Nanotechnology in Plant Pathology: Innovations for Disease Resistance and Crop Health

Vanapalli Vasanthi[1], Manjula Ramappa[2]*, Prathipati Geethika[1], Alex Khalko[3] and Kalpana[4]

[1]Department of Plant Pathology, Agricultural College, Bapatla, ANGRAU, Andhra Pradesh, India
[2]Department of Plant Pathology, College of Agriculture, Raichur, Karnataka, India
[3]Department of Plant Pathology, College of Agriculture, Jawaharlal Nehru Krishi Vishwavidyalaya, Jabalpur, MP, India-482004
[4]Department of Agricultural Entomology, College of Agriculture, Dharwad, Karnataka, India

Corresponding Author
Manjula Ramappa
Email: manjula84gvt@gmail.com

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ABSTRACT

Plant diseases pose significant threats to global food security and agricultural sustainability, leading to significant crop losses each year. Traditional methods of disease management, such as chemical pesticides and fungicides, have not only raised environmental concerns but have also led to the development of resistant strains of pathogens. In response to these challenges, nanotechnology has emerged as a cutting-edge approach, revolutionizing plant disease management with its innovative solutions. It offers an eco-friendly and efficient alternative by utilizing nanoparticles as highly effective delivery systems for agrochemicals, minimizing the quantity of active ingredients entering the ecosystem and reducing their environmental impact. Nanoparticles provide plant protection through two main mechanisms: (a) acting as carriers for pesticides and (b) serving as protective agents themselves. By enhancing the solubility and stability of pesticides, nanoparticles significantly increase their shelf life and improve the precision of site-specific targeting, thereby reducing

off-target effects and overall toxicity. Additionally, nanoparticles such as nanosilver, nanozinc, nanogold, nanosilica, nanochitosan and nanocopper have shown great promise in plant disease management, not only by enhancing the effectiveness of conventional agrochemicals but also by exhibiting antimicrobial properties themselves. Nanotechnology alters the physical, chemical and biological properties of conventional pesticides, enabling plants to combat weeds, diseases and pests more efficiently. The application of nanomaterials in agriculture thus holds the potential to address global food security challenges while promoting sustainable farming practices, offering an advanced and eco-conscious solution for crop protection in the modern era.

INTRODUCTION

Nanoparticles (NPs), defined by having at least one dimension under 100 nm, exhibit unique physical, chemical, and biological properties that distinguish them from bulk materials and molecular counterparts. The application of nanotechnology in agriculture holds immense potential, offering solutions in areas like plant hormone delivery, seed germination, water management, gene transfer, nanobarcoding, nanosensors, and controlled agrochemical release. Nanoparticles have been effectively used to combat agricultural threats such as insects, bacteria, fungi, and viruses, either through direct application to plant seeds, foliage, or roots. Metal-based nanoparticles like silver, zinc oxide, copper, and titanium dioxide have been extensively studied for their potent antibacterial, antifungal, and antiviral properties. In agricultural formulations, nanoparticles act as carriers for active molecules like fungicides, insecticides, herbicides, and RNAi-inducing molecules. By encapsulating or adhering to these molecules, nanoparticles improve solubility, reduce toxicity, and allow for sustained and targeted release, enhancing the effectiveness of these formulations. For insecticides, nanoparticles help overcome solubility issues, reducing the need for harmful organic solvents and cutting both costs and toxicity. They also increase the stability of fungicides, minimizing volatilization and enabling controlled release, while in herbicides, they reduce toxicity to non-target plants, mitigating environmental damage. Furthermore, RNA interference (RNAi) technology, where nanoparticles deliver RNAi-inducing molecules to target viruses and pests, is emerging as a promising tool for pest and pathogen management. Given that pests and plant diseases annually destroy 20% to 40% of global crops, there is an urgent need for innovative solutions like these. Traditional plant disease management relies heavily on chemical pesticides, which pose significant risks to human health and the environment. Nanoparticles offer a sustainable, eco-friendly alternative, providing enhanced protection while reducing ecological harm (Hayles *et al.*, 2017; Worrall *et al.*, 2018; Mitter *et al.*, 2017; Flood, 2010).

SYNTHESIS OF NANOPARTICLES

The synthesis of nanoparticles can be broadly categorized into two main approaches: the *Top-Down* approach and the *Bottom-Up* approach. Both strategies are widely used in nanotechnology to create nanoparticles, but they differ significantly in their principles and techniques.

1. Top-Down Approach

The *Top-Down* approach involves breaking down bulk materials into nanosized particles by using various mechanical, chemical or physical processes. In this method, the bulk material undergoes processes like milling, lithography or etching to reduce its size to the nanoscale. The primary focus is on the "carving out" or "fragmentation" of a larger structure into smaller particles.

Common Methods in the Top-Down Approach:

Ball Milling: One of the most commonly used methods, ball milling involves grinding the bulk material into fine powders using high-energy mechanical forces. The process relies on collisions between the material and the balls inside the mill to gradually break down the particles into nanoscale dimensions (Daniel *et al*., 2004).

Lithography: Lithography is often used in the semiconductor industry and involves the use of light, electron beams or ion beams to etch nanoscale patterns on the surface of a bulk material (Singh *et al.*, 2012). This is especially useful in creating nanoparticles with well-defined shapes and sizes.

Laser Ablation: In this technique, a laser is used to irradiate the surface of the bulk material, causing it to vaporize and form nanoparticles in a controlled environment (Rao *et al.*, 2010). This method is particularly useful for synthesizing metal oxide nanoparticles.

2. Bottom-Up Approach

The *Bottom-Up* approach, in contrast, builds nanoparticles from atomic or molecular levels, assembling them into larger structures by controlling the chemical or physical interactions between atoms and molecules. This method allows for greater control over the size, shape and surface characteristics of the nanoparticles and often produces more homogeneous products than the Top-Down approach.

Common Methods in the Bottom-Up Approach:

Chemical Vapor Deposition (CVD): This process involves depositing atoms or molecules in vapor form onto a substrate, where they nucleate and grow into nanoparticles (Zhang *et al.*, 2017). CVD is widely used for producing nanoparticles of metals, semiconductors and carbon-based materials.

Sol-Gel Process: In the sol-gel method, metal precursors in a solution undergo hydrolysis and condensation reactions to form a colloidal gel, which eventually solidifies into nanoparticles (Brinker and Scherer, 1990). The sol-gel process is extensively used in synthesizing oxide-based nanoparticles like silica and titanium dioxide.

Co-precipitation: This method involves mixing metal salts with a reducing agent in solution, causing the metal ions to coalesce and form nanoparticles (Banfield *et al*., 2000). Co-precipitation is frequently used for synthesizing metal oxide and magnetic nanoparticles.

Self-Assembly: Nanoparticles can also be synthesized through self-assembly, where molecules arrange themselves into ordered structures due to intermolecular forces such as van der Waals interactions, hydrogen bonding and electrostatic interactions (Grzelczak *et al.*, 2010).

Characterization of Nanoparticles: After the biosynthesis of nanoparticles, characterization is essential to analyze their surface area, chemical composition, size, shape, and dispersity.

Zeta Potential: Measures the surface charge of colloidal nanoparticles in suspension. It helps assess stability; higher zeta potential indicates greater stability.

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X-ray Diffraction (XRD): Analyzes crystal structure and phase identification by measuring the scattering angles of X-rays. Useful for determining crystalline properties but may lose accuracy with amorphous samples or very small particles.

Fourier Transform Infrared Spectroscopy (FTIR): Detects organic functional groups on nanoparticle surfaces by exposing them to infrared light. The resulting spectrum provides information on chemical composition and bonding.

Electron Microscopy (EM):

Scanning Electron Microscopy (SEM): Produces 3D images by directing electron beams at a sample, revealing nanoparticle shape, size and dispersion.

Transmission Electron Microscopy (TEM): Focuses electrons through a sample to generate 2D images, offering detailed insights into nanoparticle size, shape and distribution.

Scanning Tunneling Microscopy (STM): Utilizes quantum tunneling to create atomically accurate surface images, primarily used for topographical analysis.

Dynamic Light Scattering (DLS): Correlates nanoparticle size with velocity in suspension based on Brownian motion, providing size distribution data.

Raman Spectroscopy: Involves laser light to analyze molecular vibrations and produces material-specific fingerprints, useful for studying chemical interactions and structure.

Table 1: Type of Nanoparticles

S. no	Nanoparticle Type	Properties of the Nanoparticle	Applications
1.	Silver Nanoparticles (AgNPs)	- Size, shape and surface charge affect antimicrobial efficiency. - Small size allows easy entry into bacterial cells, especially gram-negative bacteria. - Generates reactive oxygen species (ROS), inhibits DNA/RNA synthesis, disrupts cell membranes, and causes mitochondrial damage (Jain *et al.*, 2021).	Antibacterial, antiviral and antifungal activity against plant pathogens. - AgNPs can disrupt pathogen replication and cell structure.
2.	Silica Nanoparticles (SiNPs)	- Unique properties like large surface area, reactivity, and penetrating ability. - Enhance plant resistance by activating defense enzymes, promoting antimicrobial compounds, and triggering defense gene expression (Sai *et al.*, 2018).	- Forms a physical barrier by creating a second layer on the plant cuticle, preventing pathogen penetration (e.g., *Botrytis cinerea*, *Colletotrichum* spp.).
3.	Chitosan Nanoparticles	- Derived from chitin; inhibits fungal growth and causes cytological alterations. - Interacts with microbial cell membranes, causing disruption and leakage. - Binds to DNA/RNA, disrupting protein synthesis and metabolic processes (Oliul Hassan and Taehyun Chang, 2017).	- Antifungal properties effective against Fusarium spp., Botrytis cinerea, and other pathogens. - Modifies plant defense responses.
4.	Copper Nanoparticles (CuNPs)	- Cu-based compounds are ancient antifungals. - Release of Cu ions causes ROS production, membrane damage, and enzyme malfunction. - Cu ions bind to DNA, denaturing proteins and disrupting cellular processes (Rai *et al.*, 2018).	- Widely used in agriculture to prevent fungal diseases (e.g., downy mildew) by disrupting pathogen metabolism and cell integrity.

5.	Zinc Nanoparticles (ZnNPs)	- Direct attachment to bacterial cells disrupts membranes and leads to cytoplasmic leakage. - Produces ROS, inhibits mitochondrial functions, and causes DNA damage (Singh *et al.*, 2017).	- Antibacterial activity used to combat plant bacterial pathogens, leading to enhanced crop protection.

CONCLUSION

Nanotechnology holds immense potential to revolutionize agricultural practices, particularly in plant disease management. It offers innovative approaches such as advanced disease diagnostics, enhanced control measures and improved plant health through immune elicitors. The development of nanotechnology-based solutions, like nanopesticides, provides unparalleled benefits, including increased bioavailability, reduced toxicity, extended shelf life and controlled release of active ingredients. By leveraging these advancements, nanotechnology presents a sustainable and eco-friendly alternative, paving the way for more efficient, green solutions in plant disease management and overall crop protection.

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