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# Can Nanoparticles Protect Crops? A Review of Nanotechnology-Based Approaches to Plant Disease Management

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**SUMMARY**

Plant diseases caused by fungi, bacteria, and viruses remain a major threat to global agricultural productivity, and conventional pesticide use is increasingly associated with pathogen resistance and environmental harm. Nanotechnology has emerged as a promising alternative, offering nanoparticles such as silver, copper, zinc oxide, titanium dioxide, and silica with unique physicochemical properties that enable close interaction with microbial cells and plant tissues. These nanoparticles can disrupt microbial membranes, generate reactive oxygen species, and interfere with pathogen metabolism, while also modulating plant immune signaling pathways. Beyond direct antimicrobial activity, nanoparticles are being explored as carriers for agrochemicals and nucleic acids and as components of diagnostic biosensors. This review synthesizes current evidence on nanoparticle-mediated crop protection, highlighting mechanisms of action, applications, and the safety and environmental considerations that must guide the field toward sustainable, precision-based disease management.

## INTRODUCTION

Plant diseases caused by fungal, bacterial, and viral pathogens are among the most persistent constraints to agricultural productivity worldwide, contributing to substantial yield losses and threatening food security (Hajji-Hedfi & Chhipa, 2021). For decades, chemical pesticides and antimicrobial agents have served as the primary line of defense against these pathogens. However, intensive and prolonged reliance on conventional agrochemicals has driven the emergence of pathogen resistance, contaminated soil and water systems, and produced harmful non-target effects on beneficial organisms (Hajji-Hedfi & Chhipa, 2021). These limitations have created an urgent need for alternative, more sustainable strategies for plant disease management. Nanotechnology has emerged over the past two decades as one of the most promising avenues for addressing this challenge. Engineered nanoparticles possess distinctive physicochemical characteristics, including a high surface-area-to-volume ratio, tunable surface charge, and enhanced chemical reactivity, that distinguish them from their bulk material counterparts (Muhammad et al., 2026). These properties allow nanoparticles to interact intimately with microbial cells and plant surfaces at a scale not achievable by conventional agrochemical formulations. As a result, nanomaterials such as silver, copper, zinc oxide, titanium dioxide, and silica nanoparticles are increasingly being investigated for their capacity to inhibit plant pathogens directly while also offering new platforms for pesticide delivery, disease diagnosis, and crop monitoring. This paper reviews the current state of knowledge on nanoparticle-based approaches to plant disease management. It examines the mechanisms through which nanoparticles exert antimicrobial activity and modulate plant defense responses, surveys their emerging applications as delivery vehicles and biosensor components, and considers the safety, phytotoxicity, and environmental concerns that must be resolved before these technologies can be deployed at scale.

### Mechanisms of Antimicrobial Action

The antimicrobial activity of nanoparticles against plant pathogens is governed by their composition, size, and surface chemistry. Depending on these characteristics, nanoparticles can disrupt microbial cell membranes, catalyze the generation of reactive oxygen species, release antimicrobial metal ions, and interfere with essential metabolic pathways within the pathogen (Ogwu & Izah, 2025). Collectively, these mechanisms inhibit pathogen growth, suppress spore germination, and reduce the capacity of fungi, bacteria, and viruses to establish infection in host plant tissue. Because several of these mechanisms act simultaneously and non-specifically on cellular structures, nanoparticles may also reduce the likelihood of pathogens developing resistance compared with single-target conventional pesticides.

**Modulation of Plant Immune Responses**

The role of nanoparticles extends beyond the direct killing or inhibition of pathogens. Emerging evidence indicates that certain nanomaterials can influence plant signaling networks involving reactive oxygen species, calcium ion fluxes, phytohormones, and the expression of defense-related genes (Muhammad et al., 2026). By priming or amplifying these pathways, nanoparticles may strengthen a plant's innate immune response, enabling a more rapid and robust reaction upon pathogen attack. This dual mode of action, direct antimicrobial effect combined with immune modulation, distinguishes nanoparticle-based strategies from most conventional pesticides and positions them as a potentially more holistic tool for disease management.

**Applications as Delivery Systems and Diagnostic Tools**

Beyond their intrinsic antimicrobial and immunomodulatory properties, nanoparticles are being actively developed as carriers for pesticides, nutrients, and nucleic acids, enabling more targeted and controlled release of active agents at the site of infection (Dutta et al., 2022; Hajji-Hedfi & Chhipa, 2021). Such nanocarrier systems can reduce the total quantity of agrochemical required, minimize off-target environmental exposure, and improve the efficiency of treatment. In parallel, nanoparticles are being incorporated into nanobiosensors capable of the early and sensitive detection of plant pathogens, offering the potential to identify infections before visible symptoms appear (Dutta et al., 2022). Nanohybrid antifungal systems, which combine nanoparticles with other bioactive or structural components, represent a particularly active area of research aimed at improving both the efficacy and the sustainability of antifungal treatments (Guiqiu et al., 2026).

**Safety, Phytotoxicity, and Environmental Considerations**

Despite these promising applications, the deployment of nanoparticles in agriculture requires careful evaluation of efficacy, phytotoxicity, and environmental safety. Nanoparticle size, morphology, surface chemistry, concentration, and aggregation behavior can all strongly influence biological activity, meaning that formulations effective against pathogens must also be assessed for unintended toxicity to plants (Hajji-Hedfi & Chhipa, 2021; Ogwu & Izah, 2025). Furthermore, the interactions of nanoparticles with beneficial soil microorganisms, broader soil ecosystems, and edible plant tissues remain incompletely understood and require further investigation. Encouragingly, research is increasingly progressing from laboratory-based antimicrobial assays toward whole-plant experiments, field validation trials, controlled-release delivery systems, and integration with molecular diagnostics and precision agriculture platforms, reflecting a maturing and more translational phase of the field.

**Future Perspectives**

Looking ahead, nanotechnology is likely to be increasingly integrated with biosensors, artificial intelligence, molecular biology, and precision farming systems to enable a more targeted crop-protection strategy encompassing early disease detection, accurate pathogen identification, localized treatment, and continuous monitoring of plant health (Dutta et al., 2022; Guiqiu et al., 2026). Rather than serving as a wholesale replacement for conventional pesticides, nanoparticles are more likely to become integral components of broader precision and sustainable crop-protection systems, provided that their long-term environmental and food-safety implications are thoroughly established through continued research (Hajji-Hedfi & Chhipa, 2021; Guiqiu et al., 2026).

## CONCLUSION

Nanoparticle-based strategies offer a multifaceted approach to plant disease management, combining direct antimicrobial activity with the capacity to enhance plant immune responses, deliver agrochemicals more precisely, and support early pathogen detection. Nanoparticles such as silver, copper, zinc oxide, titanium dioxide, and silica have demonstrated meaningful potential against fungal, bacterial, and viral pathogens, and nanohybrid systems in particular are advancing the field toward more effective and sustainable disease control. Nevertheless, realizing this potential at scale will depend on resolving outstanding questions regarding phytotoxicity, environmental fate, and interactions with beneficial organisms and food systems. With continued research bridging laboratory findings, field validation, and integration with precision agriculture and diagnostic technologies, nanotechnology is well positioned to become a valuable component of sustainable crop-protection strategies in the years ahead.

**REFERENCES**

Dutta, P., Kumari, A., Mahanta, M., Biswas, K. K., Dudkiewicz, A., Thakuria, D., Abdelrhim, A. S., Singh, S. B., Muthukrishnan, G., Sabarinathan, K. G., Mandal, M. K., & Mazumdar, N. (2022). Advances in nanotechnology as a potential alternative for plant viral disease management. Frontiers in Microbiology, 13, Article 935193. https://doi.org/10.3389/fmicb.2022.935193

Guiqiu, L., Lirong, Z., Hui, Y., Lihua, W., Yi, C., Xuemei, L., & Jinkui, Y. (2026). Nanohybrid antifungals for control of plant diseases: Current status and future perspectives. Journal of Fungi, 12(8), Article 595. https://doi.org/10.3390/jof12080595

Hajji-Hedfi, L., & Chhipa, H. (2021). Nano-based pesticides: Challenges for pest and disease management. Euro-Mediterranean Journal for Environmental Integration, 6, Article 69. https://doi.org/10.1007/s41207-021-00279-y

Muhammad, B. M., Munazza, L., Rafia, L., Jintao, S., Luqiong, Temoor, A., Muhammad, N., Ahmad, S., Xuqing, L., & Bin, L. (2026). Nanotechnology-based strategies for sustainable management of bacterial plant diseases: Mechanisms, applications, and future directions. Environmental Science: Nano, 13(2), 723–747. https://doi.org/10.1039/d5en00936g

Ogwu, M. C., & Izah, S. C. (2025). Nanotechnology for fungal pathogen control in crops: Innovations, public health impacts, and disease prevention. Frontiers in Fungal Biology, 6, Article 1653214. https://doi.org/10.3389/ffunb.1653214