***Review Article***

**Nanotechnology in Plant Disease Management – Applications of Nanoparticles in Pathogen Control**

**Abstract**

Plant diseases remain one of the most critical constraints in global agriculture, contributing to substantial crop losses and posing a threat to food security. Conventional disease management strategies are increasingly limited by environmental concerns, the development of resistant pathogen strains, and inefficiencies in delivery and targeting. In this context, nanotechnology offers a revolutionary platform for sustainable and efficient plant disease management. Nanoparticles (NPs), owing to their unique physicochemical properties, have demonstrated potent antimicrobial activity against fungal, bacterial, viral, and nematode pathogens. Metal-based NPs such as silver (AgNPs), copper (CuNPs), and zinc oxide (ZnO NPs), carbon-based nanomaterials like carbon nanotubes (CNTs) and graphene oxide (GO), as well as biodegradable polymer-based NPs like chitosan, play crucial roles in pathogen inhibition. Their mechanisms of action include physical disruption of pathogen structures, reactive oxygen species (ROS) generation, interference with DNA and enzyme activity, immune modulation, and targeted delivery of agrochemicals. Furthermore, green synthesis approaches enhance biocompatibility and environmental safety. Despite their promise, the widespread application of NPs faces challenges such as phytotoxicity, environmental persistence, and lack of regulatory frameworks. This review critically examines the types, mechanisms, and pathogen-specific applications of nanoparticles in agriculture, while also addressing current limitations and future perspectives for integrating nanotechnology into sustainable crop protection.

**Keywords: Nanoparticles, Plant disease management, Antimicrobial nanomaterials, Green synthesis, Pathogen control**

**Introduction**

Plant diseases pose a persistent threat to global agricultural productivity and food security, affecting an estimated 20–40% of crop yields annually (Savary et al., 2019). Traditional plant disease management strategies, which include chemical pesticides, biological control agents, and cultural practices, have played a critical role in mitigating the impact of pathogens. However, these conventional methods are increasingly facing limitations such as the emergence of pesticide-resistant pathogens, environmental pollution, and negative effects on non-target organisms (Chhipa, 2019). Moreover, the indiscriminate and excessive use of agrochemicals has led to residual toxicity in ecosystems, raising serious concerns regarding sustainability and human health (Kah et al., 2013). In this context, nanotechnology has emerged as a revolutionary tool in agriculture, offering novel and sustainable approaches to enhance plant disease management. Nanotechnology involves the manipulation and application of materials at the nanoscale, typically between 1 and 100 nanometers, where materials exhibit unique physical, chemical, and biological properties (Khot et al., 2012; Devi et al., 2023a). The integration of nanotechnology in agriculture has led to the development of nanoparticles (NPs) that can serve multiple roles (Muthukumar et al., 2023), including pathogen detection, targeted delivery of agrochemicals, and direct antimicrobial action (Elmer & White, 2018). Among the various nano-enabled innovations, the application of nanoparticles in plant disease control has gained significant attention due to their high surface area, increased reactivity, and ability to penetrate biological membranes.

Nanoparticles used in plant pathology can be broadly classified into metal-based (e.g., silver, copper, zinc oxide), carbon-based (e.g., carbon nanotubes, graphene oxide), polymer-based, and lipid-based nanoparticles (Chen & Yada, 2011). Metal-based nanoparticles, particularly silver nanoparticles (AgNPs), have demonstrated potent antimicrobial properties against a wide range of phytopathogens, including fungi, bacteria, and viruses (Jo et al., 2009). These nanoparticles disrupt microbial cell membranes, interfere with enzyme activity, and generate reactive oxygen species (ROS), leading to cell death (Sharma et al., 2022). Copper nanoparticles (CuNPs) and zinc oxide nanoparticles (ZnO NPs) also exhibit strong antifungal and antibacterial properties and are being explored as nano-fungicides and nano-bactericides, respectively (Dimkpa et al., 2013; Ramesh et al., 2014). The use of nanoparticles in plant disease management is not limited to their antimicrobial activities. Nanoparticles can also function as carriers for controlled and targeted delivery of conventional fungicides or biocontrol agents, thereby enhancing their efficacy and reducing the required dosage (Kah et al., 2018a). Such nano-formulations improve the solubility, stability, and bioavailability of active ingredients while minimizing environmental contamination. For instance, encapsulation of fungicides in polymeric nanoparticles allows for slow and sustained release, which is particularly useful in managing soil-borne pathogens (Torney et al., 2007). Additionally, nanotechnology facilitates the development of nano-biosensors for early detection of plant pathogens, enabling timely and precise disease management interventions (Gogos et al., 2012).

An important aspect of nanoparticle-based disease management is the biosynthesis of nanoparticles using plant extracts, microbes, and other biological agents, known as green synthesis. This eco-friendly approach minimizes the use of hazardous chemicals and enhances the biocompatibility of nanoparticles (Iravani, 2011; Laishram et al., 2024). Green-synthesized nanoparticles have shown considerable potential in inhibiting plant pathogens and are being actively investigated as sustainable alternatives to synthetic agrochemicals. Despite the promising applications, the use of nanoparticles in agriculture is not without challenges. Concerns regarding nanotoxicity, accumulation in the food chain, impact on soil microbiota, and long-term ecological consequences must be carefully addressed (Kah & Hofmann, 2014). Additionally, regulatory frameworks for the safe use of nanomaterials in plant protection are still in nascent stages in many countries. Therefore, a comprehensive understanding of nanoparticle behavior, fate, and interactions in agroecosystems is crucial for developing safe and effective nano-enabled plant protection strategies.

This review aims to provide an in-depth overview of the recent advancements in the use of nanoparticles for managing plant diseases. It explores various types of nanoparticles, their mechanisms of action against pathogens, methods of synthesis, delivery systems, and potential risks. By highlighting the opportunities and challenges of nanoparticle-based plant disease management, this paper seeks to contribute to the development of sustainable and innovative solutions in modern agriculture.

**2. Types of Nanoparticles Used in Plant Disease Management**

Nanotechnology has introduced a new era of precision in plant disease management by offering materials at the nanoscale that exhibit unique physicochemical properties, including high surface area, increased reactivity, and tunable functionalities (Devi et al., 2023b). These nanoparticles (NPs) can directly inhibit plant pathogens or act as carriers for conventional pesticides and biocontrol agents, improving the efficacy, stability, and target specificity of disease control strategies (Kah et al., 2013; Elmer & White, 2018) and also antimicrobial activities (Khan et al., 2024). Depending on their composition and mode of synthesis, nanoparticles used in agriculture can be categorized into metal and metal oxide nanoparticles, carbon-based nanomaterials, and polymer-based or biogenic nanoparticles. Each of these types plays a distinctive role in plant disease suppression through diverse mechanisms such as oxidative stress induction, physical disruption of pathogen cell walls, and interference with microbial DNA and protein function.

**2.1 Metal and Metal Oxide Nanoparticles**

Metal-based nanoparticles have been extensively studied for their antimicrobial properties and represent one of the most common groups of nanomaterials in plant disease management. Their nanoscale dimensions allow them to penetrate microbial cells, interfere with critical biomolecular processes, and ultimately lead to pathogen death (Chhipa, 2019). Among these, silver, copper, zinc oxide, and titanium dioxide nanoparticles are particularly noteworthy.

**Silver Nanoparticles (AgNPs):** Silver nanoparticles are among the most widely investigated metal nanoparticles due to their potent broad-spectrum antimicrobial activity. AgNPs exhibit multiple modes of action, including the disruption of microbial cell walls and membranes, interaction with sulfur- and phosphorus-containing biomolecules, and induction of reactive oxygen species (ROS) that damage cellular components (Jo et al., 2009; Sharma et al., 2022). These mechanisms make AgNPs effective against a wide range of plant pathogens, including bacteria such as *Xanthomonas campestris* and fungi such as *Botrytis cinerea* and *Fusarium oxysporum*. Their nanoscale nature ensures uniform distribution on plant surfaces, enhancing contact with pathogens while minimizing the amount required.In addition to their direct antimicrobial role, AgNPs have been shown to stimulate plant defense responses by inducing systemic acquired resistance (SAR), which primes plants for improved resistance against subsequent pathogen attacks (Salem et al., 2016). However, challenges such as cost of synthesis and potential phytotoxicity need to be addressed for their large-scale agricultural use.

**Copper Nanoparticles (CuNPs):** Copper has long been used in agriculture as a fungicide, but its nanoscale form provides superior efficacy at lower doses. Copper nanoparticles (CuNPs) disrupt microbial metabolic processes by binding to DNA and proteins, leading to enzymatic inactivation and oxidative stress (Ramesh et al., 2014). Studies have reported strong antibacterial effects of CuNPs against *Pseudomonas syringae* and antifungal activity against *Alternaria alternata* and *Phytophthora infestans* (Gogos et al., 2012).Moreover, CuNPs are less prone to inducing resistance in pathogens compared to conventional copper-based agrochemicals due to their multifaceted mode of action. However, excessive application may lead to copper accumulation in the soil, impacting microbial diversity and soil health, thereby necessitating regulated application.

**Zinc Oxide (ZnO) and Titanium Dioxide (TiO₂) Nanoparticles:** Zinc oxide (ZnO) and titanium dioxide (TiO₂) nanoparticles are known for their photocatalytic properties, which make them especially effective under UV or visible light. These nanoparticles generate reactive oxygen species (ROS) that can damage microbial lipids, proteins, and nucleic acids, leading to pathogen death (Dimkpa et al., 2013). ZnO NPs have been reported to suppress the growth of fungal pathogens like *Aspergillus niger* and *Rhizoctonia solani*, while TiO₂ NPs have demonstrated antibacterial activity against *Erwinia carotovora* and *Ralstonia solanacearum* (Chowdhury et al., 2017).The photocatalytic disinfection ability of these nanoparticles makes them ideal for surface sterilization of seeds, foliage, and agricultural tools. Furthermore, ZnO is a vital micronutrient for plants, which provides additional benefits when delivered in nano-form, including enhanced plant growth and yield.

**2.2 Carbon-Based Nanomaterials**

Carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene oxide (GO) have emerged as multifunctional tools in plant disease management. These materials possess high tensile strength, chemical stability, and electrical conductivity, making them suitable for various applications, including pathogen inhibition and agrochemical delivery.

**Carbon Nanotubes (CNTs):** CNTs have demonstrated antimicrobial activity against both fungal and bacterial phytopathogens. Their cylindrical nanostructure can physically puncture microbial membranes or walls, leading to leakage of intracellular contents and cell death (Begum et al., 2011). Moreover, CNTs can act as nano-carriers for fungicides or RNA-based gene-silencing molecules, improving delivery efficiency and reducing off-target effects (Torney et al., 2007).

**Graphene Oxide (GO):** Graphene oxide, with its large surface area and functional groups, interacts with microbial cell membranes through electrostatic forces, resulting in membrane stress and oxidative damage. GO sheets have been found to inhibit fungal pathogens like *Sclerotinia sclerotiorum* and *Fusarium solani* (Saraswat et al., 2021). Additionally, GO's ability to adsorb and deliver molecules makes it a promising candidate for smart delivery systems that respond to environmental cues, such as pathogen presence or pH changes.

**2.3 Polymer-Based and Biogenic Nanoparticles**

While metal and carbon-based nanoparticles are effective, concerns about their environmental impact have driven interest in biocompatible and biodegradable nanomaterials. Polymer-based nanoparticles, especially those synthesized through green chemistry routes, are increasingly preferred for their safety and sustainability.

**Chitosan Nanoparticles:** Chitosan, a natural polymer derived from chitin, is widely used to synthesize chitosan nanoparticles (CNPs). These nanoparticles offer biodegradability, non-toxicity, and film-forming capabilities, making them suitable for foliar sprays and seed coatings. CNPs exhibit antifungal and antibacterial properties by disrupting microbial membranes and inducing ROS generation (Badawy & Rabea, 2011). Moreover, chitosan is known to elicit plant defense mechanisms by activating pathogenesis-related (PR) proteins, enhancing resistance to various pathogens. Its dual function as a growth promoter and disease suppressant makes CNPs valuable in integrated disease management programs.

**Green-Synthesized Nanoparticles:** Green synthesis of nanoparticles using plant extracts, bacteria, fungi, and algae provides an eco-friendly and cost-effective alternative to chemical synthesis. These biogenic nanoparticles often exhibit enhanced stability and reduced toxicity due to surface functionalization with biomolecules from the biological source (Iravani, 2011). For example, silver and copper nanoparticles synthesized using neem (*Azadirachta indica*) or tulsi (*Ocimum sanctum*) extracts have shown strong antimicrobial effects against plant pathogens (Singh et al., 2015). The green synthesis approach aligns well with sustainable agriculture goals and can be scaled using locally available biomass, reducing production costs and ecological footprint.

**3. Mechanisms of Action**

Nanoparticles (NPs) employed in plant disease management act through multiple, often synergistic, mechanisms that make them highly effective against a broad spectrum of plant pathogens. Their nanoscale size, high surface-area-to-volume ratio, and unique physicochemical properties enable them to interact intimately with both pathogens and host plant systems. Unlike traditional agrochemicals, nanoparticles can achieve improved bioavailability, targeted delivery, and multi-functional activity, reducing the amount required and minimizing off-target effects (Kah et al., 2013; Elmer & White, 2018).

The modes of action of nanoparticles in plant disease control can be broadly categorized into three main types: direct antimicrobial activity, modulation of plant immune responses, and targeted delivery of active compounds. Understanding these mechanisms is crucial for designing next-generation nanoparticle-based plant protection products that are both efficient and environmentally sustainable.

**3.1 Direct Antimicrobial Activity**

One of the most widely studied and utilized mechanisms of nanoparticles in plant disease management is their direct antimicrobial activity. Nanoparticles can inhibit the growth or kill plant pathogens—bacteria, fungi, and viruses—through various pathways, including physical disruption of microbial structures, DNA damage, inhibition of enzymatic activity, and induction of oxidative stress via reactive oxygen species (ROS) (Rai et al., 2009; Jo et al., 2009).

**a) Physical Disruption of Cell Membranes:** Several nanoparticles, particularly metal-based ones like silver (AgNPs), copper (CuNPs), and zinc oxide (ZnO) nanoparticles, have been observed to interact directly with the cell walls and membranes of microbial pathogens. These interactions can lead to structural disintegration, increased membrane permeability, and subsequent leakage of intracellular contents, effectively neutralizing the pathogen (Choi & Hu, 2008). For example, AgNPs attach to the bacterial cell wall and penetrate the membrane, causing structural changes such as pitting and shrinkage. This leads to loss of vital ions and cellular contents, ultimately resulting in cell death (Morones et al., 2005). Similar effects have been observed in fungal pathogens, where nanoparticles disrupt hyphal integrity and spore germination (Elamawi et al., 2018a).

**b) DNA Damage and Protein Interaction:** Nanoparticles can penetrate microbial cells and interact with nucleic acids, leading to DNA fragmentation and inhibition of replication and transcription. Metal ions released from nanoparticles, such as Ag⁺ or Cu²⁺, can bind to sulfur- and phosphorus-containing groups in DNA and proteins, thereby impairing critical cellular functions (Sondi & Salopek-Sondi, 2004).Additionally, nanoparticles inhibit enzymes essential for microbial metabolism. For instance, AgNPs have been shown to inactivate enzymes involved in ATP production and cell wall synthesis, resulting in cellular energy deficits and structural failure (Lemire et al., 2013).

**c) Generation of Reactive Oxygen Species (ROS):** A key mode of nanoparticle-induced pathogen toxicity is the generation of ROS, such as hydroxyl radicals (•OH), superoxide anions (O₂•⁻), and hydrogen peroxide (H₂O₂). These highly reactive species cause oxidative stress, damaging cellular components including lipids, proteins, and DNA (Dimkpa et al., 2013). Photocatalytic nanoparticles like ZnO and TiO₂ are especially effective in this regard. Upon exposure to UV or visible light, they become photoactivated and generate ROS on their surfaces, which directly attack nearby microbial cells (Kumar et al., 2018). This mechanism has proven effective in controlling a range of pathogens on plant surfaces, seeds, and agricultural tools.

**3.2 Immune System Modulation**

Beyond their direct antimicrobial effects, nanoparticles can also influence the plant immune system, enhancing the plant's ability to resist or tolerate pathogen attacks. This modulation involves the activation of plant defense pathways, leading to systemic acquired resistance (SAR) and induced systemic resistance (ISR) (Choudhary et al., 2017).

**a) Induction of Plant Defense Pathways:** Certain nanoparticles, such as chitosan nanoparticles (CNPs), silver nanoparticles, and biogenic metal nanoparticles, have been shown to act as elicitors—compounds that trigger plant immune responses. These nanoparticles stimulate the production of pathogenesis-related (PR) proteins, phytoalexins, and defensive enzymes like peroxidase, polyphenol oxidase, and β-1,3-glucanase (Badawy & Rabea, 2011; Abdel-Aziz et al., 2016). For example, foliar application of CNPs in tomato plants infected with *Alternaria solani* led to significant upregulation of defense-related genes and reduced disease symptoms (El-Sharkawy et al., 2017). Similarly, AgNPs have been found to enhance the activity of antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT), helping plants cope with oxidative stress during infection.

**b) Systemic Resistance:** Nanoparticles can induce systemic resistance, providing protection beyond the site of application. In some studies, nanoparticle treatments have been shown to prime plants, a phenomenon where a plant's immune system is put in a heightened state of alert, enabling a faster and stronger response upon actual pathogen invasion (Dutta et al., 2021). This priming effect enhances disease tolerance while minimizing energy expenditure on constitutive defense mechanisms. Thus, nanoparticles not only act against pathogens directly but also enhance host resilience, making them a valuable component of integrated disease management strategies.

**3.3 Targeted Delivery**

One of the most transformative advantages of nanotechnology in agriculture is the ability to deliver active compounds—such as fungicides, bactericides, or RNA interference (RNAi) molecules—in a targeted and controlled manner. This enhances the bioavailability and persistence of agrochemicals while minimizing environmental contamination and non-target effects (Kah et al., 2013).

**a) Controlled Release of Active Ingredients:** Nanoparticles can encapsulate or adsorb active ingredients and release them gradually in response to environmental triggers such as pH, temperature, or enzymatic activity. This controlled release ensures sustained protection over time and reduces the frequency and quantity of application (Ghormade et al., 2011). For instance, polymeric nanoparticles, such as those made from chitosan, alginate, or PLGA, are often used to encapsulate fungicides or antimicrobial peptides. These nanocarriers release their payload slowly, ensuring long-lasting activity against pathogens (Kumar et al., 2019). In a study by Devkar et al. (2020), chitosan nanoparticles loaded with hexaconazole showed prolonged antifungal activity against *Fusarium oxysporum*, reducing disease severity and improving crop yield.

**b) Site-Specific Targeting:** Certain nanocarriers can be functionalized to specifically target infection sites, reducing off-target effects and enhancing efficacy. This targeting can be passive—based on size and charge—or active, involving ligand-receptor interactions. For example, lectin-conjugated nanoparticles have been developed to recognize and bind to specific glycoproteins on pathogen surfaces, delivering toxic agents directly to the target (Torney et al., 2007). Moreover, carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene oxide (GO) are being investigated as vehicles for RNAi delivery to silence pathogen-specific genes. This precision-guided control strategy represents the future of plant pathogen management with minimal collateral impact.

**4. Applications in Controlling Specific Pathogens**

Nanoparticles (NPs) have emerged as potent agents in plant disease management due to their unique physicochemical properties, enabling them to interact with and inhibit a wide range of plant pathogens. This section delves into the specific applications of various NPs in controlling fungal, bacterial, viral pathogens, and nematodes, highlighting their mechanisms of action and efficacy.

**4.1 Fungal Pathogens**

Fungal diseases significantly impact crop yields worldwide. Traditional fungicides often face challenges such as resistance development and environmental concerns. NPs, particularly silver (AgNPs) and copper nanoparticles (CuNPs), have demonstrated strong antifungal properties against various phytopathogenic fungi.

**Silver Nanoparticles (AgNPs):** AgNPs exhibit broad-spectrum antifungal activity. Studies have shown their effectiveness against Fusarium oxysporum, a pathogen causing wilt in tomatoes, by disrupting fungal cell membranes and generating reactive oxygen species (ROS) that lead to cell death (Elamawi et al., 2018b). Similarly, AgNPs have been effective against Aspergillus species, inhibiting spore germination and mycelial growth (Khan et al., 2022). In tomatoes, AgNPs synthesized using neem leaf extract enhanced resistance against early blight caused by Alternaria solani, reducing disease severity and improving plant growth (Siddiqui et al., 2023).

**Copper Nanoparticles (CuNPs):** CuNPs have also shown antifungal activity by interacting with fungal DNA and proteins, leading to structural and functional disruptions. Their application has resulted in the inhibition of fungal pathogens in crops like rice and wheat, although specific studies detailing their efficacy against Fusarium, Aspergillus, and Alternaria species are limited and warrant further research (Wang et al., 2016).

**4.2 Bacterial Pathogens**

Bacterial infections in plants, caused by pathogens such as Xanthomonas, Pseudomonas, and Erwinia species, lead to significant agricultural losses. NPs like zinc oxide (ZnO) and chitosan have been explored for their antibacterial properties.

**Zinc Oxide Nanoparticles (ZnO NPs):** ZnO NPs possess strong antibacterial activity due to their ability to generate ROS and disrupt bacterial cell membranes. They have been effective against both Gram-positive and Gram-negative bacteria. For instance, ZnO NPs synthesized with chitosan as a stabilizing agent exhibited enhanced antibacterial activity, attributed to the synergistic effects of ZnO and chitosan (Arunachalam et al., 2018).

**Chitosan Nanoparticles (CNPs):** Chitosan, a natural polymer, exhibits inherent antimicrobial properties. When formulated into nanoparticles, chitosan's efficacy against bacterial pathogens improves due to increased surface area and better interaction with microbial cells. Chitosan/ZnO nanocomposites have shown selective antibacterial activity, effectively inhibiting the growth of Escherichia coli and Staphylococcus aureus (Kumar et al., 2020).

**4.3 Viral Pathogens**

Plant viruses pose a significant threat to global agriculture, often leading to substantial yield losses. NPs offer innovative approaches to manage viral infections through direct antiviral activity and as carriers for antiviral agents.

**Direct Antiviral Activity:** AgNPs have demonstrated the ability to interfere with viral replication and coat protein formation. By binding to viral particles, AgNPs can inhibit their attachment and entry into host cells, effectively reducing infection rates (Rai et al., 2024).

**Nanoparticles as RNAi Carriers:** RNA interference (RNAi) is a promising strategy for controlling plant viruses. NPs can serve as carriers for RNAi molecules, protecting them from degradation and facilitating their delivery into plant cells. This approach has been effective against various plant viruses, including cucumber mosaic virus and potato virus Y (Singh et al., 2022).

**4.4 Nematodes**

Plant-parasitic nematodes, such as root-knot nematodes (Meloidogyne spp.), are detrimental to crop health. NPs have shown potential as nematicidal agents through direct toxicity and by inducing plant defense mechanisms.

**Silver Nanoparticles (AgNPs):** AgNPs have exhibited nematicidal activity by penetrating the nematode cuticle and disrupting nerve transmission, leading to paralysis and death. Studies have reported significant mortality rates in nematodes exposed to AgNPs, highlighting their potential as effective nematicides (Patil et al., 2024).

**Chitosan Nanoparticles (CNPs):** CNPs have also demonstrated nematicidal properties. Their mode of action includes disrupting the nematode's cuticle integrity and interfering with its physiological processes. Additionally, CNPs can induce systemic resistance in plants, enhancing their defense against nematode attacks (Mansoori et al., 2018).

**5. Advantages Over Conventional Methods**

The adoption of nanotechnology in plant disease management presents several advantages over traditional agrochemical-based approaches. These benefits span efficacy, environmental safety, resistance management, and synergy with biological systems.

**Lower Dosage Requirements:** Nanoparticles offer enhanced bioavailability and reactivity due to their high surface area-to-volume ratio. This allows for the use of significantly lower concentrations compared to conventional agrochemicals while maintaining or even improving efficacy (Kah et al., 2019). For instance, silver nanoparticles have demonstrated antifungal activity at micro- to nano-scale concentrations, drastically reducing the required dosage compared to standard fungicides (Elamawi et al., 2018a).This reduction in dosage minimizes the amount of active ingredient entering the environment, potentially lowering costs and reducing adverse effects on non-target organisms (Sekhon, 2014).

**Reduced Environmental Pollution:** Conventional pesticides often suffer from leaching, volatilization, and non-specificity, leading to environmental contamination. In contrast, nanoparticle formulations can be designed for slow release and targeted delivery, reducing the frequency and volume of application (Kah et al., 2013). Chitosan-based nanoparticles, for example, degrade naturally and pose minimal ecological risk while providing controlled pathogen suppression (Kumar et al., 2020). Moreover, the encapsulation of active agents within biodegradable polymer matrices ensures that release occurs only under specific environmental or biological triggers, preventing unnecessary exposure (Grillo et al., 2014).

**Lower Risk of Resistance Development:** Repeated use of chemical pesticides often results in the evolution of resistant pathogen strains. Nanoparticles, particularly metallic ones like AgNPs and ZnO NPs, exhibit multi-target modes of action including membrane disruption, oxidative stress induction, and interference with DNA and protein functions (Jo et al., 2009). This multifaceted attack reduces the likelihood of resistance development.Additionally, nanoparticles can be co-formulated with existing agrochemicals or antimicrobial peptides, enhancing their performance and mitigating resistance risks by rotating or combining modes of action (Rai & Ingle, 2012).

**Enhanced Plant Growth and Nutrient Uptake:** Beyond pathogen control, certain nanoparticles have demonstrated growth-promoting effects. Zinc oxide and iron oxide nanoparticles, for instance, enhance nutrient uptake by improving root development and enzymatic activity in plants (Dimkpa et al., 2017). Similarly, chitosan nanoparticles stimulate the production of phytohormones and secondary metabolites, bolstering plant vigor (Kumar et al., 2020). These dual functions—disease control and growth enhancement—position nanotechnology as a multifunctional tool for sustainable agriculture.

**Synergistic Action with Biocontrol Agents and Other Inputs:** Nanoparticles can complement biological control agents by improving their stability, survivability, and delivery. For instance, nano-encapsulation of Trichoderma spp. or Bacillus spp. in polymer-based carriers has enhanced their viability and performance under field conditions (Saharan et al., 2013). Additionally, nanoparticles can act as carriers for signalling molecules, such as salicylic acid or jasmonic acid, that prime plant defences and improve the efficacy of integrated pest management strategies (Ghormade et al., 2011). The integration of nanotechnology with organic amendments, biofertilizers, and other sustainable practices offers a promising route to reduce chemical inputs and enhance agroecosystem resilience.

**6. Challenges and Concerns**

Despite the promising applications of nanoparticles (NPs) in plant disease management, their widespread adoption is hindered by a number of significant challenges and concerns. These issues span toxicological risks, environmental implications, regulatory bottlenecks, and economic constraints, all of which must be addressed to ensure the safe and effective integration of nanotechnology in agriculture.

**Toxicological Effects:** The potential toxicity of NPs is one of the most pressing concerns associated with their use in agricultural systems. While many studies highlight the antimicrobial efficacy of NPs, they also report adverse effects on non-target organisms, including beneficial soil microbes, insects, animals, and even humans.Silver nanoparticles (AgNPs), for instance, though highly effective against pathogens, have been shown to negatively impact nitrogen-fixing bacteria and mycorrhizal fungi essential for soil health (Chinnamuthu and Kokiladevi, 2013). Similar findings have been reported for zinc oxide (ZnO) and copper nanoparticles (CuNPs), which may disrupt microbial community structures and enzymatic activities in the rhizosphere (Kumar et al., 2020). In addition, several in vitro and in vivo studies suggest that prolonged exposure to NPs can lead to oxidative stress, DNA damage, and inflammation in mammalian systems (Singh et al., 2018). These toxic effects raise concerns about the long-term implications for farmworkers and consumers, especially in the absence of rigorous safety evaluations and exposure thresholds.

**Environmental Fate:** Another significant concern relates to the environmental fate and persistence of NPs. Unlike conventional agrochemicals that degrade over time, many NPs exhibit high stability and low degradability, leading to their accumulation in soil and water bodies.Studies have demonstrated that engineered nanoparticles can persist in agricultural fields, potentially altering soil physicochemical properties and affecting nutrient cycling (Rastogi et al., 2019). Additionally, leaching of NPs into groundwater and surface water systems can disrupt aquatic ecosystems, affecting microbial and algal populations essential for ecological balance (Ma et al., 2010).Moreover, the transformation of NPs in the environment—through processes like dissolution, aggregation, and interaction with organic matter—can modify their bioavailability and toxicity, complicating risk assessment efforts (Gogos et al., 2012). There is a critical need for long-term ecotoxicological studies to understand the implications of nanoparticle accumulation and mobility in agricultural landscapes.

**Regulatory Hurdles:** The regulatory landscape for nanoparticle use in agriculture remains underdeveloped and fragmented. Most countries lack standardized protocols and clear guidelines for the testing, labeling, and approval of nanomaterials used in plant protection.Unlike conventional pesticides, which are subject to well-defined regulatory frameworks, NPs often fall into a gray area where their unique properties are not adequately accounted for by existing laws. This regulatory ambiguity poses challenges for researchers and manufacturers seeking to commercialize nanoparticle-based products (Kah et al., 2018b).Furthermore, the absence of harmonized international standards for nanoparticle characterization and safety assessment hampers global trade and collaboration. There is an urgent need for coordinated efforts among regulatory bodies, researchers, and industry stakeholders to develop risk assessment methodologies tailored to nanomaterials (Parisi et al., 2015).

**Cost and Scalability:** The high production costs of nanoparticles and associated technologies also limit their scalability and accessibility, particularly for smallholder farmers in developing regions. Synthesis methods such as chemical vapor deposition, sol-gel techniques, and laser ablation, though effective, are often energy-intensive and expensive (Nair et al., 2010).While green synthesis methods using plant extracts and biological agents offer a more sustainable alternative, these approaches are still in the experimental phase and face challenges related to reproducibility, stability, and large-scale implementation (Khan and Rizvi, 2014).In addition to production costs, the need for specialized equipment, storage conditions, and trained personnel further adds to the economic burden. Without substantial investments in research, infrastructure, and capacity-building, the widespread adoption of nano-enabled plant protection strategies may remain out of reach for many agricultural communities.

**7. Future Prospects and Research Directions**

As the agricultural sector confronts the mounting challenges of climate change, pest resistance, and food security, nanotechnology holds immense promise for revolutionizing plant disease management. However, realizing this potential requires a focused research agenda and strategic policy interventions. The following subtopics highlight key areas that future research and development should address.

**Developing Biodegradable and Environmentally Benign Nanoparticles**

One of the critical limitations of current nanomaterials is their environmental persistence and potential toxicity. Future research should aim to design and develop biodegradable, eco-friendly nanoparticles that degrade into harmless byproducts after fulfilling their function.Biogenic and polymer-based nanoparticles, such as those synthesized using chitosan, cellulose, and other natural polymers, represent a promising direction. These materials offer inherent biodegradability and compatibility with biological systems, reducing risks to non-target organisms and environmental compartments (Kumar et al., 2020). Moreover, green synthesis techniques using plant extracts or microbial agents can minimize the use of hazardous chemicals in nanoparticle production (Khan and Rizvi, 2014).Advancements in surface functionalization and nanocarrier design may also contribute to the development of targeted-release mechanisms, further enhancing the environmental safety of nanoparticle applications (Nair et al., 2010).

**Elucidating Nanoparticle–Microbe–Plant Interactions through Omics Approaches**

Understanding the complex interactions between nanoparticles, plants, and microbial communities is essential for developing safe and effective nanoformulations. Integrative omics approaches—including genomics, transcriptomics, proteomics, and metabolomics—can provide valuable insights into the molecular and physiological responses elicited by nanoparticles. For instance, transcriptomic studies can reveal how nanoparticles influence gene expression related to plant immunity, stress tolerance, and nutrient uptake (Tripathi et al., 2017). Proteomics can identify protein pathways that are modulated in response to nanomaterial exposure, while metabolomics can uncover changes in plant secondary metabolites that mediate disease resistance or toxicity responses. These multi-omics approaches, when combined with high-throughput screening techniques, can significantly accelerate the discovery of nanoparticle formulations that are both effective and biologically safe (Tiwari et al., 2019).

**Integrating Nanotechnology with Precision Agriculture and AI for Smart Disease Diagnostics and Management**

The convergence of nanotechnology, precision agriculture, and artificial intelligence (AI) presents transformative opportunities for plant disease management. Future research should explore the integration of nanosensors, AI algorithms, and real-time data analytics to develop intelligent systems for early disease detection and targeted intervention. Nanosensors, capable of detecting specific pathogens or stress markers at the molecular level, can be embedded in plant tissues or soil to provide continuous monitoring of crop health (Bhattacharyya et al., 2020). These sensors, when connected to IoT platforms and powered by machine learning models, can enable predictive diagnostics and automated decision-making, optimizing input usage and minimizing losses. Furthermore, AI-driven platforms can process large datasets generated from drone imagery, field sensors, and remote sensing to map disease outbreaks and guide the precise application of nanoparticle-based treatments (Basu et al., 2021). This synergy between nanotechnology and digital agriculture has the potential to improve efficiency, sustainability, and profitability in farming systems.

**Establishing Safety Guidelines and Regulatory Frameworks to Facilitate Field Applications**

To transition nanotechnology from laboratory research to field-scale implementation, there is a pressing need for comprehensive safety guidelines and regulatory frameworks. Currently, the lack of standardized testing protocols and approval procedures poses significant barriers to the commercialization of nanoparticle-based agro-products. Future efforts should focus on developing internationally harmonized risk assessment methodologies that account for the unique physicochemical properties of nanomaterials (Parisi et al., 2015). These guidelines should encompass environmental risk, human health impact, exposure pathways, and residue limits in food products. Public-private partnerships and multi-stakeholder dialogues involving scientists, policymakers, industry players, and farmers are essential for creating a transparent regulatory ecosystem. In addition, investment in education and training programs can build the technical capacity needed to implement and monitor nano-enabled interventions responsibly (Kah et al., 2018a).

**Conclusion**

Nanotechnology has opened a new frontier in plant disease management by offering highly effective, multifunctional, and environmentally conscious alternatives to traditional chemical pesticides. Nanoparticles demonstrate a broad spectrum of antimicrobial activities and can be tailored for targeted delivery, controlled release, and enhanced plant immune responses. Their application has shown promising results against various plant pathogens including fungi, bacteria, viruses, and nematodes, especially through the use of AgNPs, CuNPs, ZnO NPs, carbon-based nanostructures, and biogenic polymer carriers such as chitosan. While the potential benefits are substantial—including reduced chemical input, lower environmental contamination, and enhanced crop resilience—challenges persist. Concerns over nanoparticle toxicity, accumulation in ecosystems, effects on non-target organisms, and insufficient regulatory oversight need to be addressed with rigorous research and policy development. Furthermore, scalability, cost-effective green synthesis methods, and interdisciplinary collaboration will be crucial for translating lab-scale successes into field-ready solutions. Future directions should focus on the integration of nanotechnology with precision agriculture and AI-enabled diagnostics, the development of biodegradable and eco-friendly nanoparticle formulations, and the establishment of international safety and regulatory standards. As research in this field matures, nanotechnology holds the promise to redefine sustainable agriculture and revolutionize the way we approach crop protection in an era of climate change and global food insecurity.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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