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A Comprehensive Review: Nanotechnology scope and application in plant disease management

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Abstract

Nanotechnology has the potential for addressing current issues related to agriculture and is an innovative technique for increasing the production of crops. A wide variety of materials, such as metal, metallic oxides, nonmetals, ceramics, semiconductors, polymeric structures, lipid-based nanostructures, carbon-based nanostructures and quantum dots, are included in nanoparticles, which range in size from 1 to 100 nanometers. Their use asherbicides, pesticides, insecticides, and nano fertilizers has been made easier by their large surface area, strong reactivity, and nanoscale size. Furthermore, nanoparticles can be engineered to function as carriers of genetic material, molecular probes, and agrichemicals as well as biosensors in the diagnosis of plant diseases. The use of nanotechnology in plant pathology has increased dramatically in the last ten years, with nanomaterials being essential for molecular tools for study, disease management, and detection. Utilizing metallic and metallic oxide nanoparticles as antibacterial agents and nano fertilizers to inhibit infections and improve plant health has received a lot of attention. Much research has also been done on their potential as sensor technology for accurate and quick diagnosis of plant diseases. The field of nanotechnology provides promising alternatives as the need for environmentally friendly agricultural methods grows globally in the face of climate change issues. Nanoparticles have the potential to completely transform agricultural disease management techniques by reducing chemical inputs and facilitating the quick identification of pathogenic organisms, hence promoting sustainable as well as resilient food systems.

Keywords

Biosensor, Nanotechnology, Nanoparticles, Pathology

1. Introduction

According to recent estimates, the world's food supply will be required to double by 2048 in order to keep up with the growing demand. Meeting the requirement for additional agricultural output has become an imperative global concern as the globe's population continues to increase [1]. In order to combat this, a number of inventions have been attempted to increase agricultural output as well as minimize losses caused by bugs, viruses, and other causes. Micronutrients are essential to plant nutrition, including these. Plant development and profitability can be greatly impacted by a lack of these vital nutrients. The potential consequences of climate change, which could upset agricultural production patterns by causing longer periods of drought and increased temperatures on average in many agriculturally susceptible regions, enhance this dire prediction. For plant pathologists and other farming experts, these difficulties pose serious barriers. The potential of the soil to provide nutrients, the effectiveness of plant uptake of those nutrients, and the ability to move those nutrients throughout plant systems are all critical components of effective plant nourishment [2].

For the nourishment and progression of plants, iron is especially important. Furthermore, trace levels of other vital micronutrients, including copper, chloride, magnesium, silver, selenium, and silicon, are needed for the proper development of organisms of all kinds, which in consequence affects human nutrition [3]. These critical nutrients are crucial for sustainable farming practices since deficiencies in them can lead to malnutrition and associated health problems.

A promising approach for dealing with these developing challenges is nanotechnology. It is a cutting-edge and creative instrument that could revolutionize disease control and improve the condition of plants [4]. Nanotechnology has become increasingly more well-known for agricultural abnormalities research, opening the door for ground-breaking advancements even though its application in fields including genetic modification, examinations, and plant disease control is still in stages of development [5].This chapter explores the impact of nanoparticles on various plant disease-causing agents, highlighting scientific advancements in this area. It also examines the performance of different nanoparticle types, emphasizing how their nanoscale properties and treatment conditions influence their effectiveness.

As disinfectants, nanomaterials (NMs) have shown great promising; at relatively low concentrations, they can effectively control phytopathogen infections with minimal ecotoxicity. These characteristics make NMs a viable substitute for traditional bactericides and fungicides. This strategy reduces the need for chemical substances while also minimizing the energy expenditures involved in their manufacture. As a result, it supports sustainable crop health management, prevents climate change, and lessens the environmental dangers that agrochemicals pose. Nanomaterials have been criticized for their possible negative environmental impacts despite their remarkable efficacy in suppressing disease. To ensure the effectiveness and safety of nanomaterials in farming processes, more study is also necessary to improve their dosage and application techniques for field use.

2. Nanotechnology and Plant Pathology

Advancements in technology and science have significantly shaped the field of plant pathology. Among these advancements, nanotechnology offers promising approaches to managing plant diseases. One of the most common applications involves using nanoparticles on seeds, soil, or foliage to protect plants from pathogens or control infections [6]. Due to their ultra-small size—smaller than a virus—and high reactivity against microorganisms, nanoparticles are highly effective in combating plant pathogens [7]. Furthermore, researchers are utilizing nanoparticles as diagnostic probes to enhance existing diagnostic tools and address their limitations, further advancing the role of nanomaterials in plant disease management.

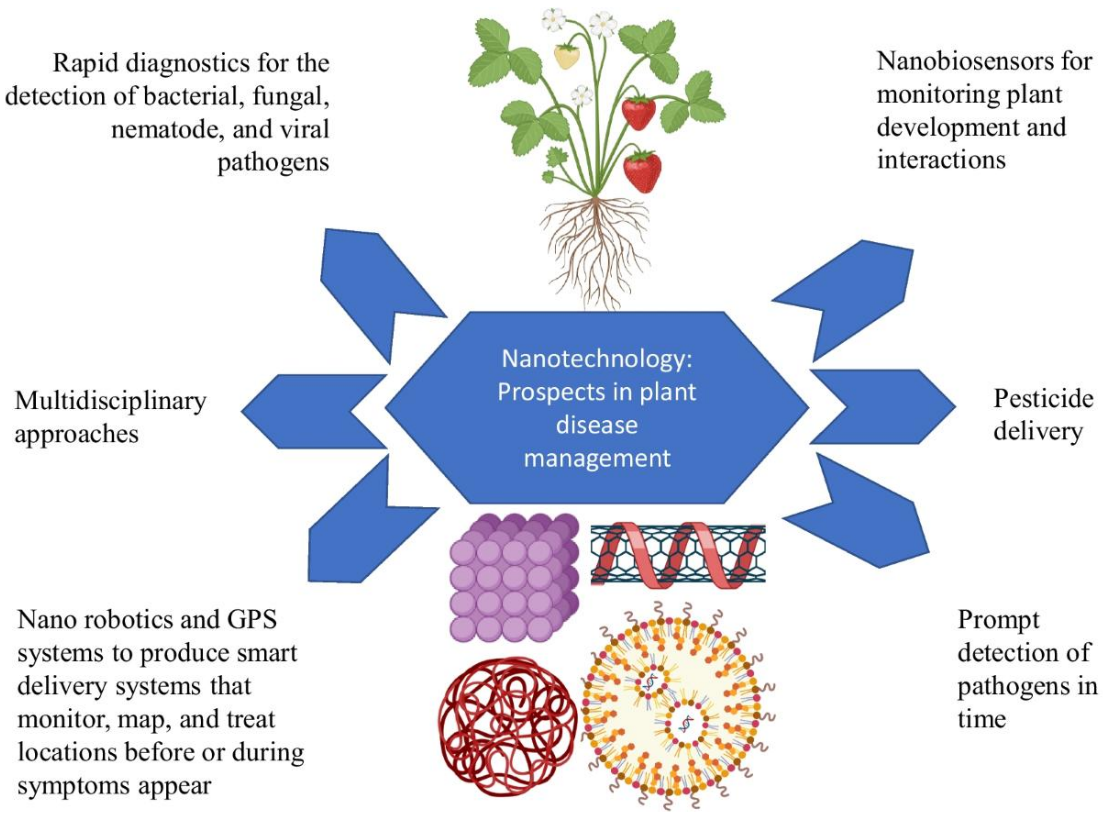

Figure 1. Nanotechnology and Plant Pathology [7]

3. Nano-Silver

Silver is renowned for its antimicrobial properties, which are significantly enhanced when transformed into nanoparticles. Silver nanoparticles (AgNPs), synthesized using various chemical and biological methods—including plant extracts, fungi, and bacteria—have been extensively studied for their superior antimicrobial effectiveness. With the growing demand for silver nanoparticles across multiple applications, research is increasingly focused on developing synthesis techniques that prioritize reduced chemical toxicity, cost efficiency, and improved nanoparticle stability, paving the way for safer and more sustainable utilization.

Silver nanoparticles (AgNPs) demonstrate significantly greater antifungal activity compared to the conventional antifungal drug amphotericin B. This enhanced efficacy is observed against various human fungal pathogens, including Aspergillus niger, Aspergillus fumigatus, Aspergillus flavus, Penicillium sp., and Candida albicans. Additionally, AgNPs exhibit superior antifungal effects against plant pathogens such as Rhizoctonia solani, Fusarium oxysporum, and Curvularia sp. [8]. The antimicrobial potential of silver nanoparticles was assessed at varying concentrations (25–100 ppm) against three pathogenic plant fungi: Alternaria solani, Corynesporacassiicola, and Fusarium spp. The evaluation was conducted in two different fungal growth media, focusing on the inhibition of radial growth. At a concentration of 100 ppm on potato dextrose agar (PDA), AgNPs achieved up to 100% inhibition for Alternaria solani and Fusarium spp., while Corynesporacassiicola showed 85% inhibition [9].

Table 1. Types of nanoparticles and their potential uses in plant pathology

Type of nanoparticles	Activity	Pathogen	Reference
Ag Nanoparticles	antifungal activity	Aspergillus niger, Rhizoctonia solani	[8]
Ag Nanoparticles	antifungal activity	Alternaria solani, Corynesporacassiicola, and Fusarium spp.	[9]
Ag Nanoparticles	antifungal activity	Fusarium oxysporum	[10]
Cu Nanoparticles	antifungal activity	F. solani, Neofusicoccum sp., and F. oxysporum	[11]
Cu Nanoparticles	antifungal activity	Colletotrichum capsici	[12]
Zn Nanoparticles	antifungal activity	Alternaria alternata	[13]
Zn Nanoparticles	antifungal activity	Botrytis cinerea	[14]

4. Nano-Copper

Copper (Cu) has long been known for its application in agriculture as an efficient plant protector against bacterial and fungal diseases [15]. As mentioned before, it is believed that plant diseases caused by bacteria, fungus, viruses, and insects cause around one-third of the world's crop yield to be lost annually. Since ancient times, copper has been used in a variety of disease control formulations to counter these enduring problems. Copper nanoparticles are well-known for their broad-spectrum antimicrobial properties. Copper's well-established antimicrobial properties and its long-standing use in controlling plant diseases make nano-copper a promising candidate for effective plant disease management [16]. Incorporating CuNPs into a hybrid composite with cellulose, embedded within a polyvinyl alcohol (PVA) film, significantly enhances their antimicrobial efficacy.Nicolaza et al., 2019, reported that strong antifungal efficacy against F. solani, Neofusicoccum sp., and F. oxysporum was demonstrated by these green-synthesized Cu-NPs. Controlling pathogenic fungus that impacts agriculture and forest species worldwide may be made easier with the help of this nanomaterial [17].

5. Nano Zinc

For plants, zinc (Zn) is a necessary micronutrient that can exist as a free ion or attached to a variety of low-molecular-weight substances. Additionally, it can incorporate into proteins and other macromolecules, where it serves as a structural, functional, or regulatory cofactor for a variety of enzymes [18]. Zinc-based nanoparticles are important and extremely adaptable substances with a variety of uses. Their remarkable antibacterial and photocatalytic qualities are a result of their small particle size, large surface area, and improved reactivity [19]. Zn-NPs also have improved cytotoxicity, high selectivity, ease of synthesis, and greater biocompatibility when compared to other metallic nanoparticles [20]. They are a promising option for anticancer drugs because of these qualities. According to Mahmoud, R. (2023), nano zinc is very successful at preventing the growth of Alternaria alternata, the fungus that causes alternarial leaf spot in beans. According to Muhammad Imran et al. (2023), T. harzianum and Zinc oxide NPs could be utilized in place of fungicides to treat tomato gray mold disease brought on by B. cinerea resistance issues.

6. Future Prospects of Nanotechnology in Phytopathology

The role of nanotechnology promises significant advancements in this field of detection through the development of pathogen sensors that are more rapid and sensitive [21]. The employment of nanoparticles as quick diagnostic instruments for bacterial, fungal and viral diseases makes simple sense [22]. By addressing all potential shortcomings in the current diagnostic instruments, researchers are working to enhance the role of nanomaterials through the use of nanoparticles as diagnostic probes [23].Global food security and agricultural productivity will be improved in the future by a strong framework for managing plant diseases sustainably created by combining nanotechnology with genomes, data analytics, and precision agriculture [24].

7. Conclusion

The most significant economic sector for people all across the world is agriculture. The greatest significant obstacle to plant productivity is thought to be plant diseases. Nanotechnology also possesses an extent to which it can be used in agriculture as a practical science to manage plant diseases and maximize element effectiveness. Compared to conventional methods, plant protection is another environmentally acceptable use of efficient nanoparticles. Nano formulations are thought to be a safer and more environmentally friendly way to treat plant diseases. Thus, With the advancement of nanotechnology, prudence is crucial. For the diagnosis and management of different diseases, pathologists use nanoparticles because of their long-term stability, high effectiveness, environmental friendliness, and ease of pathogen identification.

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