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NANOTECHNOLOGY IN PLANT DISEASE MANAGEMENT: DIAGNOSTIC INNOVATIONS AND TARGETED CONTROL STRATEGIES

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ABSTRACT

Plant pathogens responsible for crop diseases provide significant risks to the world food supply. Efficient diagnostic instruments for the prompt identification of plant diseases are crucial for ensuring agricultural sustainability and global food security. Plant infections remain the foremost agricultural challenge globally, serving as significant yield-limiting factors that substantially reduce crop output by 20-40% worldwide. Conventional disease management approaches have disadvantages, including environmental contamination, the emergence of resistance in infections and detrimental impacts on non-target species. There is a necessity for environmentally sustainable and effective alternative techniques to manage pests and diseases. Nanotechnology provides novel perspectives in biotechnology and agriculture, possessing significant potential to transform plant disease control systems through the utilisation of the distinctive characteristics of nanoparticles (NPs) and nanodevices. Consequently, efficient diagnostic techniques for the rapid detection of plant pathogens during the initial phases of infection are crucial for maintaining agricultural sustainability and food security. Plant protection is achievable through the application of nanotechnology technologies such as microneedle patches, nanopore sequencing, nanobarcodeing, nanobiosensors, quantum dots, metal nanoparticles, miRNA-based nanodiagnostics and array-based nanosensors for the diagnosis of plant pathogens. This review offers a thorough examination of nanotechnology's function in plant disease management, encompassing detection, targeted control and the enhancement of plant defence mechanisms.
***Keywords*:** Nanodiagnostics, Nanosensors, Smart Delivery, SAR, Precision Pathology.

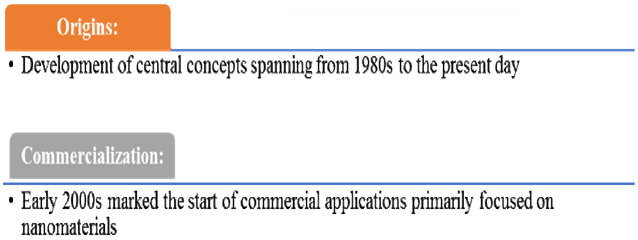
Introduction

With the increase of global food consumption due to climate change, nanotechnology has the potential to sustainably address disease concerns. Nanotechnology is recognised as the most rapidly advancing scientific discipline of the 21st century, seen as the foundation of the forthcoming industrial revolution. Nanotechnology is seen as a potential advancement in plant disease control, providing innovative solutions to address the numerous challenges confronting agriculture. Nanotechnology is a scientific subject focused on the design, production and use of structures, devices and systems by manipulating atoms and molecules at a scale of less than 100 nanometres. This alteration resulted in unique features and behaviours; its high reactivity is attributed to the greater surface area relative to volume that nanoparticles possess compared to macroscopic particles. These nanoparticles have remarkable physicochemical features, including altered thermal conductivity, chemical stability, catalytic reactivity and biological activity, which are absent in the identical materials at the macroscopic scale (Edelstein and Cammaratra, 1996). Remarkable characteristics render them advantageous in several applications, including high-sensitivity biomolecular detection, disease diagnostics and the development of antimicrobial and therapeutic medicines (Prasad, 2009).

The recent advancements in nanotechnology have significantly enhanced the utility of nanoparticles as multifaceted instruments, applicable across various domains, including high-sensitivity biomolecular detection, disease diagnostics and the formulation of antimicrobial and therapeutic agents. Throughout the years, nanotechnology has demonstrated significant potential in the management of plant diseases. All global crops are vulnerable to a wide range of bacterial, fungal and viral diseases, as well as insect infestations. The primary constraint in the agricultural sector to fulfil food security requirements is the management of plant diseases. Effective disease management in agriculture plays a crucial role, as plant diseases significantly threaten global food security by resulting in reduced food crop production, diminished yields, loss of species diversity, increased mitigation costs from control measures, adverse effects on human health and environmental degradation. Conventional disease management approaches, including chemical pesticides and fungicides, although somewhat successful, possess drawbacks such as environmental contamination, the emergence of resistance in infections and detrimental impacts on non-target species. Nanotechnology can boost plant disease resistance by delivering defense-related genes or signalling molecules. Nanocarriers target plant tissues to release chemicals. Nanotechnology helps target and treat plant diseases. Nanoscale devices and biosensors will help identify and treat biomarkers and illnesses early. It also advances new diagnostics, such as a microRNA detection system, for more accurate and faster diagnoses (Shivashakarappaa *et al*., 2022). Sustainable agriculture practises can protect crop health and productivity while reducing synthetic pesticide use. Even though nanotechnology is gaining popularity and making progress in plant disease control, more research is needed to fully understand its potential.

This review aims to address this gap by examining the latest research and advancements in nanotechnology-based methods for controlling plant diseases. This chapter aims to facilitate future research and practical applications in agricultural innovation by synthesising existing knowledge and recognising significant obstacles and possibilities. The literature for this review was gathered from Scopus, PubMed and Google Scholar databases, using keywords such as 'nanoparticles', 'plant disease management', 'nanodiagnostics', 'nanoformulations' and 'smart delivery systems'. Only peer-reviewed articles from 2005 to 2024 were considered.

History of Nanotechnology



The history of nanotechnology is extensive and diverse, spanning several centuries and encompassing contributions from a multitude of scientists and researchers. One significant milestone in the advancement of nanotechnology is Michael Faraday's investigation of gold colloids conducted in 1831. Faraday's research on colloidal properties, characterised by the uniform dispersion of one substance within another, is essential to the field of nanoparticle study. Nonetheless, the concept of nanotechnology began to emerge in the mid-20th century. The inception of nanotechnology is often attributed to Nobel Laureate Richard Feynman, who delivered a lecture entitled "There's Plenty of Room at the Bottom" in 1959. This lecture is widely regarded as the first systematic examination of nanotechnology. In the lecture, Feynman explored the potential for matter fabrication at the nanoscale and presented his audience with two challenges: the construction of a nanomotor and the miniaturisation of text to the extent that the entire Encyclopaedia Britannica could be inscribed on the head of a pin. Feynman's contributions generated considerable interest in the field, prompting other researchers to explore the potential applications of nanotechnology shortly thereafter. In 1974, Japanese researcher Norio Taniguchi introduced the term "nanotechnology" and developed materials at the nanoscale. Taniguchi built upon the foundations established by Faraday and Feynman, facilitating advancements in the field of modern nanotechnology. Significant advancements occurred in the 1980s and 1990s with the invention of the scanning tunnelling microscope and the atomic force microscope. These instruments enabled researchers to visualise and manipulate discrete atoms and molecules. Additionally, during the late 1990s and early 2000s, nearly all industrialised countries launched nanotechnology programs, leading to a worldwide expansion of nanotechnology initiatives.

Basics of Nanotechnology

Nanoparticles and their Properties

Nanoparticles (NPs) are substances characterised by dimensions on the nanometre scale, often between 1 and 100 nanometres. Owing to their diminutive dimensions, nanoparticles demonstrate distinctive features that set them apart from bulk materials.

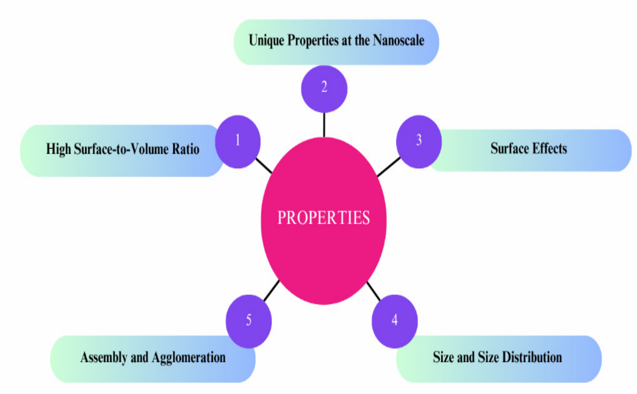


Fig. 1 : Nanoparticles Properties

A defining trait of nanoparticles is their remarkably large surface area in relation to their volume. This attribute results from their diminutive size and extensive surface area, which enhance reactivity and surface-dependent characteristics. At the nanoscale, materials frequently display unique physical, chemical, optical and mechanical characteristics that diverge from those of their bulk equivalents. These qualities may encompass augmented catalytic activity, quantum confinement phenomena, adjustable optical characteristics and heightened mechanical strength, among others. The nanoparticle surface significantly influences their characteristics and interactions with the surrounding environment. The stability, reactivity and functioning of nanoparticles can be influenced by their surface chemistry, composition, structure and shape. Nanoparticles exhibit variability in dimensions and size distribution, influencing their characteristics and uses. Regulation of particle size and size distribution is crucial for attaining the required capabilities and performance in nanoparticle-based materials and devices. Nanoparticles can self-assemble or agglomerate to create bigger structures, such as nanocomposites or nanoparticle aggregates.

Categories of nanoparticles and characterization

Nanoparticles can be categorized based on various characteristics such as their composition, size, shape, surface properties and application.

Table 1 : Categories of nanoparticles and characterization

Category	Nanoparticles	Description
Composition-based categories	Metal nanoparticles	Nanoparticles made of metals such as gold, silver, platinum, etc.
	Metal oxide nanoparticles	Nanoparticles composed of metal oxides like titanium dioxide (TiO_2), zinc oxide (ZnO), etc.
	Carbon-based nanoparticles	Including fullerenes, carbon nanotubes, graphene, carbon dots, etc.
	Polymeric nanoparticles	Nanoparticles composed of polymers like poly (lactic-co-glycolic acid) (PLGA), polystyrene, etc.
Size-based categories	Ultrafine nanoparticles	Typically, less than 100 nm in size.
	Quantum dots	Semiconductor nanoparticles with dimensions in the nanometer range, often used in electronics and medical imaging.
Shape-based categories	Spherical nanoparticles	Nanoparticles with a spherical shape.
	Rod-shaped nanoparticles	Nanoparticles with elongated, rod-like shapes.
	Wire-shaped nanoparticles	Nanoparticles with a wire-like morphology.
	Janus nanoparticles	Nanoparticles with two distinct faces or regions.
Surface functionalization-based categories	Surface-modified nanoparticles	Nanoparticles with modified surface properties for specific applications, such as PEGylation (attaching polyethylene glycol chains) for improved biocompatibility.
	Biomolecule-functionalized nanoparticles	Nanoparticles functionalized with biomolecules like proteins, antibodies, DNA, etc.

Synthesis Methods for Nanomaterials

There are various chemical, biological and physical methods by which synthesis of nanomaterials could have been performed. Each method is directed to a particular mechanism once with its advantage in producing nanomaterials with characterized properties.

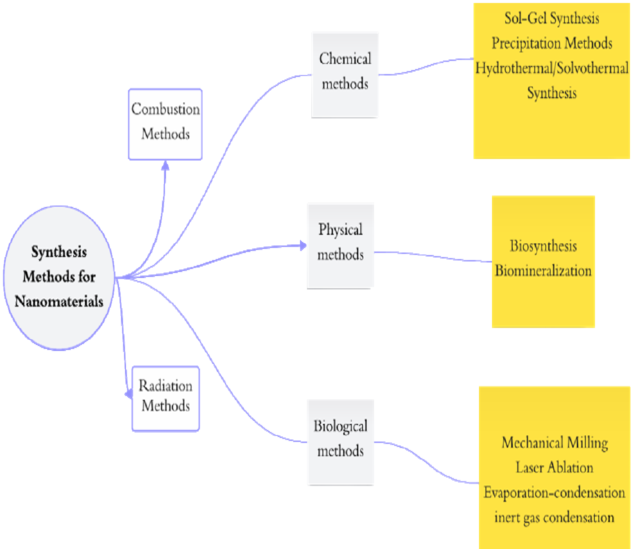


Fig. 2 : Synthesis Methods for Nanomaterials

Types of Nano-based formulations

Nanofertilizers enhance nutrient absorption, fortify plant defence mechanisms, exhibit antimicrobial properties, improve stress resilience, enable precise application, reduce ecological impacts and promote soil health improvement.

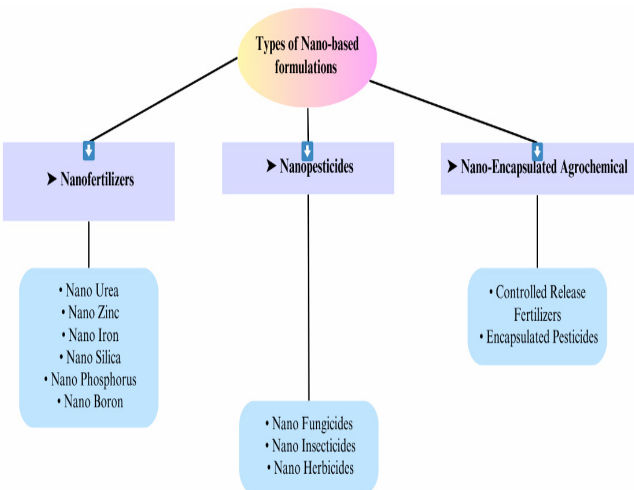


Fig. 3 : Types of Nano-based formulations

Nano Urea provides nitrogen efficiently, whereas Nano Zinc and Nano Iron facilitate the production of defence compounds and Nano Silica improves stress tolerance. Nanopesticides, which utilise nanoparticles as carriers for traditional pesticides or as active ingredients, demonstrate improved efficacy through enhanced stability, solubility and target specificity. These formulations enable the regulated release of active ingredients, thereby prolonging their effectiveness and minimising environmental impacts.

Nano-Technology in Plant Disease Management

Nanoparticles as Carriers for Insecticides, Fungicides and Herbicides

Nanoparticles serve as effective carriers for delivering pesticides to target sites within plants, ensuring precise and controlled release of active ingredients. By encapsulating pesticides within nanocarriers, their stability and bioavailability can be enhanced, leading to improved efficacy and reduced environmental impact. Examples include polymeric nanoparticles for delivering fungicides and herbicides, lipid-based nanoparticles for pesticide encapsulation and mesoporous silica nanoparticles for sustained release of active compounds.

Polymer nanoparticles example, for example, zein nanoparticles loaded with botanical insecticides demonstrated a dual advantage where, when consumed by pest larvae release of the active compound occurred and when not consumed, then very slow release occurred. Cationically capped hollow mesoporous silica nanoparticles with the loading of the insecticide avermectin by cyclodextrin have revealed controlled release that is inducible by the activity of α-amylase from the target pest species. Polysaccharide-based nanocarriers, including chitosan, pectin and cellulose, have been loaded with a variety of targeted insecticides, bactericides and botanical compounds.

The early 2000s marked the initiation of the practice of loading pesticides onto nanoparticles. Silica was examined in 8 studies, chitosan in 11 studies and lipids in 4 studies, making them the most frequently investigated nanoparticle carriers. The pests most frequently targeted were *Spodoptera litura* (5 studies), *Tetranychus urticae* (4 studies) and *Helicoverpa armigera* (4 studies). Nanoparticles can enhance the solubility of insecticides with low water solubility, thereby reducing their toxicity. Exposure of *H. armigera* larvae to dendrimers containing hydrophobic thiamethoxam resulted in increased absorption and a subsequent rise in mortality (Liu *et al.*, 2015). A common issue associated with pesticide loss post-application is the evaporation or volatilisation of the active ingredient. The application of acetone-dispersed silica encapsulated in α-pinene and linalool to castor leaves demonstrated that *S. litura* and castor semilooper, which consumed the treated leaves, exhibited reduced appetite, ultimately leading to starvation and death. This demonstrates that the volatility issues were addressed through the active's interaction with nanoparticles (Rani *et al*., 2014). The toxicity of insecticides may be diminished through the gradual release of active chemicals. Imidacloprid, when loaded onto sodium alginate nanoparticles, was evaluated for cytotoxicity. The findings indicated that the pesticide nanoformulation exhibited significantly lower toxicity compared to the original pesticide at the same dosage (Kumar *et al*., 2016).

To evaluate the efficacy of the nanofungicide, a range of fungi was utilised. The three nanoparticle carriers most frequently examined are chitosan, silica and polymer blends. The application of carbendazim-loaded polymeric nanoparticles demonstrated an enhanced fungal inhibition rate against *Fusarium oxysporum* and *Aspergillus parasiticus* compared to the use of carbendazim alone. Research on phytotoxicity demonstrated that carbendazim produced using nanotechnology exhibited reduced toxicity for the germination and root growth of *Cucumis sativa, Zea mays and Lycopersicum esculentum* (Kumar *et al*., 2017). Kaman and Dutta's 2019 study on silver nanoparticles (AgNPs) established their inhibitory efficacy against fungal pathogens, revealing a direct correlation between inhibition percentage and concentration. This study emphasises the efficacy of AgNPs as effective antifungal agents in the management of fungal diseases affecting crops. Padmavathi *et al*. (2022) examined the influence of nanotechnology on plant pathology, focussing on its role in enhancing pathogen detection and management. Sivasankarappa *et al*. (2022) emphasised the efficacy of nanobiosensors in addressing plant pathogens, facilitating swift and precise detection along with prompt intervention. These environmentally sustainable methods have demonstrated effectiveness and cost efficiency in microbial control.

Nanoparticles have been utilized as carriers for genetic material, such as nucleotides and proteins, to induce disease resistance in crops (Dong *et al*., 2022). These nanocarriers offer unique chemical and physical characteristics that facilitate the delivery of genetic materials into plant cells, overcoming barriers like the plant cell wall (Sharma *et al*., 2023). By encapsulating pesticides in controlled-release matrices, nanoparticles increase efficiency, reduce toxicity and minimize environmental contamination in crops (Banerjee *et al*., 2022). Furthermore, engineered nanoparticles can act as "magic bullets" to deliver agrochemicals precisely to specific tissues, revolutionizing crop production by improving disease resistance, nutrient utilization and crop yield (Habeeba, 2022). Nanotechnologies include pollen magnetofection and gene nanocarriers for the improvement of pest, weed and disease management in agriculture, helping to ensure better crop protection and sustainability.

Herbicide studies primarily emphasise reducing non-target toxicity compared to research on insecticide and fungal nanocarriers. A wider variety of nanoparticles has been employed in the formulation of herbicides, including nanosized tubular halloysite, platy kaolinite, amino-activated iron (II, III) oxide magnetic nanoparticles, montmorillonite clay layers coated with a pH-sensitive polymer and nanosized rice husks. Imazapic and imazapyr, two herbicides, were incorporated into chitosan nanoparticles to reduce their toxicity (Maruyama *et al*., 2016). Both nanoparticle-loaded and non-nanoparticle herbicides demonstrated comparable efficacy against the target weed, Bidens pilosa. Toxicity was lower in Chinese hamster ovary cell cultures and Allium cepa assays when compared to free herbicides.

Nanotechnology in Plant Disease Detection

Nanotechnology tools such as microneedle patches, nanobarcodeing and nanobiosensors have developed into effective diagnostic methods for the rapid and precise identification of plant pathogens, enabling high-throughput analysis and enhanced disease management. Nanostructures such as quantum dots, nanorods and nanoparticle-conjugated antibodies enhance sensitivity and specificity for rapid pathogen detection, particularly in the identification of viral pathogens in crops (Shivashakarappa *et al*., 2022).

Early Diagnosis of Disease Using Nanosensors

Among the advanced nanosensing platforms, Nanoparticle-based sensors use nanomaterials like gold, quantum dots and magnetic nanoparticles modified with antibodies or aptamers to target pathogens. In parallel, nanowire sensors use electrical characteristics to identify environmental changes caused by pathogens, offering enhanced sensitivity and real-time monitoring.

Khaledian *et al*. (2017) employed a biosensor incorporating nano-Au and single-stranded oligonucleotides to detect the genomic DNA of *Ralstonia solanacearum* in soil samples. Various studies indicate the efficacy of antibody-based biosensors in detecting plant pathogens (Chartuprayoon *et al*., 2013; Lin *et al*., 2014). Titanium Dioxide (TiO_2) and Tin Oxide (SnO_2) nanoparticles have been utilised on carbon electrodes for the detection of p-ethylguaiacol, a biomarker associated with the pathogenic fungus *Phytophthora cactorum* (Fang *et al.*, 2014). Quantum dot-based nanosensors demonstrate high sensitivity and specificity in the detection of plant viruses. QD-based sensors have been developed for the detection of exotoxin. A gene sequence derived from the bacterium *Pseudomonas aeruginosa*, recognised as a prevalent plant pathogen (Khiyami *et al.*, 2014). Bacteriophage-mediated biosensors have been developed for the detection of plant pathogens, primarily targeting viruses and bacteria. Researchers have developed bacteriophages that target *Xanthomonas oryzae* pv. *oryzae* to deliver reporter genes, including Green Fluorescent Protein (GFP) and luciferase. Upon encountering their target bacteria, these phages infect and replicate within the bacterial cells. The infection leads to the expression of reporter genes, resulting in fluorescence or luminescence in the infected bacterial cells. The emission can be detected with specialised equipment, offering a rapid and sensitive method for identifying the pathogen in rice plants (Stefani *et al.*, 2021). These biosensors leverage the selectivity of bacteriophages for their host organisms to enable rapid and sensitive pathogen detection. Magnetic gold nanoparticle biosensors (AuMNPs) can be functionalised with specific antibodies or DNA probes to capture target plant pathogens. The interaction between the pathogen and AuMNPs can be identified using techniques like ELISA or PCR. The system has been effectively utilised for detecting Ralstonia solanacearum, a bacterial wilt disease affecting various crops (Shivashakarappa *et al.*, 2022).

Nanowire biosensors function as transducers for pathogen detection in plants. Silicon nanowire field-effect transistors are utilised for the detection of plant viruses by monitoring changes in electrical signals caused by virus binding to the nanowire surface. Film of nanostructured cerium oxide Immunosensors employ cerium oxide nanofilms for the immobilisation of antibodies targeting specific plant pathogens. The electrochemical response of the sensor is a consequence of the pathogen's binding to the antibodies, enabling swift and precise diagnosis. This method has recently been employed for the detection of mycotoxins produced by fungi. Gold nanoparticle arrays, modified with chemical ligands, exhibit unique colour patterns upon exposure to volatile organic compounds emitted by diseased plants. Electronic nose sensors are capable of distinguishing among different plant pathogens and abiotic stresses by analysing their volatile organic compound profiles. Nanosensors are engineered to detect viroids, which are small, single-stranded RNA molecules capable of causing diseases in plants.The MFDetectTM technology serves as a rapid, specific and high-throughput assay for detecting the Hop Latent Viroid in cannabis plants. The technology employs a novel, precise and high-throughput method for the early detection of HLVd in plant development, thereby providing a reliable assay for mitigating the spread of the viroid (Marti *et al.*, 2023). Nanopore sequencing of barcoded molecular probes has been effectively utilised for the highly multiplexed detection of diverse biological targets, such as microRNAs, proteins and small molecules. Researchers have developed a label-free method for detecting microRNA expression patterns with enhanced sensitivity by utilising DNA computing technology on nanopores. This advancement has markedly enhanced detection limits, facilitating the prospective application of this method in the early and uncomplicated diagnosis of diseases (Koch *et al.*, 2023).

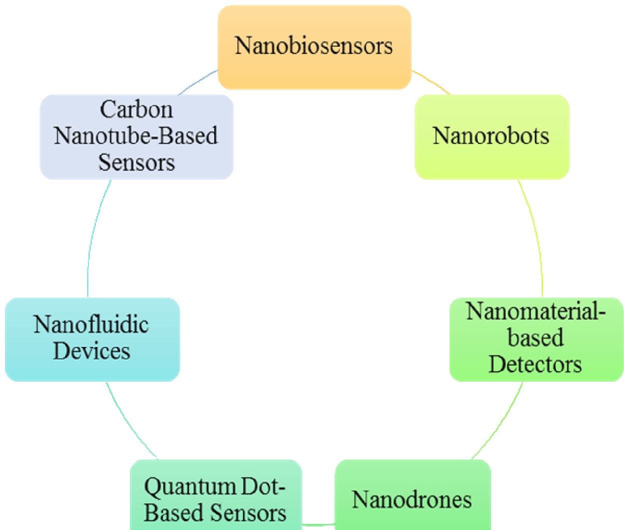


Fig. 4 : Main Types of Nanodevices

Nanotechnology for Targeted Disease Control

Nanoparticles as Antimicrobials:

Various types of nanoparticles, such as silver nanoparticles, titanium dioxide nanoparticles and zinc oxide nanoparticles, exhibit antimicrobial properties that can be harnessed for disease control in plants. These nanoparticles can interact with microbial cell membranes, leading to structural damage and eventual cell death.

Table 2 : Different types of metal/ metalloid nanoparticles as antimicrobials.

Nanoparticles	Mode of action	Reference
Metallic NPs	Cause hyphal plasmolysis, damaging fungal cell walls, resulting in cell death	Zhang *et al.*, 2022
Copper NPs	Direct toxicity, induction of oxidative stress, inhibition of enzymes and nutrient uptake and alteration of gene expression, while also potentially enhancing the plant's defense mechanisms.	Rai *et al.*, 2018
Chitosan NPs	Induce viral resistance in plant tissues by protecting them against infections caused by the mosaic virus of alfalfa, snuff, peanut, potato and cucumber	Kashyap *et al.*, 2015
Iron NPs	Direct contact with fungal cell membranes and disturb the cell's permeability, reducing the cell's growth and eventually causing death through the development of oxidative stress. FeONPs synthesized using plant extracts like *Mentha spicata* strongly inhibited the growth of the plant pathogen *Phytophthora infestans.*	Khan *et al.*, 2022
Silver NPs	Direct interaction with microbial cells, causing physical damage, oxidative stress and disruption of cellular functions. Silver nanoparticles also inhibited the activity of *Alternaria alternata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Rhizoctonia solani*, *Botrytis cinerea* and *Curvularia lunata.*	Krisnaraj *et al.,* 2012; Tariq *et al.*, 2022
Silica NPs	Induce plant immunity, activate the signaling pathways of SA and thus lead to the production of systemic acquired resistance. This SA-dependent resistance reduced disease severity by almost 70% in rice when challenged with the rice blast fungus *Magnaporthe oryzae.* SiNPs were also reported to reduce the severity of several important diseases such as sheath blight, brown spot and grain discoloration in rice.	Goswami *et al.*, 2022
Gold NPs	When poly-dispersed gold nanoparticles were introduced into plants through mechanical abrasion, they were observed to melt and dissolve the Barley yellow mosaic virus particles, thereby conferring resistance to the plant.	Alkubaisi *et al.*, 2017
Zinc NPs	Platelet-shaped ZnO particles possess antifungal activity against *Fusarium solani*.	Pariona *et al.*, 2020
Titanium dioxide NPs	Reported effective in controlling Xanthomonas bacterial blight in geranium and leaf spot on poinsettia (Norman and Chen, 2011). Tio_2 NPs in fertilizers have produced protection from bacteria and inactivation of viruses.	Sadeghi *et al.*, 2017

Mechanism of action of nanoparticle-based systems and their effects

The interactions between nanoparticles and microbes are complex and multi-dimensional, leading to various mechanisms that facilitate pathogen inactivation, inhibit growth and suppress virulence factors.

Physisorption

Physical adsorption refers to the process in which nanoparticles adhere to pathogen surfaces through van der Waals forces, electrostatic interactions, or hydrophobic interactions. This binding may inhibit pathogen growth and suppress virulence factors. AgNPs have been shown to inhibit bacterial growth through physical adsorption on the bacterial surface, leading to disruption of the cell membrane and inhibition of metabolic processes.

Disruption of Membranes

Membrane disruption represents a mechanism through which nanoparticles interact with pathogens by compromising their cell membranes. This can occur through various mechanisms, including the generation of reactive oxygen species (ROS), the creation of pores in the cell membrane, or the disruption of cell wall structures. ZnO nanoparticles have been shown to cause membrane disruption in bacteria through the generation of reactive oxygen species and subsequent leakage of cellular contents.

Induction of Oxidative Stress

Oxidative stress induction represents a mechanism through which nanoparticles interact with pathogens, leading to the formation of reactive oxygen species that can damage cellular components and disrupt metabolic processes. This can occur via multiple mechanisms, including the release of metal ions, the generation of reactive oxygen species during nanoparticle decomposition and the inhibition of antioxidant enzymes. AgNPs and CuNPs have been shown to induce oxidative stress in bacteria by releasing metal ions and generating reactive oxygen species.

Size and Morphology of Nanoparticles

The dimensions and morphology of nanoparticles influence their interactions with pathogens. Smaller nanoparticles typically exhibit greater efficacy in inducing oxidative stress and membrane perturbation due to their enhanced surface area and reactivity. Larger nanoparticles may exhibit enhanced efficacy in physically adsorbing onto pathogen surfaces, attributable to their increased size and surface area.

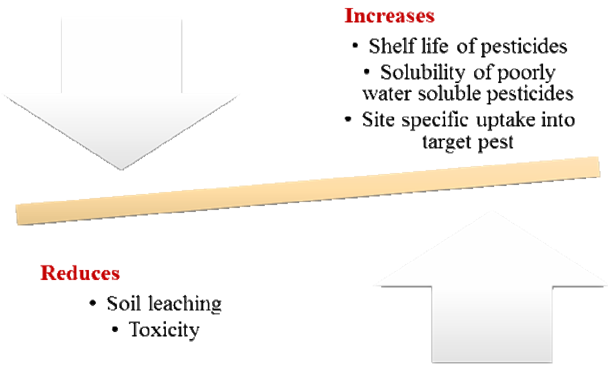
Surface Chemistry of Nanoparticles

The surface chemistry of nanoparticles is a factor that may affect interactions with pathogens. Hydrophilic surface characteristics of nanoparticles enhance their efficacy in inducing oxidative stress and disrupting membranes, attributed to their heightened reactivity and capacity for interaction with cellular components. Nanoparticles with hydrophobic surfaces may exhibit greater efficacy in physically adsorbing onto pathogen surfaces due to their enhanced affinity for lipids and other hydrophobic molecules.

Application of nanoparticles in the management of plant diseases

Nanoformulations of traditional pesticides provide multiple benefits, including enhanced bioavailability, improved pathogen targeting and decreased dosage requirements. Reducing pesticide particle size to the nanoscale improves their ability to penetrate plant tissues, facilitating enhanced uptake and distribution (Wang *et al*., 2022). Nanopesticides featuring stimuli-responsive release mechanisms can be engineered and regulated by variables including light, humidity, pH and temperature. This approach aims to improve utilisation efficiency, minimise short-term effects, ensure effective pest control, decrease leaching and drift losses and mitigate environmental damage (Chaud *et al*., 2021). Polymeric and hydrogel-based nanoparticles provide significant benefits for drug delivery due to their favourable safety profile, high loading capacity and resistance to degradation. This distinctive nanomaterial approach is effective in facilitating spatial and temporal cargo release from cellular and animal models in response to environmental stimuli (e.g., UV, NIR, ultrasound, etc.).

The overuse of pesticides presents environmental risks and health issues, leading to a decline in their preference due to associated health concerns. Fewer than 0.1% of pesticides effectively reach their intended sites of action, attributable to factors such as air loss, runoff, spray drift, off-target deposition and photodegradation. These nanoparticles present viable alternatives to chemical pesticides in crop protection, attributed to their distinctive properties such as a high surface area-to-volume ratio, adjustable surface chemistry and biocompatibility.



Illustrative schematic 1. Nanoparticles act as carriers and can provide several benefits

Challenges and Limitations

Nanoparticles in agriculture pose risks to human health and the environment because of their small size, unique characteristics and the possibility of bioaccumulation. The regulatory challenges include toxicology, environmental impact and non-target organism effects. Technically, this involves nanoparticle stability, delivery efficacy and issues of scalability. Other obstacles to adoption relate to the high cost, unknown and unexplored nanoparticle interactions and the lack of infrastructure on disease diagnostics and treatment. The convergence of nanotechnology with gene editing, precision agriculture and digital farming will be able to improve crop health and productivity, enhance disease resistance, reduce chemical usage and optimize input use. The agricultural sector must examine the environmental effects of nanomaterials to mitigate potential risks to ecosystems and human health. Investigating the stability, mobility and bioaccumulation of nanoparticles in soil and water systems is essential. Global regulatory authorities are formulating guidelines for the responsible application of nanotechnology in agriculture, focusing on comprehensive risk assessment, labelling and monitoring practices.

Conclusion and Future Prospects

Nanotechnology has been a game-changing tool in modern plant disease control, offering precise, effective and environmentally friendly substitutes to conventional methods. The physicochemical properties of nanoparticles such as a high surface area-to-volume ratio, tunable surface functionality and controlled release behavior have been exploited for pathogen detection, targeted agrochemical delivery and plant immunity improvement. Nanosensors, nanopesticides and nanoformulations are transforming early diagnosis and targeted treatment, enabling real-time monitoring and precision agriculture. Despite such promising developments, the scale-up of nanotechnology in agriculture is currently hampered by regulatory uncertainties, nanoparticle biosafety, environmental fate and the scalability of green synthesis protocols. Interdisciplinary research that combines plant pathology, material science and nano-biotechnology is needed to realize the full potential of nanotechnological interventions against crop diseases. Future studies need to emphasize the integration of nanodevices with digital agriculture platforms, the creation of biodegradable nanomaterials and the tightening of risk assessment measures. With further innovation and judicious application, nanotechnology can construct robust agroecosystems, improve food security and enable sustainable agricultural systems in the context of climate change and new phytopathogens.

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