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MECHANISM OF USING NANOPARTICLES IN PLANT DISEASE CONTROL

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SUMMARY

Nanomaterials and their use can be powerful tools for managing plant resistance and disease control and could play a remarkable role in the agrotechnological revolution. Addressing food supply issues using modern methods also requires increased efficiency and in-depth understanding of their impact on the environment and humans. Furthermore, it is also critical for producers to ensure the sustainable use of such technologies and understand their mechanism of action, cost-effectiveness, and ease of use. The concerned study aimed to examine the modern approaches for improving the use of nanoparticles in plant disease management and control. Several methods for producing and analyzing nanoparticles, as well as their application in plant pathology, were in focus. The results associated with the synthesis of silver, copper, and zinc oxide nanoparticles were notable, with their morphology, structure, and biological activity also studied. Nanoparticles (<40 nm) appeared to exhibit the highest fungicidal activity against *Fusarium oxysporum, Alternaria solani, Phytophthora infestans,* and *Helminthosporium turcicum.* The study described mechanisms of nanoparticles' antimicrobial activities, proposing improved approaches for their beneficial use in plant protection.

Keywords: Nanoparticles, plant diseases, silver, copper, zinc oxide, fungicidal activity, nanotechnology, environment and human's health

Key findings: Metals and metal-oxide nanoparticles (AgNPs, CuNPs, ZnONPs, and FeNPs) (<40 nm) exhibited robust antifungal activity against primary phytopathogens through membrane damage and reactive oxygen species (ROS) generation. The integration of AgNPs + ZnONPs revealed the highest efficacy, providing 90%–95% pathogen suppression with enhanced seed germination.

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INTRODUCTION

In the agriculture sector, plant diseases are the challenging problems causing considerable yield reduction (20%–40%) in various crop plants annually. The widespread prevalence of fungal pathogens (*Fusarium, Alternaria, Phytophthora,* and *Helminthosporium*) requires new, highly effective, environmentally friendly, and safe methods of protection. In the present era, nanotechnology has emerged as a promising area of phytosanitary management due to the high biological activity of nanomaterials, their ability to penetrate pathogen cellular structures, and the formation of stable antimicrobial barriers (Singh *et al.,* 2021; Chen *et al.,* 2026).

Phytosynthesized nanoparticles demonstrated robust antifungal activity through various mechanisms, including disruption of cell wall integrity, induction of reactive oxygen species (ROS), mitochondrial dysfunction, DNA damage, and inhibition of spore germination and mycelial growth (Trzcinska-Wencel *et al.,* 2023). Past studies reported plant-mediated silver and metal oxide nanoparticles exhibited broad-spectrum antifungal activities with reduced environmental toxicity compared with conventional fungicides (Parveen *et al.*, 2023).

Nanoparticles also enhance plant defense responses by activating antioxidant enzymes and modulating stress-related signaling pathways, proving them as promising candidates for sustainable crop protection strategies. The development of innovative agricultural technologies capable of simultaneously ensuring food security for humanity and preserving the potential of natural resources in the biosphere is a strategically important area for developing countries. With limited land and water resources, as well as the increasing impact of climate change, the transition to sustainable and highly efficient agricultural production models has become essential (Parveen *et al.,* 2023).

Modern agroecosystem management methods, including precision farming, biotechnology solutions, the use of nanomaterials, integrated crop protection systems, and digitalization of production processes, can considerably enhance crop yields, optimize resource consumption, and minimize the ecological footprint (Sharma *et al.*, 2023; Fei *et al.,* 2025). Thus, exploring agriculture scientifically and technologically could ensure a significant contribution to developing a sustainable food system highly adaptable to existing environmental stress factors, rational use of natural resources, and long-term environmental stability (Singh *et al.,* 2025).

Engineered nanomaterials (ENMs) range from 1 to 100 nm in size and include metalloids, metal oxides, nonmetals, and carbon nanomaterials. Their smallest size authenticates their unique properties, such as large surface area and high reactivity. Nanomaterials can also have specific functions and entail development for biosensor uses, such as plant disease diagnostics and as delivery systems for target substances (nucleic acids and agrochemicals). Numerous studies have demonstrated that engineered nanomaterials can be more effective at delivering agrochemicals and genetic elements, potentially reducing their environmental dispersion. Furthermore, nanomaterials enhance plants' defense mechanisms against various plant pathogens. Based on the above discussion, the timely study aimed to examine and improve the mechanism of using nanoparticles in the fight against plant diseases by optimizing the methods of obtaining, analyzing, and applying nanosystems. (Khan *et al*., 2022; Perveen *et al*., 2023).

Accordingly, nanomaterials have emerged as promising tools for enhancing plant resistance and managing plant diseases, with the potential to contribute significantly to modern agricultural development. However, their application requires careful consideration of environmental safety, mechanisms of action, cost-effectiveness, and practical usability. Recent studies have demonstrated that nanoparticles, such as silver, copper, and zinc oxide, exhibit strong antimicrobial activity against major plant pathogens, including *Fusarium oxysporum, Alternaria solani, Phytophthora infestans,* and *Helminthosporium* *turcicum*. These effects are mainly due to membrane disruption, oxidative stress induction, and metabolic inhibition. Despite these advances, further optimization is still necessary to ensure their safe and efficient use in plant disease management. The following study also aimed to investigate modern approaches to the synthesis, characterization, and application of nanoparticles in plant disease management, as well as to evaluate their antimicrobial activity and mechanisms of action against major phytopathogens.

MATERIALS AND METHODS

Chemicals and reagents

In the following experiment, the inorganic metal salts—silver nitrate ($AgNO_3$), copper sulfate ($CuSO_4$), zinc chloride ($ZnCl_2$), and iron(III) chloride ($FeCl_3$)—served as precursors for nanoparticle synthesis. The study used plant extracts of aloe, green tea, and garlic as natural bioreductants and biocatalysts. Polyvinylpyrrolidone (PVP) and gelatin also served as stabilizing and shape-controlling agents to ensure colloidal stability and controlled nanoparticle morphology.

The use of phytopathogenic fungi (*F. oxysporum, A. solani, P. infestans,* and *H. turcicum*) sought to evaluate the antifungal activity in vitro. Wheat, maize, tomato, and potato crops were visibly highly susceptible to these pathogens; thus, their selection as model plants (Keinath *et al*., 2023). Nanoparticle characterization, as performed, used UV–Vis spectroscopy, transmission electron microscopy (TEM), atomic force microscopy (AFM), dynamic light scattering (DLS), and X-ray diffraction (XRD). Auxiliary equipment included centrifuges and pH meters to control the existing conditions involved in the synthesis.

Synthesis of nanoparticles

Nanoparticle synthesis used biogenic, chemical, and physical processes to obtain materials with controlled size and morphology. Biogenic synthesis employed plant extracts rich in polyphenols and antioxidants as reducing agents, enabling environmentally friendly nanoparticle formation at room temperature. The said process produced nanoparticles predominantly in the 10–40 nm range with high colloidal stability (Mohamed *et al*., 2021).

Physical methods included laser ablation of metal targets in aqueous media and ultrasonic dispersion, producing high-purity nanoparticles without chemical reagents. Chemical synthesis involved the reduction of metal salt solutions with citric acid at 60 °C–80 °C, followed by stabilization with PVP, resulting in AgNPs, CuNPs, ZnONPs, and FeNPs, with sizes of 20–60 nm and uniform morphology (Piesik *et al*., 2024; Baka, 2025).

Characterization of nanoparticles

The UV–Vis absorption spectra recording was in the 200–800 nm range to recognize the nanoparticle formation. Metallic nanoparticles (AgNPs and CuNPs) reached identification by their characteristic surface plasmon resonance (SPR) bands (AgNPs ≈ 420 nm; CuNPs ≈ 560 nm). The ZnONPs revealed a robust absorption peak in the UV region (≈ 365 nm) corresponding to excitonic transitions typical of semiconductor nanostructures. The FeNPs showed a characteristic absorption peak ≈ 370 nm in the UV-Vis region, indicating the formation of iron nanoparticles. The photon energy calculation employed the Einstein–Planck equation.

Fungal strains and culture conditions

The procurement of phytopathogenic fungi *F. oxysporum*, *A. solani*, *P. infestans*, and *H. turcicum* came from a certified microbiological collection. Fungal cultures entailed maintenance on potato dextrose agar (PDA) at 25 °C ± 2 °C under standard laboratory conditions.

Application methods and biological evaluation

Applying synthesized nanoparticles as colloidal solutions, suspensions, and nanocomposite formulations used seed treatment, foliar spraying, soil application, and in vitro assays. Their nanoscale size ensured effective penetration into plant tissues and direct interaction with pathogen cells, leading to membrane disruption, enzyme inhibition, and metabolic impairment (Malandrakis *et al*., 2022).

The incorporation of nanoparticles also ensued into biopolymer matrices (PVP, chitosan, gelatin, and alginate) to enhance the stability and provide controlled release of active ions. These nanocomposite coatings succeeded in their application to seeds and foliage to improve the germination and stress resistance and protect plants against soil- and air-borne pathogens (Alghuthaymi *et al*., 2022). Recent advances in unmanned aerial vehicle (UAV)-assisted delivery systems have further expanded the applicability of such formulations, enabling precise and efficient deployment of biological agents and encapsulated materials under field conditions (Rysbekova *et al*., 2025).

Methods of nanoparticle application

Seed treatment involved immersion or spraying of seeds with aqueous nanoparticle suspensions, followed by controlled drying. This approach enhanced the enzymatic activity, water uptake, and early seedling development and provided prolonged protection against the pathogens, viz., *F. oxysporum, A. solani, P. infestans,* and *H. turcicum* (Paraguay-Delgado *et al*., 2022).

Foliar application ensured direct contact of nanoparticles with leaf surfaces and phytopathogens. Nanoparticles AgNPs, CuNPs, ZnONPs, and FeNPs induced ROS formation, disrupted pathogen membranes, inhibited respiratory enzymes, and suppressed further fungal growth and development, while also enhancing the photosynthetic activity and antioxidant responses in crop plants (Mohamed *et al*., 2021).

Soil application of nanoparticles as suspensions and polymer-nanocomposites enabled uniform distribution in the rhizosphere, suppression of soil-borne pathogens, improved nutrient availability, and stimulation of root development. Stabilized nanoparticles provided prolonged ion release and enhanced plant stress tolerance, evaluating effectiveness through microbiological, biochemical, and morphometric analyses (Veronica *et al*., 2021; Sharma *et al*., 2023).

Nanocomposite films based on biopolymers (PVP, chitosan, gelatin, and alginate) incorporating nanoparticles (AgNPs, CuNPs, ZnONPs, and FeNPs) formed stable protective coatings on seeds and leaves, allowing controlled ion release and long-term fungistatic effects. Further assessment of their performance used spectroscopy, microscopy (TEM, AFM), mechanical testing, and bioassays (Zudyte and Luksiene, 2021; Bilesky-José *et al*., 2021; Fujikawa *et al*., 2021; Salam *et al*., 2026; Cao and Tan, 2026).

RESULTS AND DISCUSSION

The XRD analysis confirmed the purity phase of synthesized nanoparticles and enunciated the characteristic crystallographic features of nanomaterials: for AgNPs and CuNPs, intense reflections corresponding to the face-centered cubic (fcc) structure with typical reflection planes (111), (200), and (220) were evident, revealing the highest level of crystallinity and absence of secondary phases. The diffraction profile of ZnONPs showed a set of peaks, characteristic of the hexagonal wurtzite (hcp) structure, including the planes (100), (002), and (101), confirming the anatase-like hexagonal symmetry and the stability of the crystalline phase of zinc oxide.

Nanoparticles' mechanism of action

The fungal cell walls' destruction is one of the key mechanisms of the antifungal action of nanoparticles, since metallic nanostructures (AgNPs, CuNPs, ZnONPs, and FeNPs) having the highest specific surface area and pronounced catalytic activity actively interact with cell membrane components. These disrupt the integrity of the lipid bilayer, peptide glycan framework, and structural polysaccharides (chitin and β-glucans). Consequently, it leads to mechanical rupture of the membrane, the formation of nanopores, loss of osmotic balance, and subsequent leakage of cytoplasmic contents outside the cell, accompanied by the complete death of pathogenic fungi. Rizwana *et al.'s* (2023) findings demonstrated that AgNPs caused severe structural deformation and pore formation in the cell walls of *Candida* and plant-pathogenic fungi, ultimately leading to cytoplasmic leakage and cell collapse. Their electron microscopy analyses confirmed the direct fastening of nanoparticles to chitin-rich regions of the fungal wall (Rizwana *et al*., 2023).

Moreover, a previous study reported that ZnONPs and CuNPs induced significant membrane permeability variations in *Fusarium* spp. associated with a β-glucan disruption and oxidative membrane damage. The said study also concluded a nanoscale size (<50 nm) enhanced the surface reactivity, thereby amplifying antifungal efficiency, which greatly supported these present findings (Trzcinska-Wencel *et al*., 2023).

In the antimicrobial action of nanoparticles, the generation of reactive oxygen species (ROS) is an important mechanism. Since the metal nanostructures (AgNPs, CuNPs, ZnONPs, and FeNPs), having a catalytic surface and the ability to induce photocatalytic and electrochemical reactions, initiate the formation of ROS, including superoxide anions, hydroxyl radicals, and hydrogen peroxide. These then penetrate pathogen cells and cause oxidative damage to membrane lipids, proteins, and nucleic acids. Furthermore, they disrupt cellular metabolic pathways and membrane potential, which leads to induced apoptosis, cytoplasmic degradation, and subsequent death of fungal cells (Yao *et al.,* 2021).

Consistent with the presented findings, a previous study demonstrated the nanoparticle ZnONPs generate substantial levels of intracellular ROS in fungal pathogens, leading to lipid peroxidation and mitochondrial dysfunction. The said study further confirmed oxidative stress was a primary driver of growth inhibition and suppression of the spore germination (Shojaei *et al.,* 2025). Similarly, Salam *et al.* (2026) reported an exposure to AgNP triggered excessive ROS accumulation in *Botrytis cinerea* and *F. oxysporum*, resulting in DNA fragmentation and enzyme inactivation. Their study further emphasized that nanoscale particle size considerably enhanced the redox activity, thereby strengthening antifungal performance, and these past findings emerged as greatly analogous to the latest results (Salam *et al.,* 2026).

The binding of nanoparticles to the DNA of pathogens is a key mechanism of their antimicrobial action, since metal nanoparticles (AgNPs, CuNPs, ZnONPs, and FeNPs), having the highest surface energy and a positive charge, enable a quick adsorption on nucleic acids. Subsequently, they form robust complex interactions with nitrogenous bases and phosphate groups, which leads to blocking of DNA replication and transcription processes. In turn, it disrupts mRNA and protein synthesis, arrests the cell cycle, and ultimately, the death of fungal cells occurs.

Supporting this mechanism, Hosny *et al.* (2025) reported that AgNPs penetrate fungal cells and interact directly with genomic DNA, causing structural alterations and inhibition of DNA replication. Their spectroscopic and molecular analyses also confirmed the binding of nanoparticles with phosphate backbones and purine bases. Likewise, Prasad *et al.'s* (2024) findings demonstrated nanoparticle ZnONPs and CuNPs induced genotoxic stress in phytopathogenic fungi by promoting DNA fragmentation and suppressing transcriptional activities. The said past study concluded that nanoparticle-DNA interactions played a decisive role in cell cycle arrest and antifungal lethality, corroborating the presented findings.

Despite their effectiveness in plant disease control, the environmental safety and potential toxicity of engineered nanoparticles remain vital concerns. Given their small size and high reactivity, nanoparticles, such as AgNPs, CuNPs, and ZnONPs, may interact with non-target organisms, including beneficial soil microorganisms, plants, and aquatic biota, potentially disrupting ecosystem balance (Wassie and Yemata, 2025; Kalu *et al*., 2026). Additionally, the release of metal ions (e.g., Ag^{+} and Cu^{2+}) could induce oxidative stress, membrane damage, and enzymatic inhibition in non-target species at elevated concentrations (Singh *et al*., 2026; Vijayalakshmi *et al*., 2025). Environmental factors, such as pH, organic matter content, and redox conditions, further influence nanoparticle stability, transformation, and mobility, thereby affecting their bioavailability and toxicity (Islam, 2025). Therefore, although nanoparticles offer significant advantages in agricultural applications, their careful use should be optimal to minimize ecological risks. Furthermore, future studies should focus on long-term ecotoxicological assessment, dose regulation, and the development of environmentally safe and biodegradable nanomaterials.

Nanoparticles to control plant diseases

In the antimicrobial activities of nanoparticles, the catalytic destruction of pathogen spores is an essential component, since metal nanostructures (AgNPs, CuNPs, ZnONPs, and FeNPs) revealed the high specific surface area and the ability to act as catalytic centers. Likewise, they induce the formation of locally highly reactive chemical species, including ROS and hydroxyl radicals, which interact with the protective shells of spores, destroying multilayer polysaccharide-protein structures and disrupting hydration and osmotic stability. This leads to the destruction of membrane barriers, inhibition of germination, and death of spore-forming cells, providing a long-term fungistatic effect in the soil and rhizosphere environment (Yugay *et al.,* 2021).

Similarly, reports of photocatalytic and catalytic nanomaterials have stated to keep inactive the resistant spores through oxidative and surface-mediated mechanisms. Enhanced spore inactivation kinetics were evident with nanoscale catalysts due to their higher surface reactivity and radical generation capacity, confirming the crucial role of catalytic nanostructures in antimicrobial spore destruction (Allahverdy and Jafari, 2026).

This relevant research comprised the synthesis of physical and biogenic metal nanoparticles (Ag, Cu, ZnO, and Fe) using plant extracts, chemical reduction with citric acid, and physical methods (laser ablation, ultrasonic dispersion), obtaining stable colloidal systems with controlled particle sizes (10–60 nm). These nanoparticles were distinct with the highest morphological homogeneity, spherical and slightly elliptical shape, as well as low aggregation due to stabilization with polyvinylpyrrolidone and biopolymers. The UV spectroscopy revealed characteristics of surface plasmon resonances for AgNPs (420 nm), CuNPs (560 nm), ZnONPs (365 nm), and FeNPs (375 nm). TEM allowed visualization of the distribution and shape of nanoparticles at the nanoscale, AFM established the surface topography and the degree of aggregation, and DLS revealed the hydrodynamic diameter and polydispersity. Meanwhile, XRD determined the phase composition and the degree of crystallinity and crystallographic structures of the synthesized nanomaterials. This confirmed the successful formation of nanoparticles with desired physicochemical properties suitable for subsequent application in phytopathology and agrotechnology (Piesik *et al*., 2024; Baka, 2025).

The four test tubes show the colloidal solutions of the synthesized nanoparticles: AgNPs, CuNPs, ZnONPs, and FeNPs (from left to right) (Figure 1). Each sample exhibited a color characteristic of the corresponding nanoparticle type, confirming their successful synthesis. From left to right, the first test tube contains AgNPs, which exhibit a typical yellow-brown hue due to surface plasmon resonance of silver in the 400–450 nm range. The second test tube, containing CuNPs, has a rich reddish color characteristic of copper plasmon absorption in the 560–600 nm range. The third test tube contains ZnONPs, with a milky white solution due to intense scattering of light by ZnO nanocrystals. The fourth test tube on the right end displays a dark brown shade, corresponding to the FeNPs colloid, which is typical of metallic iron with a thin oxide shell. The color differences revealed the colloidal stability of the nanoparticles and confirmed the successful synthesis of each type of nanostructure (Table 1) (Mohamed *et al*., 2021; Paraguay-Delgado *et al*., 2022).

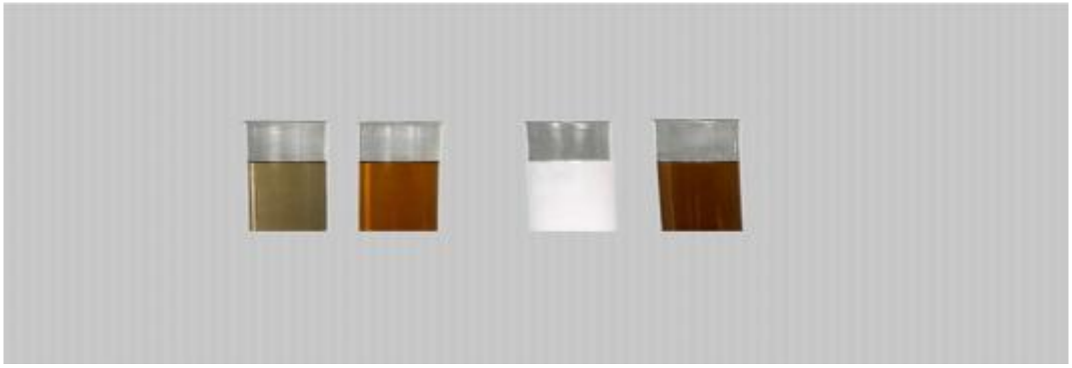

Figure 1. Test tubes with colloidal solutions of synthesized nanoparticles: AgNPs, CuNPs, ZnONPs, and FeNPs.

Table 1. Characteristics of synthesized nanoparticles.

Type of nanoparticles	Method	Size (nm)	Stability	Color of the solution
AgNPs	chemical	25–40	high	yellow-brown
CuNPs	ablation	30–60	very high	reddish
ZnONPs	biosynthesis	20–50	average	lactic
FeNPs	chemical	20–50	average	dark brown

Method for obtaining AgNPs, and the chemical method consisted of the following: reactor → reducing agent → stabilizer → nanoparticles.

In the studied nanoparticles, the obtained UV spectra demonstrated the formation of characteristic electronic absorption bands reflecting the features of interband transitions, the degree of expression of the quantum-size effect, and the stability of the colloidal dispersion. The observed main absorption considerably corresponds to the energy gap between the valence and conduction bands (band gap) and exhibited a shift to the short-wavelength region (blue shift), which recognized reduced particle sizes and an increase in quantum-size effects. The symmetry of the bands and the values of its half-width disclosed a morphological homogeneity, a low degree of aggregation, and a narrow particle size distribution. Meanwhile, the stability of the optical density over time confirmed the effectiveness of surface passivation and system stabilization with polyvinylpyrrolidone (PVP), which prevents agglomeration of nanoparticles and ensures long-term colloidal stability (Shojaei *et al.,* 2025; Salam *et al.,* 2026).

An SPR peak characteristic for silver nanoparticles emerged with the range of ≈400–450 nm, corresponding to resonant collective oscillations of free electrons on the silver surface. The peak's narrow shape revealed a monodispersed distribution and the absence of significant aggregation. The peak's position confirmed the successful synthesis of AgNPs without side phases and impurities. Copper nanoparticles exhibited a broad absorption band with a range of ≈560–600 nm, typical for SPR CuNPs. The absence of additional bands associated with copper oxide (CuO, peak typically ≈280–320 nm) enunciated that the synthesis was clean and the reduced particles were metallic in nature. The bandwidth was due to the highest reactivity of copper and partial surface passivation (Yoo *et al.,* 2021; Trzcinska-Wencel *et al*., 2023).

The nanoparticle ZnONPs exhibited an intense peak at ≈360–380 nm, corresponding to an interband transition and typical of nanostructured zinc oxide. The shift of the peak relative to bulk ZnO (≈385 nm) was due to a quantum-size effect. A Tauc plot revealed an enhanced band gap (≈3.3–3.5 eV), authenticating the nanoscale nature of the particles. Iron nanoparticles (FeNPs) were characteristic of a broad and weak absorption band ranging at ≈250–300 nm, which may refer to the absence of a pronounced SPR characteristic of noble metals. Iron has the highest optical absorption capacity and magnetic properties, resulting in a smoothed spectrum without narrow resonance maxima. The slight broadening of the absorption band may be ascribable to the surface oxidation and superparamagnetic nature of FeNPs, which is a typical trait of iron in contact with air. The spectral features confirmed the successful synthesis of dispersed iron nanoparticles without significant aggregation and the formation of distinct oxide phases (Shojaei *et al*., 2025; Hosny *et al.,* 2025).

The simulated UV–Vis spectral plots, along with the corresponding wavelength maxima and frequency–wavelength relationship for each type of nanoparticle, appear as above (Figure 1). The characteristic absorption maxima were noticeably at approximately 430 nm for AgNPs, 580 nm for CuNPs, 370 nm for ZnONPs, and 275 nm for FeNPs. The observed absorption peaks were consistent with previously reported values for these nanostructures, confirming successful nanoparticle synthesis and the absence of secondary phases and significant impurities. The stability of the optical density over time and the absence of additional absorption bands revealed an effective surface stabilization and high colloidal stability of the nanoparticles suspension.

By using TEM, the morphological characterization displayed predominantly spherical and quasi-spherical nanoparticles with a narrow size distribution and uniform dispersion. Nonsignificant agglomeration was evident, which further confirmed the stability of the synthesized nanomaterials and the controllability of the synthesis process. Morphological characteristics observed with nanoparticle TEM analysis revealed that the synthesized nanoparticles possess different geometric configurations, determined by the nature of the material and nucleation conditions. The AgNPs were characteristic of a predominantly spherical morphology with a smooth surface and narrow size distribution. The CuNPs exhibited a polyhedral shape, including cubic, octahedral, and truncated structures, found associated with the anisotropic growth of copper crystal planes. The ZnONPs form clearly defined hexagonal nanocrystals, typical of the wurtzite structure of ZnO, confirming directional growth along the c-axis and the highest degree of crystallinity (Figure 1) (Rizwana *et al.,* 2023; Prasad *et al.,* 2024).

The XRD analysis confirmed the phase purity of the synthesized nanoparticles and demonstrated the characteristic crystallographic features of the materials. For nanomaterials AgNPs and CuNPs, intense reflections corresponding to the face-centered cubic (fcc) structure with typical reflection planes (111), (200), and (220) were notable, indicating the highest levels of crystallinity and the absence of secondary phases. The diffraction profile of ZnONPs showed a set of peak characteristics of the hexagonal wurtzite (hcp) structure, including the planes (100), (002), and (101), confirming the anatase-like hexagonal symmetry and stability of the crystalline phase of zinc oxide. Similarly, ZnO nanoparticles were typical to adopt a hexagonal wurtzite crystal structure, where reflections from the planes (100), (002), and (101) dominate the diffraction pattern. Earlier reports have also confirmed that the sharpness and intensity of these peaks proved associated with crystallite stability and high structural order, supporting the structural integrity observed in this present study (Piesik *et al*., 2024; Baka, 2025).

The use of metal and oxide nanoparticles revealed the pronounced antimicrobial and fungistatic effects against the main pathogens of vegetable and grain crops. The nanoparticles AgNPs, CuNPs, and ZnONPs and their combination (AgNPs + ZnONPs) exhibited varied levels of inhibitory activity associated with their structural features, surface reactivity, and mechanism of interactions with fungal cellular components.

Table 2. Efficacy of nanoparticles against pathogens.

Pathogens	AgNPs	CuNPs	ZnONPs	FeNPs	Combination Ag+ZnO
F. oxysporum	78%	65%	54%	58%	91%
A. solani	72%	59%	47%	52%	86%
P. infestans	68%	70%	51%	55%	88%
H. turcicum	75%	73%	56%	60%	89%

The silver nanoparticles (AgNPs) displayed the most pronounced fungicidal activity due to the release of Ag^+ ions, the generation of ROS, and disruption of the fungal cell membrane (Table 2). The nanoparticles effectively inhibited the growth of pathogens *F. oxysporum* and *A. solani,* resulting in hyphal deformation, cell wall destruction, and reduced sporulation. The nanoparticles enunciated a robust anti-oomycete effect against the *P. infestans*. In *H. turcicum*, the nanoparticles caused lysis of conidia and delayed spore germination (Bakry *et al*., 2024).

The copper nanoparticles (CuNPs) showed a pronounced antifungal activity due to the ability of Cu^+/Cu^{2+} to ionize and undergo Fenton reactions, inducing oxidative stress in the cells. However, the highest effect resulted against *H. turcicum* and *A. solani*. The results further revealed that moderate but stable inhibition of *F. oxysporum* growth was evident. The activity of the nanoparticles CuNPs' inhibition against *P. infestans* was lower than that of AgNPs; however, significant suppression of mycelium remained. The mechanism of action of zinc oxide nanoparticles (ZnONPs) indicated an association with photocatalytic activity, ROS formation, and damage to membrane lipids. The ZnONPs effectively suppressed the *F. oxysporum* by impairing membrane potential and permeability. Moderate activity was noteworthy against *A. solani.* Against *P. infestans*, effectiveness increases in the presence of light (photocatalysis) upon observation. The zinc oxide nanoparticles showcased moderate fungistatic activity against the *H. turcicum.*

The integration of AgNPs and ZnONPs has a synergistic effect, enhancing ROS generation and disrupting pathogen metabolism through multiple pathways simultaneously (Kamal *et al.,* 2023). Maximum inhibition of mycelial growth (85%–95%) was visible against *F. oxysporum*. Against *P. infestans*, the combination of the above two nanomaterials outperformed compared with their individual use. A consistent synergistic effect with pronounced hyphal destruction manifested against the pathogens *A. solani* and *H. turcicum.*

The difference between the treated and untreated plots can be visible in the dramatic reduction in damage with the application of the nanoparticle combination. Overall, with nanoparticle application, the germination rose by 12%–18% with seed treatment, and plant infestation decreased by 50%–90%, depending on the pathogen. Maximum effectiveness was successful with the combination of AgNPs and ZnONPs. Studies on Ag- and ZnO-based nanocomposites further demonstrated extensive hyphal shrinkage, cytoplasmic leakage, and inhibition of spore germination in *Fusarium* and *Alternaria* species. The results revealed synergistic nanoparticle interactions intensify the structural and metabolic damage in fungal pathogens.

CONCLUSIONS

The timely study demonstrated the successful synthesis of metal and metal-oxide nanoparticles using biogenic approaches, resulting in stable colloidal systems with controlled nanoscale dimensions. The comprehensive physicochemical characterization confirmed their high crystallinity, phase purity, and morphological uniformity, as evidenced by XRD, UV–Vis spectroscopy, TEM, AFM, and DLS analyses. Biological assays revealed all tested nanoparticles exhibited significant antifungal activity against major phytopathogens, including *F. oxysporum*, *A. solani*, *P. infestans*, and *H. turcicum*. The antimicrobial effects showed a primary association with the generation of ROS, membrane disruption, enzymatic inhibition, and DNA damage, leading to growth suppression and cell death. Among the tested materials, AgNPs showed the highest individual antifungal activity, while ZnONPs demonstrated strong photocatalytic effects. The combined application of AgNPs and ZnONPs exhibited a pronounced synergistic effect, achieving up to 90% inhibition of fungal growth and significantly enhancing plant protection efficiency. Overall, the results confirm that engineered nanoparticles represent highly effective agents for plant disease control. Their multifunctional mechanisms and strong bioactivity highlight their potential for integration into sustainable and environmentally oriented agricultural practices.

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