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The Power of Tiny: Nanoparticle Mediated Biological Control of Plant Pathogens

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The increasing population of the world is demanding food grains at an exponential rate. The rise in food grain demands has also invited more and more incidences of diseases at regular intervals. Diseases are one of the most significant restrictions in commercial crop production, as they cause significant productivity losses (Patel *et al*., 2023) Combined with the abiotic stress conditions diseases are almost prevalent in every part of the world. Globally it is estimated that 20 to 40% of crop losses are due to diseases and pests. The current management practices of using pesticides, fungicides, nematicides and herbicides have created a detrimental effect on the both biotic and abiotic components of the environment. The alternative to synthetic chemicals is the biological control of disease where in a living entity such as bacteria, fungi or viruses can be used for the control of diseases.

The biocontrol agents (BCAs) promote plant growth, as it induces the production of phytohormones that activate plant supplements and produce secondary metabolites, being used as biofertilizers. However, the available formulations of BCAs in the market have some disadvantages such as no longer shelf life, bulky carrier-based formulations, application of certain formulations is a problem. There are many formulations of fungi such as *Trichoderma* spp. that act as an antagonistic fungus and controls many soil-borne diseases. Though they are still not that efficient in controlling the diseases. The storage and application of such microbe-based formulations is a problem many farmers face. So, to solve the above-mentioned problems nanotechnology could provide a possible solution to many of the problems in agriculture. Nanotechnology is the science of using the particles that are in the size ranged from 1 to 100 nm, and can be designed with unique chemical, physical and biological properties, to distinctively differ from those of their molecular and bulk counterparts. The remarkable characteristics of nanoparticles, such as biocompatibility, excessive productivity, speed of production, cost-effectiveness and protection, have an impact on biomedical food and engineering programmes (Mistry *et al*., 2022) Nanoparticles alone have the potential to be directly applied to plant seeds, foliage, or roots for protection against pest and pathogens, such as insects, bacteria, fungi, and viruses. Metal nanoparticles such as silver, copper, zinc oxide, and titanium dioxide have been intensively researched for their antibacterial and antifungal properties, and are known for their antiviral properties. Synthesis of NPs using BCAs, suggests that it may have mechanisms of tolerance to these structures, which could be used synergically to develop products that improve crop weight and treatment against phytopathogens.

In this article, we will explore the principles, applications and potential benefits of nanoparticle-mediated biological control of plant diseases. We will delve into the mechanisms by which nanoparticles enhance the effectiveness of BCAs, examine the latest research findings and innovations in the field, and discuss the implications of this emerging technology for sustainable agriculture. By harnessing the power of nanotechnology, nanoformulation-based biological control offers a promising pathway towards more resilient, environmentally friendly, and productive agricultural systems.

Mechanism of Nanoparticle-Mediated Biological Control

Several modes of action, including antibiosis, competition for nutrients and space, and the creation of systemic resistance in plants, are employed by the microbes in these NPs. Furthermore, biogenic NPs can be tailored to target particular phytopathogens based on their size, shape, and surface features, which makes them extremely effective and selective. The metallic NPs such as silver, gold, manganese, zinc, copper, titanium, etc. have been investigated the most (Li *et al*., 2023). One of the mechanisms by which biogenic NPs interact with plant pathogens is through their physical and chemical properties (Xu *et al*., 2021; Noman *et al*., 2022). These NPs might include substances that cause the pathogen's cell membrane to rupture, resulting in cell lysis and decreased pathogen viability. Furthermore, after being exposed to NPs, the generation of reactive oxygen species (ROS) such as hydrogen peroxide, superoxide anions, and hydroxyl radicals damages DNA and prevents the creation of mRNA and proteins, which ultimately results in the death of the pathogen (Ogunsona *et al*., 2020). The various direct and indirect effects on the pathogen, the plant, and their interconnections that comprise the overall complex mechanisms of disease control mediated by nanoparticles are noteworthy. To maximize the safety and effectiveness of nanoparticle-based methods for the treatment of plant diseases, more investigation is required to completely comprehend the underlying mechanisms. A summary of various types of microbe-based NPs against plant diseases is shown in Table 1:

Table 1: Successful examples of nanoparticle-mediated biological control of plant pathogens

Nano-particle	BCA	Size (nm)	Pathogen	Reference
Silver	*Trichoderma harzianum*	31.13	*Sclerotium rolfsii* and *S. sclerotiorum*	El-Ashmony *et al.* (2022)
	T. virens	5–50	*S. sclerotiorum*	Tomah *et al.* (2020)
	Fusarium solani	5-30	*Aspergillus* spp., *Fusarium* spp., *Rhizopus stolonifera* and *Alternaria* spp.	Ali *et al*. (2020)
	Pseudomonas rhodesiae	20–100	*Dickeya dadantii*	Hossain *et al.* (2019)
Copper	*Streptomyces apillispiralis*	4–59	*A. niger*, *Fusarium* spp., *Pythium* spp. and *Alternaria* spp.	Hassan SE-D *et al.* (2018)
	Streptomyces griseus	5-50	*Poria hypolateritia*	Ponmurugan *et al.* (2016)
Zinc oxide	*Enterobacter* sp.	33-75	*Pestalotiopsis versicolor*	Ahmed *et al.* (2021)
	Paenibacillus polymyxa	62	*Xanthomonas oryzae* pv. *oryzae*	Ogunyemi *et al.* (2020)
	Aeromonas hydrophila	57-72	*A. flavus*	Noman *et al.* (2020)
	Trichoderma spp.	75	*X. oryzae* pv. *oryzae*	Shobha *et al.* (2020)

Application Methods of Nano-Formulated BCAs

Delivery methods play a crucial role in ensuring the effective deployment of nanoparticle-coated bioagents for plant disease management. These methods determine how efficiently the bioagents are transported to the target sites within plants, where they can exert their beneficial effects against pathogens. Several delivery methods have been developed to achieve this goal, each with its unique advantages and applications

a) **Foliar Sprays:** Foliar sprays are one of the most common delivery methods for nanoparticle-coated bioagents. In this method, the bioagent nanoparticles are suspended in a liquid carrier solution and sprayed onto the foliage of plants. The nanoparticles adhere to the leaf surfaces and are absorbed through the stomata or directly through the cuticle, allowing the bioagents to colonize the plant tissues and exert their antifungal or antibacterial effects.
b) **Seed Treatment:** Seed treatment involves coating seeds with nanoparticle-formulated bioagents before planting. This method ensures the systemic distribution of bioagents throughout the plant as it grows, protecting against soilborne pathogens and early-season infections. Nanoparticle coatings enhance the adhesion of bioagents to the seed surface and promote their uptake by the emerging seedlings, resulting in improved disease resistance from the early stages of plant development.
c) **Soil Drenches:** Soil drenches involve the application of nanoparticle-coated bioagents directly to the soil around the plant roots. The nanoparticles release the bioagents gradually into the soil, where they can colonize the rhizosphere and establish beneficial interactions with the plant roots. Soil drenches are particularly effective for controlling soilborne pathogens and promoting plant growth and vigour by enhancing nutrient uptake and root development.
d) **Root Dipping:** Root dipping is a method commonly used for transplanting seedlings or establishing new plantings. In this method, the roots of the plants are immersed in a solution containing nanoparticle-coated bioagents before planting them in the field or greenhouse. The nanoparticles adhere to the root surfaces and facilitate the colonization of the rhizosphere by the bioagents, providing protection against soilborne pathogens and promoting root health and development.
e) **Microbial Consortium Sprays:** In some cases, a combination of different bioagents with complementary modes of action may be used to achieve synergistic effects in disease control. Nanoparticle coatings can facilitate the delivery of microbial consortia, which consist of multiple beneficial microorganisms, such as bacteria, fungi, and viruses, that work together to suppress plant diseases. Microbial consortium sprays can be applied using conventional foliar spray equipment, providing broad-spectrum protection against a wide range of plant pathogens.
f) **Encapsulated Formulations:** Nanoparticle-coated bioagents can also be encapsulated within biodegradable polymer matrices to form controlled-release formulations. These encapsulated formulations protect the bioagents from environmental stresses and release them gradually over time, prolonging their activity and reducing the need for frequent applications. Encapsulated formulations can be applied using various delivery methods, including foliar sprays, soil drenches, and seed treatments, depending on the specific requirements of the target crop and pathogens.

Advantages of Nanoparticle Mediated Biological Control

a) **Enhanced Stability and Shelf Life:** Nanoparticles can protect BCAs from environmental stresses, such as UV radiation, temperature fluctuations, and enzymatic degradation. Encapsulating BCAs in nanoparticles can improve their stability and prolong their shelf life, ensuring their viability and efficacy over a longer period.

b) **Improved Adhesion and Colonization:** Nanoparticles can enhance the adhesion of BCAs to plant surfaces and promote their colonization of the rhizosphere and phyllosphere. Surface modification of nanoparticles can facilitate interaction with plant tissues and enhance the establishment of BCAs, thereby improving their ability to compete with and antagonize plant pathogens.

c) **Targeted Delivery and Release:** Nanoformulations can be engineered to deliver BCAs to specific target sites within plants, such as roots, stems, or leaves, where they are most needed for disease control. Controlled release formulations can release BCAs gradually over time, prolonging their activity and reducing the frequency of applications.

d) **Synergistic Effects:** Nanoparticles can enhance the activity of BCAs by promoting synergistic interactions between different components of the formulation. For example, nanoparticles can act as carriers for bioactive compounds that stimulate the growth and activity of BCAs, leading to improved disease suppression.

e) **Increased Penetration and Efficacy:** Nanoparticles can improve the penetration of BCAs into plant tissues, allowing them to reach target pathogens more effectively. Enhanced penetration can lead to greater efficacy of BCAs against both foliar and soil-borne pathogens, resulting in better disease control and crop protection.

f) **Reduced Environmental Impact:** Nanoformulations offer the potential to reduce the environmental impact of biological control practices by minimizing the need for synthetic chemicals. By enhancing the efficacy of BCAs, nanoformulations can decrease the reliance on conventional pesticides and fungicides, leading to lower chemical residues in the environment and reduced risks to non-target organisms.

g) **Compatibility with Sustainable Agriculture**: Nanoformulation-based biological control aligns well with principles of sustainable agriculture by promoting the use of environmentally friendly and economically viable disease management strategies. By harnessing the potential of nanotechnology, these approaches can contribute to more sustainable crop production systems with reduced dependence on synthetic inputs.

Conclusion

Nanoparticle-mediated biological control represents a promising and sustainable approach to plant disease management. By harnessing the unique properties of nanoparticles, researchers can enhance the stability, delivery and efficacy of BCAs, leading to more effective disease suppression and improved crop yields. As we continue to advance our understanding of nanotechnology and its applications in agriculture, nanoformulations hold immense promise for the future of sustainable crop production, offering farmers a powerful tool to combat plant diseases while minimizing environmental impact.

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