Management

For smut species that infect host crops during reproductive growth stages such as *Ustilago maydis* or *Tilletia indica* during flowering foliar applications of green AgNPs provide targeted protection for developing floral spikes. Foliar sprays form a protective barrier over floral structures, preventing airborne sporidia from colonizing ovaries. Integrating seed nanopriming with targeted foliar applications establishes a multi-stage defense strategy that protects cereal crops from early seedling emergence through grain filling (Reuveni & Reuveni, 1998).

## 6. Biosafety, Environmental Ecotoxicology, and Risk Assessment

While green-synthesized AgNPs show high antifungal efficacy, deploying metallic nanomaterials in agricultural ecosystems requires thorough biosafety evaluations regarding host plant health, non-target soil organisms, aquatic environments, and human safety (Hilbeck et al., 2011).

### 6.1 Host-Plant Biosafety and Selective Toxicity Dynamics

A key advantage of green-synthesized AgNPs is their high selective toxicity toward fungal pathogens compared to host cereal crops. This selective toxicity is largely driven by key structural differences in cell membrane lipid profiles:

- Fungal cell membranes rely on **ergosterol** to maintain structural integrity and membrane fluidity.
- Host plant cell membranes are composed predominantly of **phytosterols** (such as  $\beta$ -sitosterol and stigmasterol) (Buyel, 2023).

Green AgNPs selectively target ergosterol synthesis and membrane stability, causing fungal cell lysis without disrupting plant cell membranes. Phytotoxicity bioassays confirm that applying

optimized green AgNP formulations (including Ch-AgNPs at concentrations up to  $1.0 \text{ mg} \cdot \text{mL}^{-1}$ ) produces no adverse effects on cereal seedling growth. Instead, these treatments frequently stimulate root elongation, enhance photosynthetic pigment levels, and boost overall plant biomass (Peterson et al., 2016).

### **6.2 Ecotoxicity in Non-Target Organisms and Aquatic Systems**

Green synthesis routes enable the synthesis of AgNPs with reduced ecotoxicity as compared to chemically synthesized AgNPs or traditional chemical fungicides. The biological capping layer generated from plant extract/microbial extract caps the particle surface and a certain degree of silver ion leaching is curtailed thus reducing non specific oxidative damage through environmental soil and water (Isidori et al., 2005).

Aquatic toxicity tested with the brine shrimp model (*Artemia salina*) confirms that biogenic AgNPs (RFE-AgNPs) possess much higher median lethal concentrations ( $\text{LC}_{50}$ ) when compared with commercial chemical fungicides (e.g. isoprothiolane) and chemically synthesized AgNPs. This confirms a broader safety margin for non-target aquatic life in the agroecosystem (Pereira et al. 2009).

### **6.3 Environmental Fate, Bioaccumulation, and Regulatory Thresholds**

However, even if they have a favorable safety profile, the environmental fate of metallic nanomaterials needs to be tracked to avoid unintended ecological consequences. Repeated high-dose applications of metallic nanoparticles result in the build-up of silver in topsoils, which may be detrimental to keystone soil microbial communities, such as nitrogen-fixing bacteria and mycorrhizal fungi (Conder et al., 2008). In addition, the potential for nanoparticle accumulation within plant tissues to be transferred trophically and threaten food chain safety needs to be carefully evaluated. Regulatory agencies, such as the European Food Safety Authority (EFSA), have developed stringent safety limits for the use of silver nanomaterials in food

and agricultural applications. These safety standards, when incorporated into optimized dosing schedules and standardized application procedures, are necessary for the commercial viability of nano-fungicides (Beek et al., 2001).

### **Conclusion**

Green-synthesized silver nanoparticles (AgNPs) are a potential eco-friendly, cost-effective, and sustainable alternative to chemical fungicides for the control of cereal smut and bunt diseases. Green synthesis uses botanical and microbial reducing and capping agents, avoiding hazardous chemical reductants and generating stable, bioactive AgNPs with broad-spectrum antifungal activity. These nanoparticles function via several simultaneous processes: cell wall and membrane disruption, induction of oxidative stress, enzyme inactivation, DNA damage, and interference with cAMP signaling, which significantly decreases the chances of resistance development. Formulations like chitosan-silver nanocomposites and seed nanopriming strategies facilitate enhanced targeted delivery, provide sustained protection, and offer additional agronomic benefits such as improved germination, seedling vigor, and nutrient uptake. AgNPs selectively target ergosterol-containing fungal membranes, and their lower ecotoxicity compared to chemically synthesized nanoparticles makes them a safer option for host crops and non-target organisms. However, challenges remain in terms of long-term environmental fate, the potential for silver accumulation in soils and plant tissues, and compliance with regulatory limits (e.g., EFSA). Standardized synthesis protocols, field-scale efficacy validation in various agroecosystems, thorough ecotoxicological risk assessment, and optimized dosing regimens should inform future research directions. With appropriate development and regulatory framework, green AgNP-based nano-fungicides can play a significant role in integrated disease management, food security, and sustainable cereal production globally.

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