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REVIEW

Plant Disease Management: The Promising Role of Nanotechnology

Chandan Das
Department of Botany, MUC Women's College, BC Road, Burdwan- 713104, West Bengal, India
Correspondence for materials should be addressed to CD (email: cdburdwan@gmail.com)

Abstract

Nowadays, plant pests and pathogens are responsible for the loss of more than 20-30% of crops. Unfortunately, traditional plant disease management strategies rely heavily on toxic pesticides and fungicides, which pose significant risks to humans and the environment. Fortunately, nanomaterials show great promise in crop protection and plant disease management. These materials can mimic the action of chemical pesticides by serving as carriers of active ingredients such as host-defense-inducing chemicals and pesticides to target pathogens. Due to their ultra-small size, nanomaterials can precisely target and hit pathogens. Nanotechnology offers several benefits to traditional pesticides, such as reducing toxicity, improving shelf-life, and increasing the solubility of poorly water-soluble pesticides. Additionally, nanosensors could revolutionize disease diagnosis, pathogen detection, and residual analysis, making them more precise and faster. Nanoparticles can be utilized in various ways for plant disease management, either as protectants, nanocarriers for insecticides, fungicides, herbicides, and RNA-interference molecules, or as nanocomposites. Despite the many potential advantages of using nanoparticles, very few nanoparticle-based products have been commercialized for agricultural purposes. This is likely due to insufficient field trials and underutilization of pest-crop host systems. Other industries have made great strides in nanotechnology, and to keep up with this progress, agricultural applications must address essential research questions and fill scientific gaps to create realistic and commercialize nanoproducts. This study analyzes the relevance, scope, and potential applications of nanotechnology in plant disease management for the future.

Keywords: Nanotechnology; Nanoparticle; Plant; Agriculture; Disease management

Introduction

In the present scenario, different types of plant diseases are a major alarming situation for sustainable crop production affecting 20–30% of the total annual loss (Nezhad, 2014). Pathologists are using nanotechnology for diagnosing and monitoring features of plant pathogenic diseases to assess environmentally friendly analytical methods. Advanced molecular techniques with nano-based tools are used for checking the microbial dynamics and plant microorganism interactions between host and pathogen. Sliver, silica, zinc, and copper nanoparticles have been used as antifungal and antibacterial means. Nanotechnology has an extensive application in agriculture and disease management which can revolutionize the entire society. Generally, agricultural production decreases due to different plant diseases every year. Researchers are actively trying to find other measures to overcome pathogens like fungi, bacteria, and viruses in agriculture by using various nanoparticles (Ramezani et al., 2019). The current scenario of the world population is growing rapidly and is projected to reach 10 billion by 2050 (Conforti, 2017). In this context, it would require increasing food production by 50%. Plant infections are a significant alarming situation in sustainable crop production, causing 20–30% of the total annual loss (FAO, 2017). The nanotechnology-based specific delivery systems will help the agricultural industry combat viruses and other crop pathogens. Several nanoparticles are being used in plant disease management, which is a very effective approach for the future with the progress of the application aspect of nanobiotechnology. So, nanotechnology has two major approaches, first, the synthesis of nanomaterials, and second, the application of nanomaterials to desired sites (Mujeebur-Rehman and Tanveer, 2014). Scientists have designed nanoparticles with desired properties, like shape, pore size, and surface area so that they can be used as protectants or for precise drug delivery via adsorption, encapsulation and / or conjugation of an active, such as a pesticide (Shanmugam et al., 2024; Sivakumar et al., 2023; Goyal et al., 2023; Rani et al., 2024; Mahajan, 2023; Ghosh et al., 2024; Bhatt et al., 2024; Khandwal et al., 2016).

Nanoparticles can be used in two ways to protect plants, (a) nanoparticles are applied directly themselves for providing crop protection, or (b) nanoparticles are used as carriers for existing pesticides, insecticide, and weedicide and these can be applied by spray application or drenching/soaking onto seeds, foliar tissue, or roots. Moreover, using nanoparticles helps to provide several benefits, like increasing the shelf-life of targeted crops, enhancing the solubility of pesticides, and improving site-specific uptake into the target pest (Hayles et al., 2017). Nanocarrier also increases the efficacy of the activity and stability of the pesticides under different environmental factors such as UV and rain, significantly reducing the number of applications, thereby decreasing toxicity and reducing their costs (Elizabeth et al., 2018). In this context, early detection of diseases is of key importance to prevent disease spread with minimal loss to crop production. The adverse effects of using pesticides are a major barrier to achieving food safety and sustainable agriculture. Therefore, we urgently need biological control agents that act on the pathogens without any adverse effect on the environment (Adetunji et al., 2017). Nanoparticles interact directly with virus particles and damage the physical structure of viruses (Dutta et al., 2022).

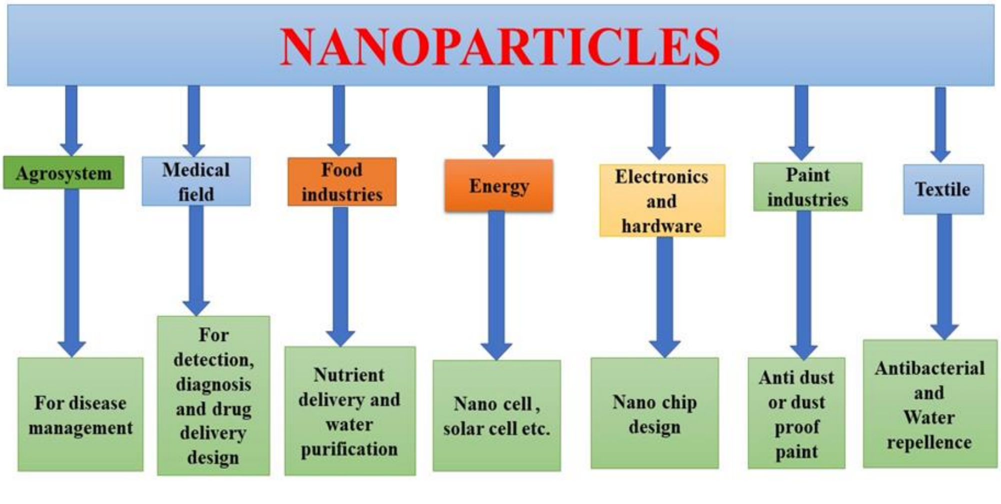

Fig 1. Prospects of nanotechnology in various fields

Nanoparticles: Used for plant pathogen control

Nanoparticles that exist, most do not have application in plant pathology. Though, this is likely to change as applications presently being discovered in nanomedicine against human pathogens make their way into the plant disease management system. Now a days, metalloids, metallic oxides, nonmetals (single and composites), carbon nanomaterials like single- and multiwalled carbon nanotubes, graphene oxides, and fullerenes, and different functionalized forms of dendrimers, liposomes, and quantum dots have started to be used in plant pathology and disease management systems (Wade and Jason, 2018).

Nanoparticles: Probable mechanism over pathogen (bacteria)

Nanoparticle show different mechanism of action of against pathogenic organisms that is disruption of the cell membrane, inhibition of enzyme (H+-ATPase activity), inhibition of transcription (mRNA synthesis), proteins(translation), inhibition of toxin production, suppress the microbial growth, and blockage of the nutrient flow (Dakal et al., 2016; Malerba and Cerano 2016).

Nanoparticles: Metal, Metalloid and Non-metal

Several studies reveal that silver nanoparticle was investigated to the field of plant disease management. In this connection silver NPs used as fungicide for the suppression of plant disease such as powdery mildew (Lamsal et al., 2011; Kim et al., 2008; Kim et al., 2009; Park et al., 2006). Zinc nanoparticles show antibacterial effect on *Pseudomonas aeruginosa* and antifungal effect on *Aspergillus flavus* (Jayaseelan et al., 2012). Another remarkable study report that a combined effects of silver nanoparticles and polyvinylpyrrolidone shows antibacterial effect against gram positive bacteria (*Staphylococcus aureus*), gram negative bacteria (*Escherichia coli*), nonfermented negative bacteria (*Pseudomonas aeruginosa*) and spore of *Bacillus subtillis* (Bryaskova et al., 2011).

Nanoparticles of copper oxide (CuO) also show the antibacterial activity on *S. aureus*, *B. subtillis*, *P. aeruginosa* and *E. coli* (Azam et al., 2012). A study reveals that two-post harvested fungal pathogen like *Botrytis cinera* and *Penicillium expansum* suppressed their hyphal growth by the treatment with zinc oxide (ZnO) nanoparticles (Krishnaraj et al., 2012). Nanosilver is utilized for crop protection, which exhibit strong broad spectrum of antimicrobial activities, due to its high surface area and high fraction of surface atoms in contrast to its bulk properties (Suman et al., 2010; Prasad and Swamy, 2013). Several reports indicated that silver nanoparticles (AgNPs) can inhibit of fungal hyphal growth and conidial germination in *Rhizoctonia. solani*, *Sclerotinia sclerotiorum* and *Sarracenia minor*, *Bipolaris sorokiniana*, and *Magnaporthe grisea* under *in-vitro* experimental conditions (Kim et al., 2012; Jo et al., 2009).

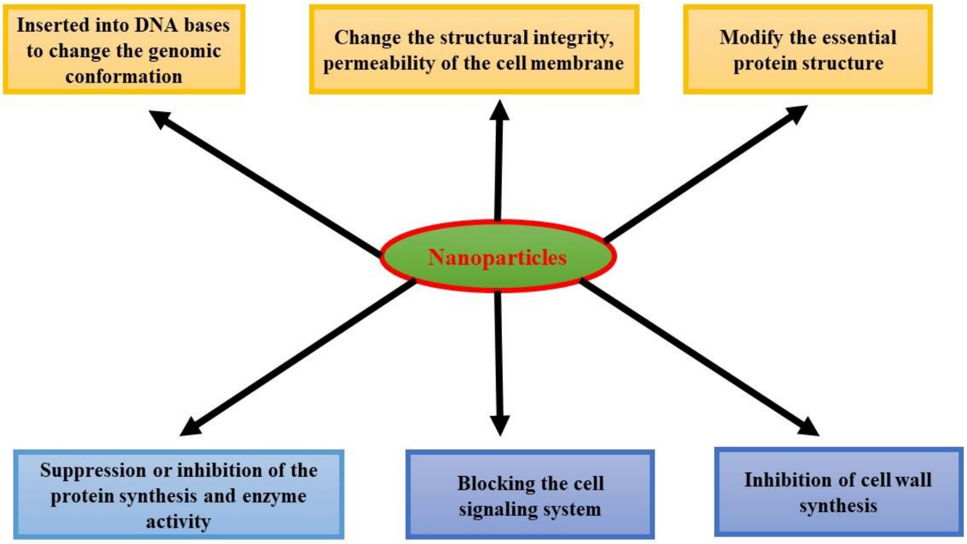

Fig 2. Nanoparticles act over pathogenic bacterial cells at their biomolecular level

Indeed, nanotechnology has a promising scope of application in the area of agrosystem, medicine design and food processing sector. Nanoparticles have great potential if exploited properly. In the use of NPs encapsulated pesticides, fertilizers and protective agrochemicals against several pathogens and pest, etc. Many plant diseases and pollutants including pesticidal residues detected by using nanosensors. Using nanotechnology, it can progress the entire society (Ghormade et al., 2011; Fu et al., 2020). Study revealed that the efficiency and mechanisms of various silver nanoparticles and their composites show potential for antibacterial activity (Wahab et al., 2021).

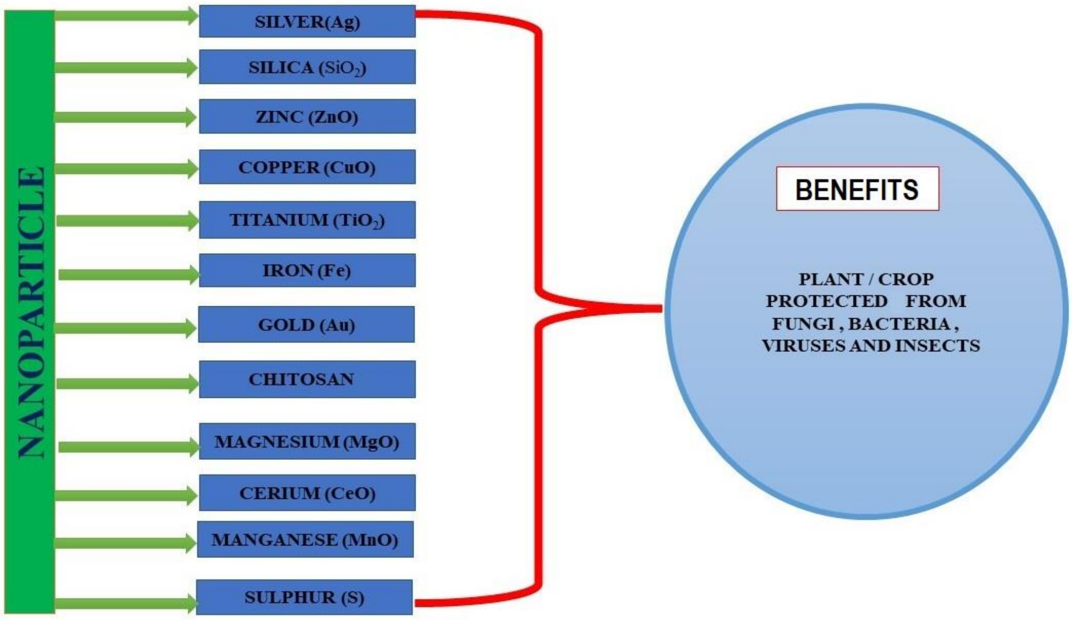

Fig 3. Nanoparticles involved in plant disease management and protection

Table 1. Effects of nanoparticles on various types of pathogens

Nanoparticles	Effect on pathogenic organism	References
Silver (Ag)	*Fusarium udum*, *Fusarium oxysporum f. sp. ciceris (Foc)*, *Stemphylium vericans*, and *Xanthomonas PV punicea*	(Kim, 2009)
	Bipolaris sorokiniana & (spot blotch of wheat) and *Magnaporthe grisea* (rice blast)	(Jo et al., 2009)
	Trichoderma sp. and *Candida albicans* and *Phoma glomerata*	(Gajbhiye et al., 2009)
	Salmonella typhi, E. coli, Staphylococcus aureus and *Bacillus subtilis*	(Sadeghi and Gholamhoseinpoor, 2015)
	Klebsiella pneumoniae, Bacillus subtilis, Pseudomonas aeruginosa and Salmonella paratyphi	(Sadeghi et al., 2015)
	Streptococcus pyogenes, Pseudomonas aeruginosa, Escherichia coli, Bacillus subtilis and Staphylococcus aureus	(Mariselvam et al., 2014)
	Aeromonas hydrophila, Pseudomonas fluorescens and Flavobacterium branchiophilum	(Vijay Kumar et al., 2014)
	Alternaria alternata, Sclerotinia sclerotiorum, Macrophomina phaseolina, Rhizoctonia solani, Botrytis cinerea, and *Curvularia lunata*	(Krishnaraj et al., 2012)
	Sarocladium oryzae	(Das and Dutta, 2021)
	Colletotrichum sp.	(Goswami et al., 2020)
	E. coli, Klebsiella granulomatis, Staphylococcus aureus, and *Pseudomonas aeruginosa;* fungi *(Aspergillus niger, Aspergillus flavus,* and *Aspergillus fumigatus*	(Elegbede et al., 2018)
	Fusarium oxysporum	(Shivashakarappa et al., 2022)
	(Staphylococcus aureus ATCC29213), Gram-negative bacteria (Escherichia coli ATCC25922), and fungi (Aspergillus niger NRC53, Fusarium solani NRC15	(Alharbi et al., 2023)
	Escherichia coli, Pseudomonas aeruginosa, Salmonella enterica, Staphylococcus aureus, Bacillus subtilis, and *Candida albicans*	(Mohammed et al., 2023)
Silica (SiO_2)	*Botrytis cinerea, Rhizoctonia solani, Collectotrichum gloeosporioides*	(Park et al., 2006)
Zinc (ZnO)	*Aspergillus fumigatus*	(Patra and Goswami, 2012)
	Penicillium expansum and *Botrytis cinerea*	(He et al., 2011)
Copper (CuO)	*Fusarium graminearum*	(Brunel et al., 2013)
	Fusarium oxysporum f. sp. Niveum, F. oxysporum f. sp. lycopersici or Verticillium dahliae	(Elmer and White, 2016)
	Xanthomonas campestris pv. Phaseoli, Xanthomonas oryzae pv.oryzae)	(An et al., 2022)
Titanium (TiO_2)	*Proteus mirabilis* (MTCC-442), bacteria *Aeromonas hydrophila* (MTCC-1739), *Escherichia coli* (MTCC-1677), *Pseudomonas aeruginosa* (MTCC-4030), and *Staphylococcus aureus* (MTCC-3160).	(Santhoshkumar et al., 2014)
	Broad bean stain virus (BBSV)	(Elsharkaway and Derbalah, 2018)
	Staphylococcus aureus, Escherichia coli	(Rajakumar et al., 2012)
Iron (Fe)	*Meloidogyne incognita*	(Sharma et al., 2017)
Gold (Au)	Barley yellow mosaic virus	(Alkubaisi et al., 2015)
Chitosan	Aphid (*Aphis nerii*), cotton leafworm (*Spodoptera littoralis*), root-knot nematode (*Meloidogyne javanica*), and nymphs of the spear psylla (*Cacopsylla pyricola*)	(Malerba and Cerana, 2016)
Magnesium (MgO)	*Ralstonia solanacearum*	(Imada et al., 2016)
	Alternaria alternata, Fusarium oxysporum, Rhizopus stolonifera, and Mucor plumbeus	(Wani and Shah, 2012)
Cerium (CeO)	*F. oxysporum f. sp. lycopersici*	(SNO, 2023)
Manganese (MnO)	*V. dahliae* on eggplant and *F. oxysporum f. sp. niveum* on watermelon.	(Elmer et al., 2018)
Sulphur	*A. niger, F. oxysporum, F. solani, and Venturia inaequalis*	(Choudhury et al., 2010; Rao and Paria, 2013)
Carbon Nanotube	Tobacco Mosaic Virus (TMV)	(Adeel et al., 2021)
Nickel oxide NPs (NiO NPs)	Cucumber mosaic virus (CMV)	(Hamed Derbalah and Elsharkawy, 2019)

Nanobiosensor

According to the density of pathogen showing signal due to biomolecular interaction between pathogen (analyte) and nanoparticles which is then recognized by digital detector. A study revealed that a nanobiosensor used nano-gold (Au) to identify single-stranded oligonucleotides to detect as little as 15 ng of *R. solanacearum* genomic DNA in the farm soil (Khaledian et al., 2014). Study report that *Cowpea mosaic virus*, *Tobacco mosaic virus*, and *Lettuce mosaic virus* were detected through nanobased biosensors (Chartuprayoon et al., 2013; Lin et al., 2014). Another study revealed that useful detection of a viral disease rhizomania caused by *Beet necrotic yellow vein virus* in *Polymyxa betae* through Quantum dot biosensors (Safarpour et al., 2012). To check the use of harmful agrochemical, nanobiosensor technology is the emerging tool for early detection of pathogenic inputs thus increasing yield and profits (Bergeson, 2010; Khot et al., 2012).

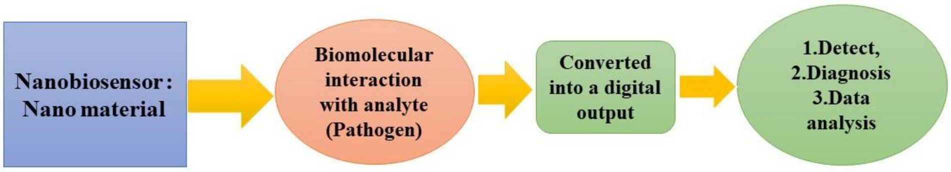

Fig 4: Working principle of nanobiosensor

Nanoparticles as vehicles for plant disease management

For the development of agricultural nano formulation several types of nanoparticles used as vehicles or carrier.

Table 2. Summary of some nanoparticle vehicles

Name of the nanoparticle vehicles	Nature of the vehicles	Type and mode Carrier materials	References
PHSNs/ MSNs	Spherical, porous hollow substances	Pesticides	(Mody et al., 2014; Barik et al. 2008)
Chitosan formulation	Aqueous media	Copolymer	(Kashyap et al., 2015; Li et al., 2011; Malerba and Cerana, 2016)
SLNs	Emulsion	Decreased organism's molecular mobility	(Yadav et al., 2013; Borel and Sabliov, 2014; Kumari et al., 2020)
LDHs	Hexagonal sheets	Molecular trap	(Xu et al., 2006; Mitter et al., 2017; Bao et al., 2016)
# PHSNs=porous hollow silica nanoparticles, MSNs= mesoporous silica nanoparticles, SLNs=Solid lipid nanoparticles & LDHs=Layered double hydroxides			

Conclusion

Over the past decade, there has been incredible progress in the field of nanotechnology across various sectors. This tremendous progress has resulted in the development of promising nanomaterials and nanoparticles for commercial applications. The agricultural sector has also benefited from nanotechnology, which has immense potential to mitigate environmental challenges such as drought, salinity, and disease management. Various methodologies have been adopted, with primary attention required in the agrosystem, including nanoparticles as a vehicle delivery system, nanofertilizers, nanoencapsulation, pest and disease management using nanoformulations of insecticides, herbicides, pesticides, bactericidal and fungicides. Nanobiosensors monitoring systems are also excellent tools for early disease diagnosis and agronomic trait monitoring for sustainable agriculture. Nanotechnology is progressing rapidly in its fields, and nanoparticles have the potential to provide efficient and green alternatives for plant protection and disease management in agriculture without harming the natural environment.

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