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Applications of Nanotechnology in Plant Disease Management

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SUMMARY

Ensuring food security requires effective plant disease management, a challenge currently addressed through chemical-based solutions such as fungicides, bactericides, and nematicides. While these chemicals provide rapid action, their drawbacks—such as environmental degradation, harm to beneficial organisms, and the emergence of resistant pathogens—necessitate alternative strategies. Nanotechnology has emerged as a sustainable and efficient approach for combating plant diseases. Research indicates that nanoparticles exhibit significant potential in controlling bacterial and fungal infections, offering enhanced efficacy with minimal ecological impact. Among the various advancements, nanobiotechnology integrates cutting-edge tools like biosensors for early disease detection, nanofungicides, and targeted delivery systems. These innovations not only improve disease control but also contribute to sustainable agricultural practices by reducing dependency on harmful chemicals. This paper explores the role of nanotechnology in plant disease management, emphasizing its advantages and future potential in ensuring global food security.

INTRODUCTION

Agriculture plays a vital role in a nation’s economy as it serves as the primary source of food and provides essential raw materials for various industries. However, plant diseases pose a significant challenge to agricultural productivity, causing an estimated 20-40% yield loss annually worldwide. One of the major obstacles in ensuring food security is effective plant disease management. Currently, chemical-based solutions such as fungicides, bactericides, and nematicides are widely used due to their quick action and easy availability. However, these chemicals have several drawbacks, including negative effects on non-target organisms, soil degradation, and the emergence of resistant pathogens. Additionally, research suggests that 85-90% of pesticides applied are lost before or after reaching the target. To address these challenges, nanotechnology offers a promising and eco-friendly approach to plant disease management. Studies have shown remarkable success in using nanoparticles to combat bacterial and fungal infections in plants. Among the various strategies, nanobiotechnology plays a crucial role, incorporating advanced tools such as biosensors for disease detection, nanofungicides, and targeted delivery systems. Nanoencapsulation is a notable mechanism that enhances the efficiency of disease control by regulating the release of active compounds to plants. This technique not only improves the stability of pesticides and other chemicals but also minimizes their degradation, reducing the quantity required for application. Moreover, nanofabrication technologies have significantly improved plant disease management by providing insights into the physical, chemical, and biological interactions between plant hosts and pathogens. For instance, the development of microfabricated xylem vessels with nanoscale features has revolutionized the study of xylem-inhabiting bacteria. Previously, researchers relied on destructive sampling techniques to analyze bacterial populations at different points from the inoculation site, which limited their understanding of colonization patterns. With the introduction of these microfabricated xylem vessels, scientists can now observe bacterial movement, colonization, and re-colonization more effectively. Another breakthrough in nanotechnology is the use of clay nanotubes as pesticide carriers, which enhances pesticide adherence to plants while significantly reducing the required application amount—by up to 80%. This not only cuts down treatment costs but also minimizes environmental impact. Furthermore, nanoparticles contribute to bioremediation by breaking down resistant pesticides into non-toxic compounds. This process enhances food safety by preventing harmful chemicals from entering the food chain, which could otherwise pose serious health risks to consumers. Additionally, nanoparticles serve as disinfectants and have extensive applications in food engineering and postharvest technology, further ensuring food quality and safety. By integrating nanotechnology into agriculture, sustainable and efficient plant disease management can be achieved, reducing reliance on harmful chemicals while promoting environmental well-being and food security.

What is Nanotechnology?

- The term "Nanotechnology" was first introduced by Taniguchi in 1974.

- It is a branch of science focused on the synthesis and application of nanoparticles ranging in size from 1 to 100 nm.
- Nanotechnology plays a significant role in various fields, including energy production, enhancing agricultural productivity, purifying drinking water, and diagnosing diseases.
- Nanotechnology offers numerous benefits across various fields.
- One notable benefit is the significant reduction in the amount of active chemicals introduced into the agroecosystem.
- A significant portion of applied fungicides, bactericides, and fertilizers fails to reach their intended target, often seeping into groundwater and contaminating the ecosystem. Nanotechnology serves as a powerful tool to address these challenges and protect plant health.
- Nanotechnology contributes to agriculture by enhancing pesticide production and improving plant disease management while reducing environmental challenges.
- The significance of nanotechnology lies in its capability to operate at the molecular level while also forming larger structures with novel molecular arrangements.
- The primary goal of nanotechnology is to harness these properties and utilize them effectively across various fields.
- Nanotechnology has introduced innovative solutions to challenges in agriculture and food science, particularly in post-harvest management. It also offers advanced methods for improving plant disease management and serves as an effective tool for disease detection.
- Nanoparticles such as silver, gold, and silicon have been recognized for their effectiveness in this field.

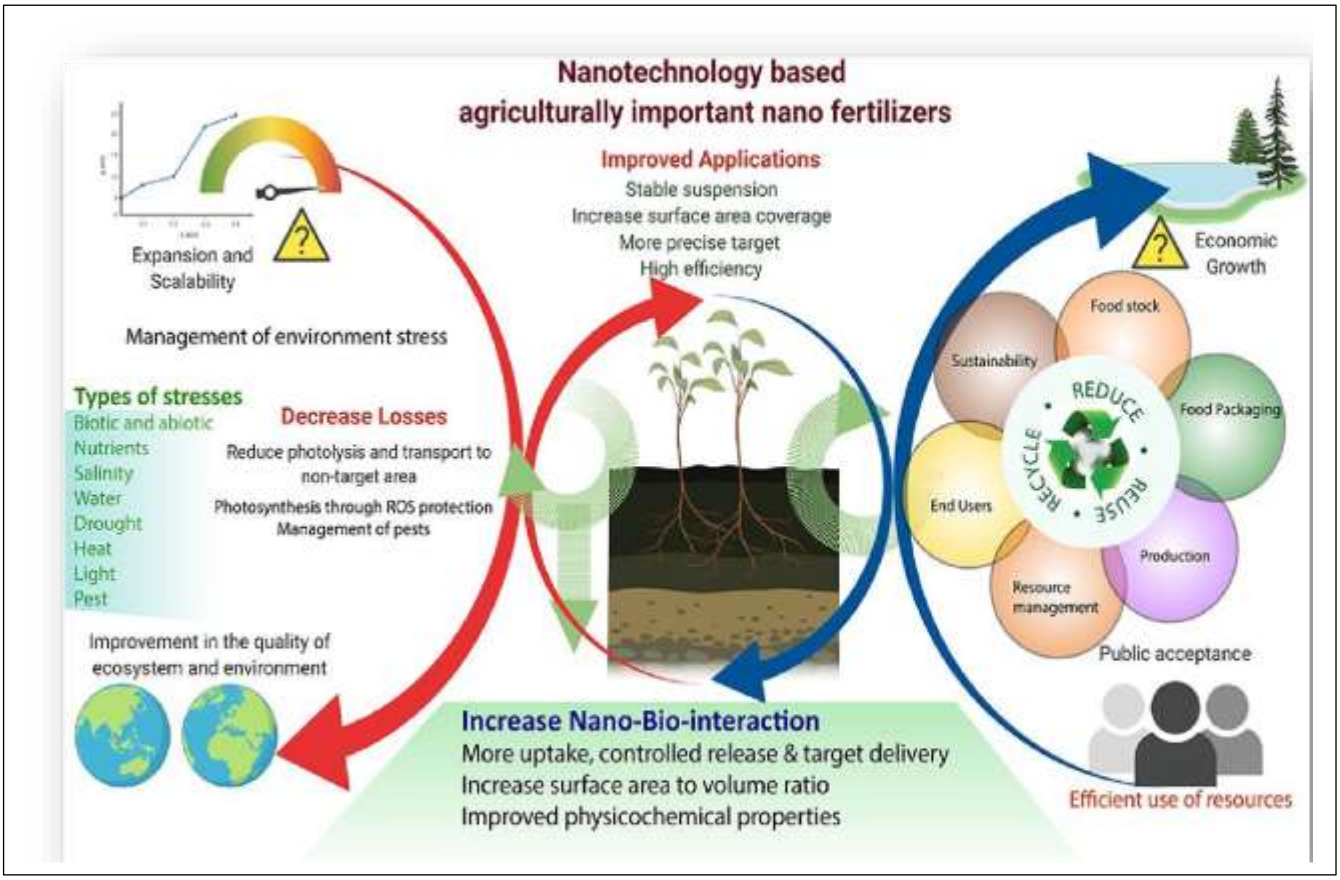
Application of Nanoparticles in Management of Plant Diseases

The nanoparticles are used to protect plants in two different mechanisms-

(a)Nanoparticle act as carrier for pesticides can be applied by spray application. Nanoparticle act as carrier can provide several benefits-

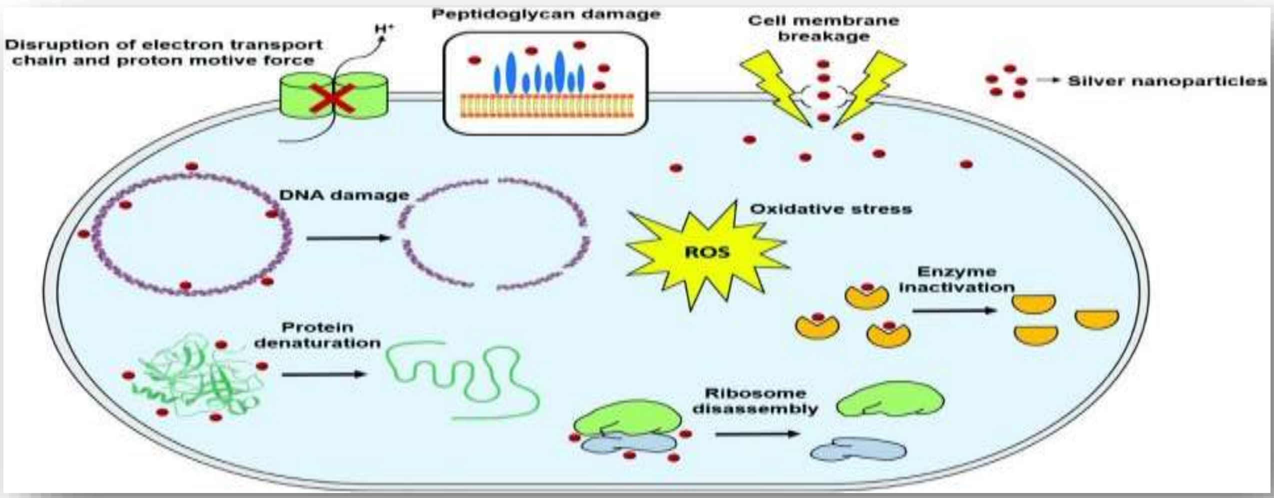
(i) Extends the shelf life of pesticides.
(ii) Enhances the solubility of pesticides with low water solubility.
(iii) Improves targeted delivery and absorption by specific pests.
(iv) Minimizes toxicity levels.

(b) Nanoparticles themselves play a role in crop protection.



Mechanism of Antimicrobial Activity By Nanoparticles

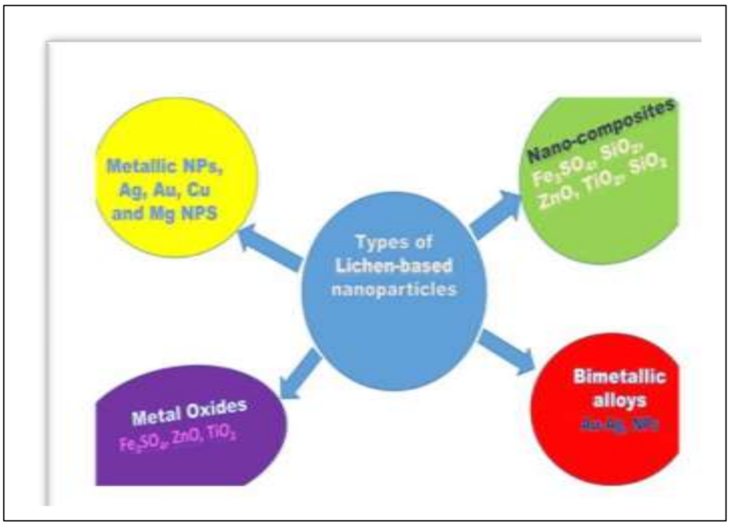
- The antimicrobial properties of nanoparticles function through multiple mechanisms, including metal ion release, oxidative stress, non-oxidative processes, and cell destruction.
- These mechanisms are interconnected, interdependent, and operate simultaneously.
- Recent research has identified key antibacterial effects of nanoparticles, such as disrupting bacterial cell membranes, inducing oxidative stress, and penetrating the bacterial membrane.
- Inside the bacterial cell, nanoparticles interfere with essential molecular pathways, including DNA replication and protein synthesis inhibition.
- The excessive production of reactive oxygen species (ROS) is a crucial mechanism through which nanotechnology is applied in plant disease management.
- Silver nanoparticles (AgNPs) have demonstrated bactericidal activity against plant pathogens like *Xanthomonas* and *Ralstonia solanacearum* by generating ROS.
- The primary antibacterial mechanisms of nanoparticles include altering membrane properties.
- Nanoparticles induce ROS release, which interacts with membrane lipids, disrupting membrane integrity, leading to permeability issues, membrane perforation, and eventually cell death.
- Gold nanoparticles (AuNPs) cause DNA damage in pathogenic bacteria by interfering with transcription.
- The bactericidal action of nanoparticles is mainly achieved through enzyme deactivation, such as the inhibition of galactosidase by zinc oxide nanoparticles (ZnO).
- Due to their multiple antibacterial mechanisms, silver nanoparticles (AgNPs) are widely utilized in plant disease management.



Commonly Used Nanoparticles for Plant Disease Management

- Nanoparticles derived from metalloids, nonmetals, metal oxides, and carbon exhibit both antifungal and antibacterial properties.
- Certain nanoparticles provide nutritional benefits to plants while also enhancing their resistance to diseases.
- Copper oxide (CuO) and silicon dioxide (SiO_2) nanoparticles strengthen plant defense mechanisms against pathogens.
- The most commonly used nanoparticles for carrying fungicides, insecticides, and herbicides include the following:

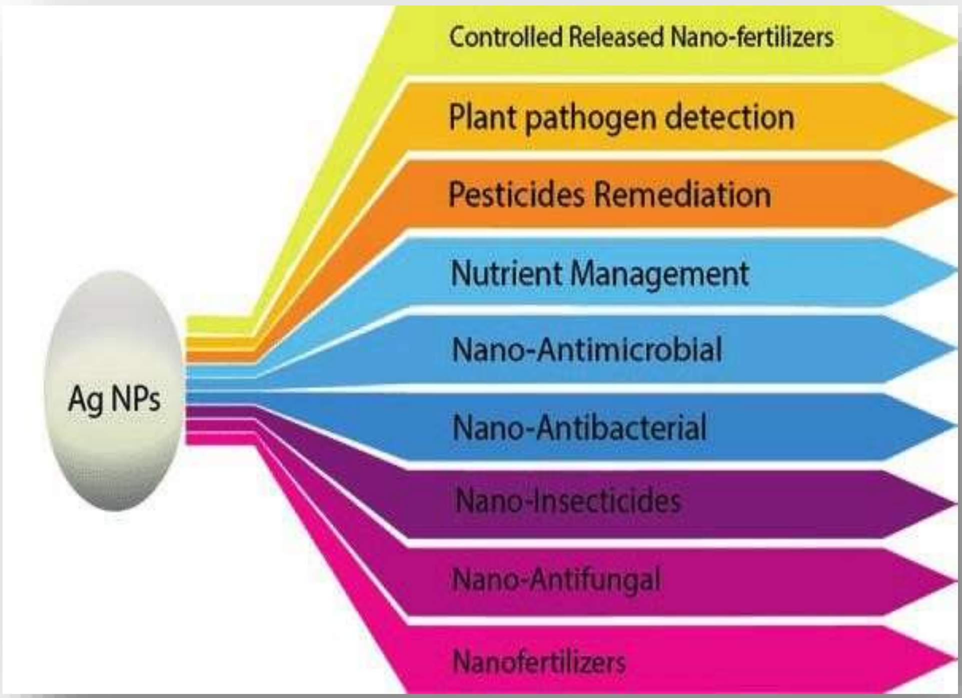
1. Silver nanoparticle.
2. Silica nanoparticle.
3. Chitosan nanoparticle.
4. Copper nanoparticle.
5. Gold nanoparticle.



6. Zinc nanoparticle.
7. Nano-biosensors.

Silver Nanoparticle

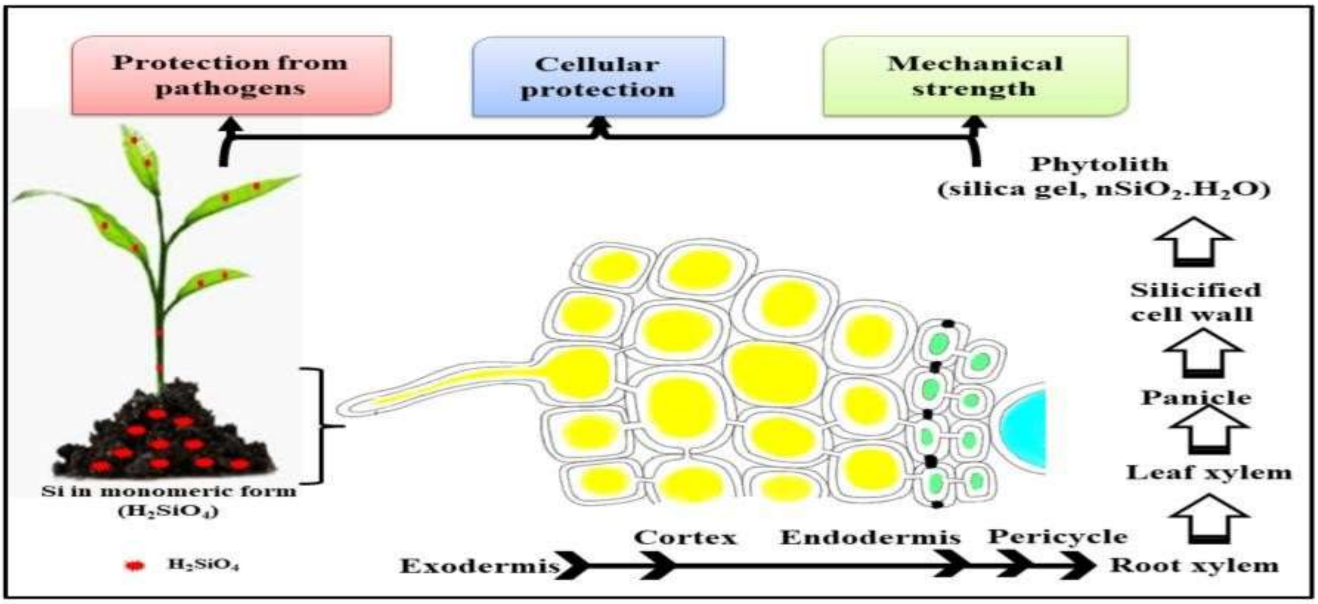
• Silver has the ability to disinfect nearly 650 microbial species while being non-toxic to humans, yet it effectively disrupts microbial metabolism.
• It serves as a safer alternative to synthetic fungicides for controlling various plant pathogens.
• Nano-silver effectively reduces plant diseases caused by spore-producing fungal pathogens.
• Silver nanoparticles are applied before fungal spores penetrate and colonize plant tissues.
• The small particle size (1-5 nm) of silver enhances its effectiveness in managing diseases like powdery mildew.
• Both *in vitro* and *in vivo* studies have demonstrated that silver nanoparticles significantly reduce disease development caused by *Bipolaris sorokiniana* and *Magnaporthe grisea*.
• Applying silver nanoparticles three hours before spore inoculation showed the highest effectiveness, whereas application 24 hours post-inoculation resulted in reduced efficacy.
• The antifungal properties of three different silver nanoparticles (AgNPs) were tested against several plant pathogenic fungi, including *Alternaria brassicicola*, *Botrytis cinerea*, *Cladosporium cucumerinum*, *Fusarium oxysporum* (f. sp. *cucumerinum*, *lycopersici*, *solani*), *Glomerella cingulata*, and *Pythium aphanidermatum* in vitro.
• Silver nanoparticles have demonstrated antifungal activity against *Alternaria alternata*, *Sclerotinia sclerotiorum*, *Rhizoctonia solani*, and *Curvularia lunata*.



Silica Nanoparticle

• Silica is known to enhance plant resistance against diseases and environmental stress.
• Silica nanoparticles can be synthesized with precise control over size and shape, making them effective delivery vehicles. They promote plant growth, enhance physiological activity, and improve resistance to diseases and stress.
• The porous hollow structure of silica nanoparticles protects active molecules from degradation caused by UV light.
• The silica coating allows nanoparticles to pass through the plant cell wall, enabling gene delivery in a precise and controlled manner without toxic effects.
• This technique has been successfully used to introduce DNA into plants such as corn and tobacco.

- Silica-silver nanoparticles have demonstrated antifungal properties against *Botrytis cinerea*, *Rhizoctonia solani*, and *Colletotrichum gloeosporioides*.



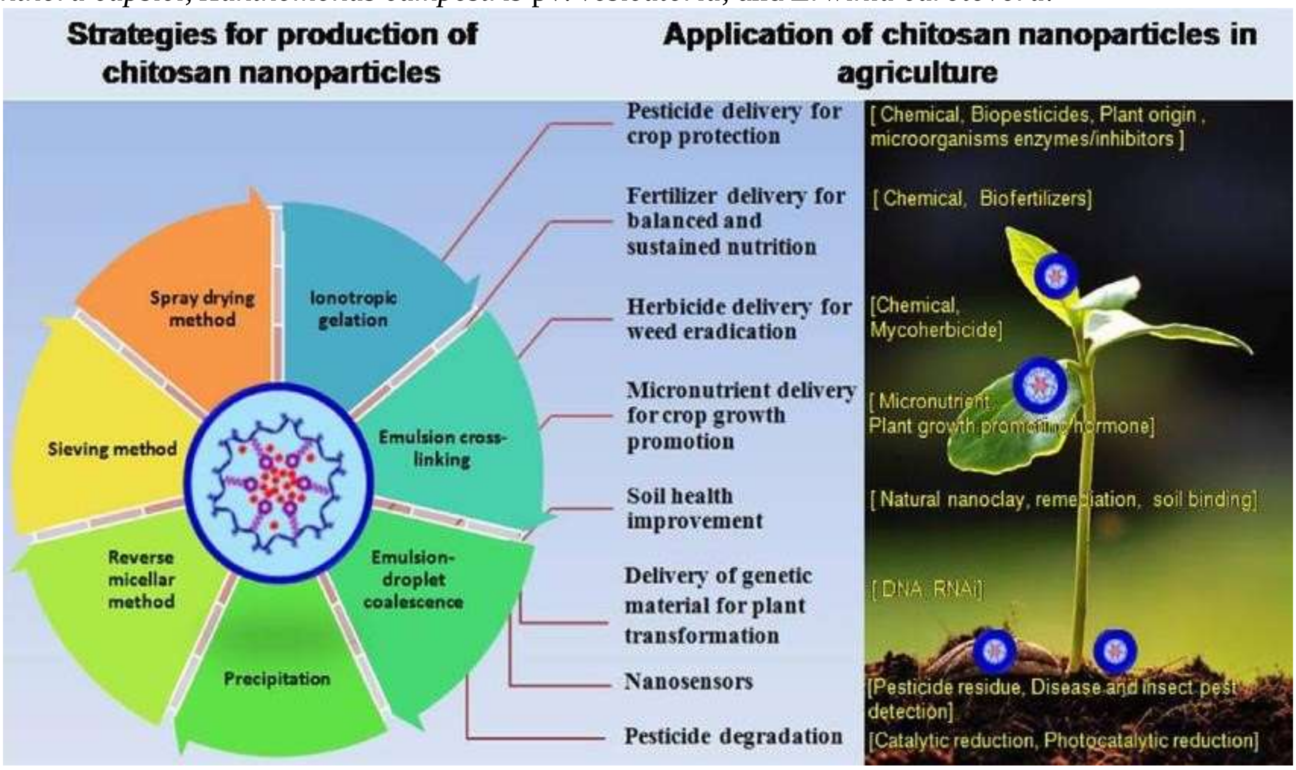
Chitosan Nanoparticle

- Chitosan nanoparticles possess hydrophobic properties, making them poorly soluble in aqueous solutions. To improve solubility, they are often combined with organic and inorganic compounds.
- The antifungal action of chitosan operates through three key mechanisms:

(i) Chitosan is believed to penetrate the fungal cell wall, bind to DNA, and inhibit mRNA synthesis, thereby disrupting the production of essential enzymes and proteins.

(ii)Chitosan interacts with metal ions, which may contribute to its antimicrobial activity. (iii) The positively charged chitosan binds to the negatively charged phospholipids in the fungal cell membrane, altering permeability, leading to cellular leakage, and ultimately causing cell death.

- Chitosan nanoparticles have demonstrated antifungal properties in vitro and effectively protected finger millet plants from blast disease caused by *Pyricularia grisea*.
- They have also been reported to combat plant pathogenic fungi and bacteria affecting tomato crops.
- The highest growth inhibition was observed in *Fusarium oxysporum*, followed by *Phytophthora capsici*, *Xanthomonas campestris* pv. *vesicatoria*, and *Erwinia carotovora*.



Copper Nanoparticle

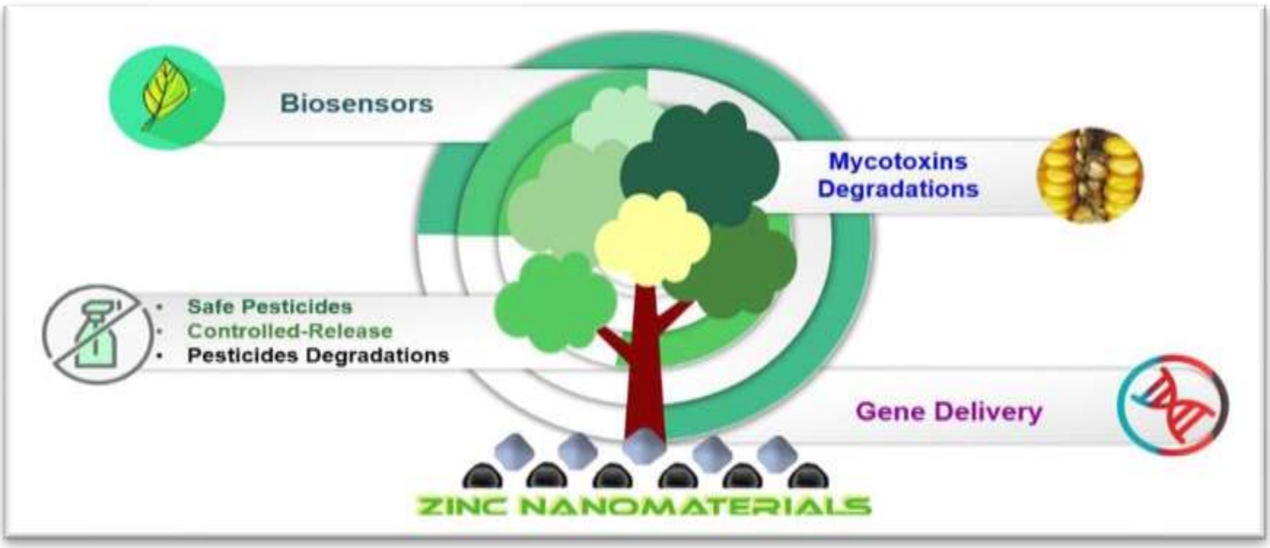
- Copper-based compounds have been used for centuries to manage plant pathogens due to their broad-spectrum antimicrobial properties.
- The earliest metal-based fungicides utilized in plant disease management contained copper, including formulations like copper oxychloride, copper hydroxide, and Bordeaux mixture, which are still used today to control bacterial blight in pomegranate.
- Bordeaux mixture, composed of lime, copper sulfate, and water, was traditionally used to combat grapevine downy mildew disease caused by the oomycete pathogen *Plasmopara viticola*.
- Copper nanoparticles (CuNPs) have the ability to break down fungal and bacterial cellular material by generating hydroxyl radicals, similar to the action of fungicides.
- Nanoparticles have been found effective in controlling bacterial diseases such as leaf spot in mung beans and bacterial leaf blight in rice.
- Copper nanoparticles at a concentration of 200 mg/L were shown to inhibit *Pseudomonas syringae* while being non-toxic to *Rhizobium* spp. and *Trichoderma harzianum* when compared to copper oxychloride.
- Copper nanoparticles have also been effective in managing *Colletotrichum capsici*.

Gold Nanoparticle

- Gold nanoparticles introduced into plants through mechanical abrasion were observed to dissolve *Barley yellow mosaic virus* particles, thereby providing resistance to the plant.
- Optical immunosensors utilizing gold nanoparticles have been developed for detecting *Karnal bunt* disease in wheat.
- DNA-functionalized gold nanoparticle probes have emerged as a promising new generation of biosensors for identifying pathogenic microorganisms.
- A color signal was generated when gold nanoparticle-tagged antibodies bound to pesticide residues, allowing for easy visual detection.
- The dipstick technique based on gold nanoparticles has proven effective for detecting various toxins in environmental and food samples and is suitable for rapid on-site pesticide analysis.
- Gold nanoparticle-based colorimetric biosensing assays have gained significant attention for microbial detection and diagnosis due to their simplicity and adaptability.

Zinc Nanoparticle

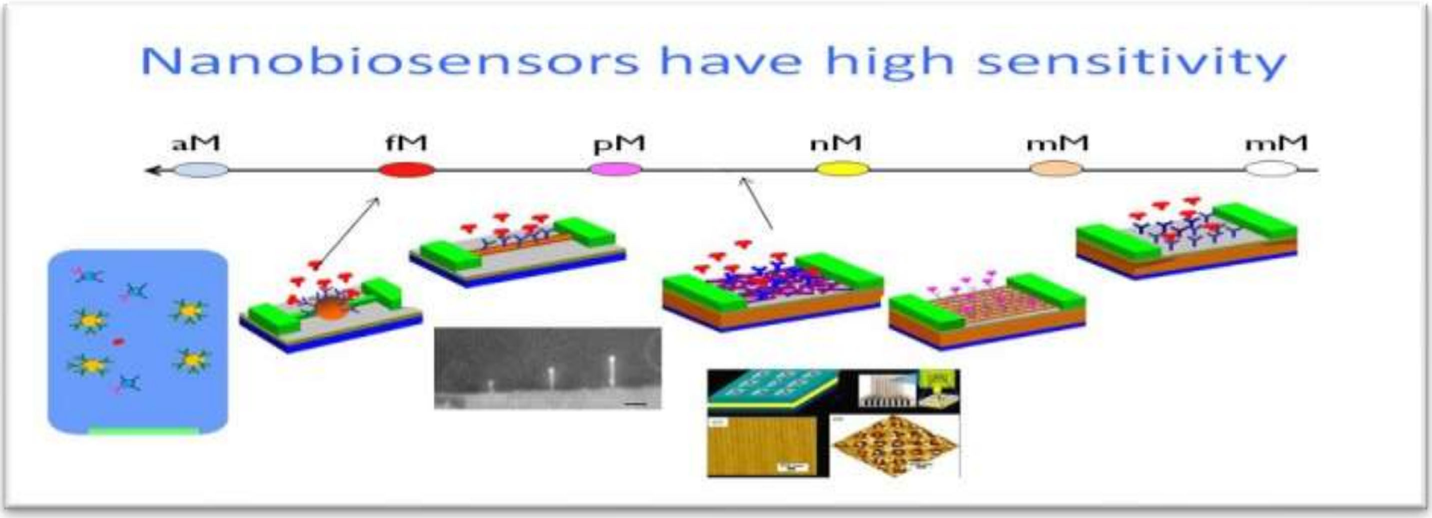
- In agriculture, zinc oxide (ZnO) is primarily utilized as a micronutrient fertilizer, but it is also well recognized for its antimicrobial properties.
- The mechanism of action of nano-ZnO derived from zinc nitrate against *Aspergillus fumigatus* demonstrated that hydroxyl and superoxide radicals caused cell wall deformities, leading to fungal death due to high energy transfer.
- ZnO nanoparticles have been reported to effectively inhibit two postharvest pathogenic fungi, *Botrytis cinerea* and *Penicillium* sp., thereby contributing to agricultural and food safety applications.
- ZnO nanoparticles hindered the formation of conidiophores and conidia in *Penicillium expansum*, ultimately resulting in the death of fungal hyphae.



Nano-Biosensors

- Sensors are advanced instruments that detect biological and physicochemical changes and convert them into signals or outputs that can be interpreted by humans.
- They enable the identification of contaminants, including pests, microbes, plant stress, and nutrient deficiencies caused by insect or pathogen activity.
- Nanomaterials such as metal and metal oxide nanoparticles are commonly used in biosensor development.

- DNA-AuNP probes, a new generation of biosensor-based detection tools, provide a highly precise technology for applications in biological sciences.
- The use of nanosensors in Controlled Environmental Agriculture (CEA) enhances the ability to assess crop health, determine the optimal harvest time, and analyze microbial or chemical composition in crops.



CONCLUSION

Nanotechnology offers innovative solutions for agricultural applications and has the potential to transform current disease management techniques. It plays a crucial role in developing new methods to enhance plant health by contributing to disease diagnostics, disease control, and strengthening plant immunity through immune elicitors. The advancement of nano-pesticides presents numerous benefits, such as improved bioavailability, increased efficiency, reduced toxicity, extended shelf life, and controlled release of active ingredients. The application of nanotechnology and nanoscale science plays a significant role in developing improved and innovative solutions for agricultural challenges. Nano-sized materials modify their biological, physical, and chemical properties, contributing to the enhancement of certain pesticides, making them more effective against weeds, diseases, and pests. Plant disease management predominantly relies on chemical-based pesticides. Excessive and improper use of conventional pesticides has resulted in pesticide resistance and has posed risks to human health and the environment. The misuse of chemical pesticides and insecticides leads to environmental contamination as they enter soil and water bodies, eventually accumulating in the food chain. This has driven efforts to develop alternative disease management strategies. Researchers are exploring nanotechnology as an eco-friendly alternative antimicrobial agent for crop protection. Despite extensive research on nanomaterials, the toxicity levels of many nanoparticles remain uncertain. The adoption of these materials is limited due to insufficient knowledge about their risk assessments and potential impacts on human health, particularly regarding soil and water contamination. Although there are certain limitations, the use of nanoparticles in crop protection presents a broad range of promising applications.

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