

Nano-Enabled Strategies for Combating Plant Pathogens: Mechanisms and Applications

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Introduction

Phytopathogens including fungi, bacteria, viruses and nematodes have been serious threat to the various field and horticultural crops which led to significant reduction in the crop productivity and food security. Plant-pathogen interaction is a dynamic process involving the intricate physiological, biochemical and molecular responses. Conventional control practices involve use of chemicals which pose considerable impact on the human health as well as development of pesticide-tolerant pathogens. Demand of eco-friendly and sustainable management practices for disease mitigation has led researchers to think about modern strategies, while minimizing the impact of chemicals on the environment.

In Recent times, utilizing nanoparticles to combat pathogen attacks and augment plant immunity emerged as revolutionary step for plant disease management. NPs have gained attention due to their unique physicochemical properties and exceptional versatility. Recent studies show that NPs can enhance the plant immunity and reduce disease susceptibility. For instance, it has been concluded that manganese and copper NPs at a concentration of 100

µg/mL, stimulate innate immune responses in watermelon plants against bacterial fruit blotch and Fusarium wilt respectively. This article emphasizes the various roles of NPs in sustainable crop disease management. The purpose of this research is to provide a thorough understanding of the mechanisms underlying the NP-mediated modulation of plant immunity as well as the effects of NPs on different crops.

Mechanisms

NPs have emerged as versatile tools in the realm of disease management, offering novel approaches to combat phytopathogens and mitigate the devastating impacts of plant diseases. The unique physicochemical characteristics of NPs, such as their small size, surface area-to-volume ratio and catalytic potential—NPs can act as powerful antimicrobial agents by interfering with the growth, multiplication and infection process of pathogens and as modulators of plant immunity by controlling important defense-related pathways to increase resistance to pathogens. New developments in this study have brought attention to the various ways that NPs manage diseases and their efficiency countering phytopathogens (Table 1).

Table 1

S No	Nano-particles	Nanoparticles Properties	Target Pathogens	Host Plants	Mechanisms
1	Silver (AgNPs)	Small size allows easy entry bacterial especially into cells, gram negative bacteria. Generates reactive oxygen species (ROS), inhibits DNA/RNA synthesis, disrupts cell membranes. Size, shape and surface charge affect antimicrobial efficiency.	<i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i>	Tomato	Inhibited mycelial growth by inducing significant structural damages
			<i>Pectobacterium carotovorum</i>	Sugar beet	Activated antioxidative defense for suppressing soft rot disease
			<i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	Rice	Inhibited disease incidence by activating plant antioxidative defense system
			<i>Acidovorax oryzae</i>	Rice	Inhibited pathogen survival, biofilm formation, and swarming motility
2	Copper (CuNPs)	Cu-based compounds are ancient antifungals. Release of Cu ions causes ROS production, membrane damage and enzyme malfunction.	<i>Rhizoctonia solani</i>	Tomato	Suppressed disease progression by activating defense response
			<i>Acidovorax citrulli</i>	Water-melon	Activated stomatal immunity for disease suppression

		Cu ions bind to DNA, denaturing proteins and disrupting cellular processes	<i>Colletotrichum capsici</i>	Chilli	Reduced disease symptoms by directly inhibiting pathogen growth
3	Zinc (ZnNPs)	Direct attachment to bacterial cells disrupts membranes and leads to cytoplasmic leakage. -Produces ROS, inhibits mitochondrial functions and causes DNA damage	<i>Fusarium oxysporum</i> f. sp. <i>melongenae</i>	Egg-plant	Suppressed disease severity by activating plant biochemical and physiological mechanisms
			<i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	Rice	Showed direct antibacterial activity against bacterial pathogen
			<i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i>	Tomato	Reduced disease incidence by inducing defense responses
4	Chitosan Nano-particles	Derived from chitin; inhibits fungal growth and causes cytological alterations. Interacts with microbial cell membrane causing disruption and leakage.	<i>Botrytis cineria</i>	Straw-berry	Nanoparticles straightforwardly penetrate and are easily taken up by the cell and inhibits the growth of fungus.

NPs as antimicrobial agents:

NPs possess inherent antimicrobial properties that can be used to target a broad spectrum of pathogens. Particularly NPs with strong antimicrobial capacity such as copper and silver NPs, these have ability to damage cell membranes and interfere with cellular mechanisms which can ultimately lead to death of pathogen, thus preventing the disease onset and progression.

Disruption of pathogen structures:

NPs can inhibit the growth and proliferation of pathogens, preventing them to establish infection and spread within plant tissues. The interactions between NPs and microbial pathogens can alter key physiological processes, including nutrient uptake, enzymatic activities and cell division. This disturbance leads to lower population of pathogens. For instance, it has been demonstrated that iron and copper nanocomposites at concentrations of 15 µg/mL and 32 µg/mL respectively create a protective sheath on rice leaves inhibiting *Xanthomonas oryzae* pv. *oryzae* infection by interfering with its metabolic pathways and disrupting cellular structures. Additionally, it has been found that manganese and copper nanoparticles (at concentrations of 16 µg/mL and 100 µg/mL, respectively) disrupts the integrity of vital macromolecules including proteins and nucleic acids, further slowing the growth of pathogens.

Inhibition of infection process:

The complex processes of pathogen infection, including attachment to host tissues, chemotrophic/invasive development and the formation of infection structures can

be hampered by NPs. NPs can stop pathogen adherence by altering surface properties and preventing microbial cell development. Moreover, NPs have the ability to interfere with biofilm formation, which is essential for the establishment of numerous infections. For example, Manganese, copper and sulphur NPs have been shown to alter the physicochemical properties of plant surfaces, making them less conducive to pathogen attachment and colonization.

NPs as modulators of plant immunity

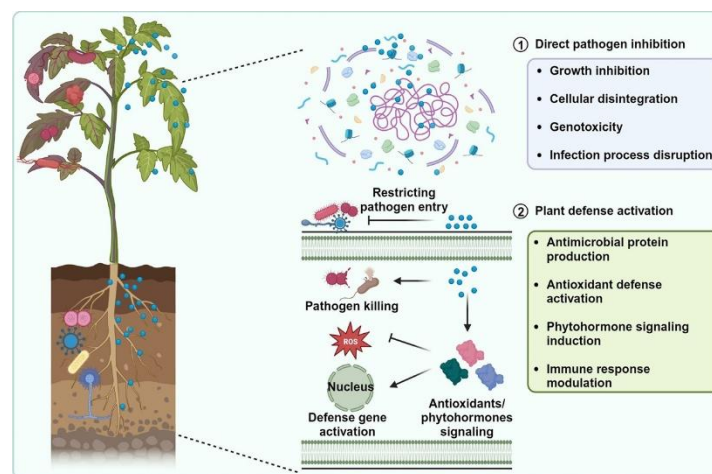


Fig 1: Mechanistic roles of NPs (represented as blue-colored particles) in plant disease management. NPs can either directly or indirectly interact with phytopathogens. In direct interaction, NPs prevent infection, development and reproduction of pathogens, which eventually lead to pathogen death. By entering plant cells indirectly, NPs trigger

immune responses, such as the synthesis of antioxidants, phytohormones, pathogenesis-related protein, and antimicrobial metabolites, giving plants resistance against pathogen infection.

To protect themselves from phytopathogenic intruders, plants have developed a complex innate immune system, highlighting the importance of plant autoimmunity in safeguarding their health. A novel strategy to strengthen plant immune responses is provided by the use of NPs as immune modulators, potentially leading to improved broad-spectrum resistance against a wide range of pathogens. NPs have the ability to efficiently initiate and intensify a number of plant defense mechanisms, encompassing both early and late immune signaling and defense responses. Recent studies have highlighted different mechanisms by which NPs modulate plant immune responses to suppress diseases in crops (Table 1).

Applications

In the domain of plant disease management, NPs have emerged as revolutionary and cutting-edge tool. In an era where sustainable agriculture is crucial, NPs provide innovative solutions to the intricate problems brought on by diverse plant pathogens. One of the primary functions of NPs in crop disease management is the ability to augment plant immune responses. When NPs interact with plants, they can trigger various defense pathways, including the induction of defense genes, oxidative signaling, and phytohormone dependent molecular events. These reactions prepare plants to identify and fight against invasive pathogens more successfully, providing natural defense. For instance, it has been shown that phytogetic silica nanoparticles (100 µg/mL) stimulate inherent defensive mechanisms and antioxidant system in wheat plants against *Rhizoctonia solani*. Similarly, it has been demonstrated that chitosan-coated iron nanoparticles (NPs) produced by *Bacillus aryabhattai* RNT7 activate the expression of PR proteins and genes encoding antioxidant enzymes to prevent bacterial leaf blight disease in rice. Additionally, NPs act as carriers for essential nutrients therefore making it easier for plants to absorb and effectively use them. This improves the health of the plants and increases their resistance to diseases. For example, at a 30 mg/L concentration, chemogenic sulfur NPs suppressed Fusarium wilt in tomato plants by improving in planta sulfur accumulation and plant biomass. Similarly, chemogenic silica nanoparticles (1500 mg/L) have been used to strengthen resistance in watermelon plants against the Fusarium wilt pathogen, *Fusarium oxysporum* f. sp. *niveum*, therefore lessening the severity of the disease by increasing the silicon concentration in plant tissues. Furthermore, NPs can directly produce antimicrobial effects by disrupting

pathogen structures, functions and infection ability, making them effective tools against invasive phytopathogens. For example, 16 µg/mL of phytogetic zinc and chitosan NPs stabilized with tomato extract showed considerable antibacterial activity against *Xanthomonas oryzae* pv. *oryzae* inhibiting pathogen growth, biofilm production and swarming motility. Microscopic observations showed that these NPs induced morphological and oxidative damage to bacterial cells ultimately resulted in pathogen death. By offering a multifaceted approach to disease management, NPs contribute to sustainable farming practices by reducing the need for chemical pesticides, promoting environment-friendly agriculture and enhancing crop productivity. Different NPs and their potential in crop disease management are provided in Table 1.

Conclusions

In light of above facts, NPs' inclusion in crop disease management initiatives marks a significant change in modern agricultural systems. Their ability to enhance food security, promote sustainable agriculture, and reduce environmental impacts of traditional disease management methods highlight their significance. As research continue to reveal the complexities of NPs in crop disease management, their role in maintaining the resilience and health of global crop ecosystems is becoming more and more prominent.

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