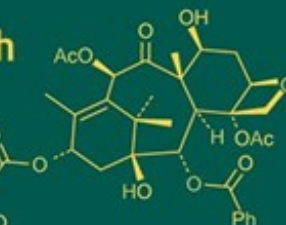


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Emerging nanotechnological approaches for plant disease diagnosis and sustainable crop management

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ABSTRACT

Agricultural nanotechnology has emerged as a promising approach for addressing the increasing challenges of plant diseases, environmental stresses, and the need for sustainable crop production. (Ali *et al.*, 2020; Nandini *et al.*, 2023) [1, 2] Conventional disease-management practices, particularly the excessive use of chemical pesticides and fertilizers, can cause environmental contamination, pathogen resistance, and adverse effects on beneficial microorganisms. (Ali *et al.*, 2020; Nandini *et al.*, 2023) [1, 2] Nanoparticles (NPs), owing to their unique physicochemical properties, high surface area to volume ratio, enhanced reactivity, and tunable surface characteristics, offer innovative solutions for sustainable agriculture. This review provides an overview of the major types of nanoparticles, their synthesis approaches, characterization techniques, and their applications in plant disease diagnosis and management. Particular emphasis is given to biological or green synthesis using plants, bacteria, fungi, algae, and plant viruses as environmentally compatible alternatives to conventional physical and chemical methods. (Ameen *et al.*, 2021; Avila-Quezada *et al.*, 2022) [3, 4] Various nanoparticles, including chitosan, silver, zinc oxide, silica, copper, iron oxide, and titanium dioxide, have demonstrated antimicrobial activity against diverse fungal, bacterial, and viral phytopathogens through mechanisms involving reactive oxygen species generation, membrane disruption, enzyme inhibition, and damage to nucleic acids. (Ameen *et al.*, 2021; Avila-Quezada *et al.*, 2022) [3, 4] Nanotechnology based nanosensors, nanochips, quantum dots, and nano biosensors also provide rapid and sensitive tools for early detection of plant pathogens, supporting timely and precision disease management. (Wasule *et al.*, 2024; Bora *et al.*, 2022) [5, 6] In addition, nanoparticles can enhance plant tolerance to abiotic stresses such as drought, salinity, heat, cold, and heavy-metal stress by improving antioxidant defense, nutrient uptake, photosynthetic activity, and stress responsive mechanisms. (Wasule *et al.*, 2024; Bora *et al.*, 2022) [5, 6] Nanoformulations and nanocarriers further enable controlled and targeted delivery of pesticides, fungicides, and RNA-based molecules, potentially reducing agrochemical use and environmental losses. (Cardoso *et al.*, 2022; Shivashakarappa *et al.*, 2022) [7, 8] Despite these advantages, concerns regarding nanoparticle toxicity, environmental persistence, bioaccumulation, effects on beneficial microorganisms, production costs, and large scale application remain. (Cardoso *et al.*, 2022; Shivashakarappa *et al.*, 2022) [7, 8] Future research should therefore focus on developing biodegradable and eco friendly nanoparticles, standardized safety assessments, long term field evaluation, cost effective production, and appropriate regulatory frameworks. (Chandrashekar *et al.*, 2023; Mgadi *et al.*, 2024) [9, 10] Overall, nanotechnology has significant potential to contribute to precision agriculture, sustainable crop protection, food security, and climate resilient farming. (Chandrashekar *et al.*, 2023; Mgadi *et al.*, 2024) [9, 10]

Keywords: Agricultural nanotechnology, Plant disease diagnosis, Nanoparticles, Sustainable crop management, Green synthesis

Introduction

Agriculture, which encompasses the diverse methods by which cultivated plants and domesticated animals support the global population through the provision of food and other essential goods, has served as a fundamental pillar of human civilization, delivering nourishment, economic value, and critical resources throughout history. (Kalu *et al.*, 2026; Nandini *et al.*, 2023) [11, 2] The need for sustainable agricultural methods that guarantee food security while reducing disease incidence in plant production has increased with the world's population growth. (Kalu *et al.*, 2026; Nandini *et al.*, 2023) [11, 2] Globally, plant diseases caused by various phytopathogens, including nematodes, bacteria, viruses, and fungi, drastically reduce crop yield and quality. (Worrall *et al.*, 2018; Ameen *et al.*, 2021) [12, 3] Despite their effectiveness, traditional disease control techniques such as chemical pesticides and synthetic fertilisers often pollute the environment, promote the emergence of resistant pathogens, and negatively affect beneficial microorganisms that are not their intended targets. (Worrall *et al.*, 2018; Ameen *et al.*, 2021) [12, 3] These limitations highlight the pressing need for innovative, environmentally sustainable, and practical strategies in plant disease management. (Avila-Quezada *et*

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et al., 2022) [4] Nanotechnology has emerged as a promising tool to address these challenges by providing innovative solutions, such as NPs with unique physicochemical properties, including a high surface area to volume ratio, increased reactivity, and adjustable release profiles. (Avila-Quezada *et al.*, 2022) [4] 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. The word “nano” means one billionth of a meter. 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. This review provides a comprehensive overview of various methods of nanoparticle synthesis, the different types of NPs, and their characterization techniques. It further highlights the pivotal role of NPs in plant pathology, with a particular focus on their applications in disease detection and management. In addition, the review explores how NPs influence phytohormone signalling pathways, contributing to the mitigation of abiotic and biotic stress in plants. Nanotechnology is increasingly recognized as a critical tool in addressing challenges related to global food production and food security. NPs interact with plants through various mechanisms, including nutrient uptake enhancement, modulation of the antioxidant system, and regulation of hormonal pathways. These interactions enhance the use of NPs in plant disease identification and treatment. NPs’ application in plant disease management improved plant defence mechanisms, reduced the need for hazardous chemicals, and increased overall crop productivity. Silver (Ag-NPs), zinc oxide (ZnO NPs), copper oxide (CuO-NPs), and titanium dioxide (TiO₂-NPs) are examples of metal and metal oxide NPs that exhibit antimicrobial activity against a range of phytopathogens. Metal NPs, such as ZnO and FeO₄, enhance plant growth and productivity. Plant immune responses can be stimulated by NPs, increasing resistance to diseases. Some NPs, such as copper and silver, show antimicrobial properties, preventing pathogenic microorganisms while supporting beneficial microbes. (Kalu *et al.*, 2026; Jabran *et al.*, 2024) [11, 13]

Nanotechnology in agriculture

Nanoparticles (NPs), generally 1–100 nm in size, possess unique properties such as a high surface area to volume ratio and strong adsorption capacity, making them useful in modern agriculture. (Kalu *et al.*, 2026; Nandini *et al.*, 2023) [11, 2] They are used as nanopesticides, nanofungicides, nanobactericides, nanoherbicides, nanofertilizers, nanosensors, and nanoremediators. (Kalu *et al.*, 2026; Nandini *et al.*, 2023) [11, 2] NPs can improve plant resistance to both biotic and abiotic stresses by influencing stress related signaling pathways and phytohormones such as auxin, ethylene, and abscisic acid (ABA). (Worrall *et al.*, 2018; Khan *et al.*, 2022) [12, 14] They can also alter the expression of stress responsive genes and enhance plant defense mechanisms. (Worrall *et al.*, 2018; Khan *et al.*, 2022) [12, 14] Therefore, NPs have considerable potential for developing climate resilient and sustainable agriculture. (Chandrashekar *et al.*, 2023; Mgadi *et al.*, 2024) [9, 10] However, their exact mechanisms of interaction with plants, particularly their effects on phytohormone biosynthesis

and signaling, are still not fully understood and require further research. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Ali *et al.*, 2020) [11, 13, 1]

Among the various applications of nanotechnology in agriculture, nanoparticles (NPs) are particularly important because of their unique physicochemical properties, including high surface area, enhanced reactivity, and the ability to interact with biological systems at the molecular level. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] NPs have diverse applications in sustainable agriculture. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] Nanoformulated herbicides, such as atrazine loaded PCL nanoparticles, can improve weed control while reducing their impact on crops. (Chauhan *et al.*, 2023; Bora *et al.*, 2022) [15, 6] Similarly, fungicide loaded nanoparticles, including chitosan based formulations, can enhance antifungal activity and minimize phytotoxic effects. (Chauhan *et al.*, 2023; Bora *et al.*, 2022) [15, 6] Insecticide nanoparticles can improve pest control efficiency while reducing toxicity to non target organisms. (Qiao *et al.*, 2024; Zhang *et al.*, 2024) [16, 17] In addition, nanoparticles can be used for the controlled delivery of plant growth regulators, promoting plant growth and enhancing tolerance to environmental stresses. (Qiao *et al.*, 2024; Zhang *et al.*, 2024) [16, 17] Overall, major applications of nanoparticles in sustainable agriculture include nanofertilizers, nanopesticides, nanosensors, and improved soil and water management, which contribute to efficient resource utilization and environmentally sustainable crop production. (Kalu *et al.*, 2026; Dutta *et al.*, 2023; Worrall *et al.*, 2018) [11, 18, 12]

Basics of nanotechnology

Nanoparticles and their properties

Nanoparticles can be classified according to different criteria, including composition, size, shape, surface characteristics, and intended application. (Nandini *et al.*, 2023; Wadhwa *et al.*, 2022) [2, 19] Based on their composition, common categories include metal nanoparticles, metal oxide nanoparticles, carbon based nanoparticles, polymeric nanoparticles, and biological or organic nanoparticles. (Nandini *et al.*, 2023; Wadhwa *et al.*, 2022) [2, 19] Characterization of these nanoparticles generally involves evaluating their size, morphology, surface properties, chemical composition, stability, and other physicochemical characteristics to determine their suitability for specific applications. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Ali *et al.*, 2020) [11, 13, 1]

Nanoparticles and their formation

Nanoparticles (NPs) can occur in different shapes and structural forms, depending on the material used and the method of synthesis. (Nandini *et al.*, 2023; Wadhwa *et al.*, 2022) [2, 19] Common morphologies include spherical, tubular, rod shaped, triangular, cubic, and irregular forms. (Nandini *et al.*, 2023; Wadhwa *et al.*, 2022) [2, 19] Their shape and size strongly influence properties such as surface area, reactivity, stability, mobility, and interaction with plant tissues. (Daniel *et al.*, 2023; Ameen *et al.*, 2021) [22, 3] NPs may also occur as dispersed particles, aggregates, or agglomerates. (Daniel *et al.*, 2023; Ameen *et al.*, 2021) [22, 3] Well-dispersed nanoparticles remain separated in a medium, whereas aggregation or agglomeration occurs when particles come together because of weak attractive forces or inadequate stabilization. Therefore, synthesis and stabilization conditions are important for maintaining the desired particle size and morphology. (Ali *et al.*, 2020; Yadav *et al.*, 2018) [1, 20]

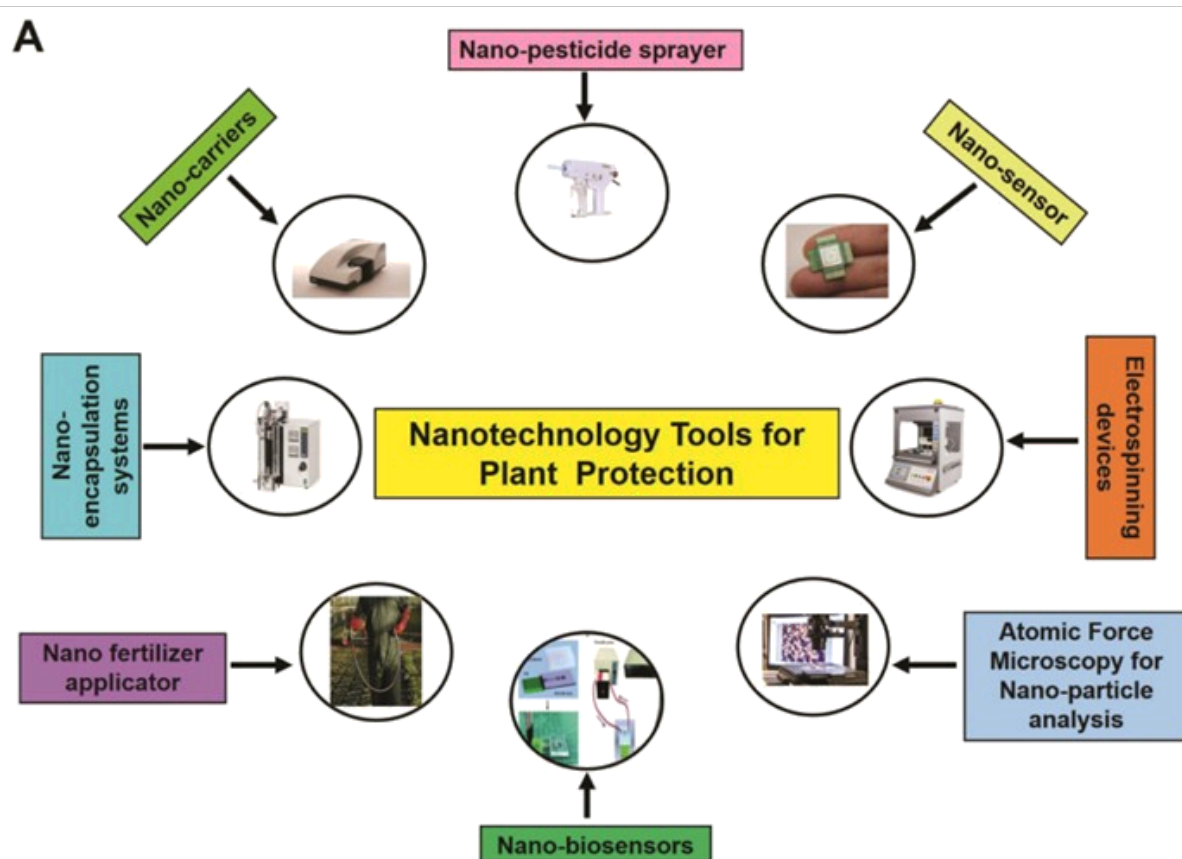


Table 1 : Categories of nanoparticles and characterization

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.

Figure 1. Nanotechnology tools for plant protection. Yadav *et al.* (2018) [20] and Kalu *et al.* (2026) [20, 11].

1. Top-down approach

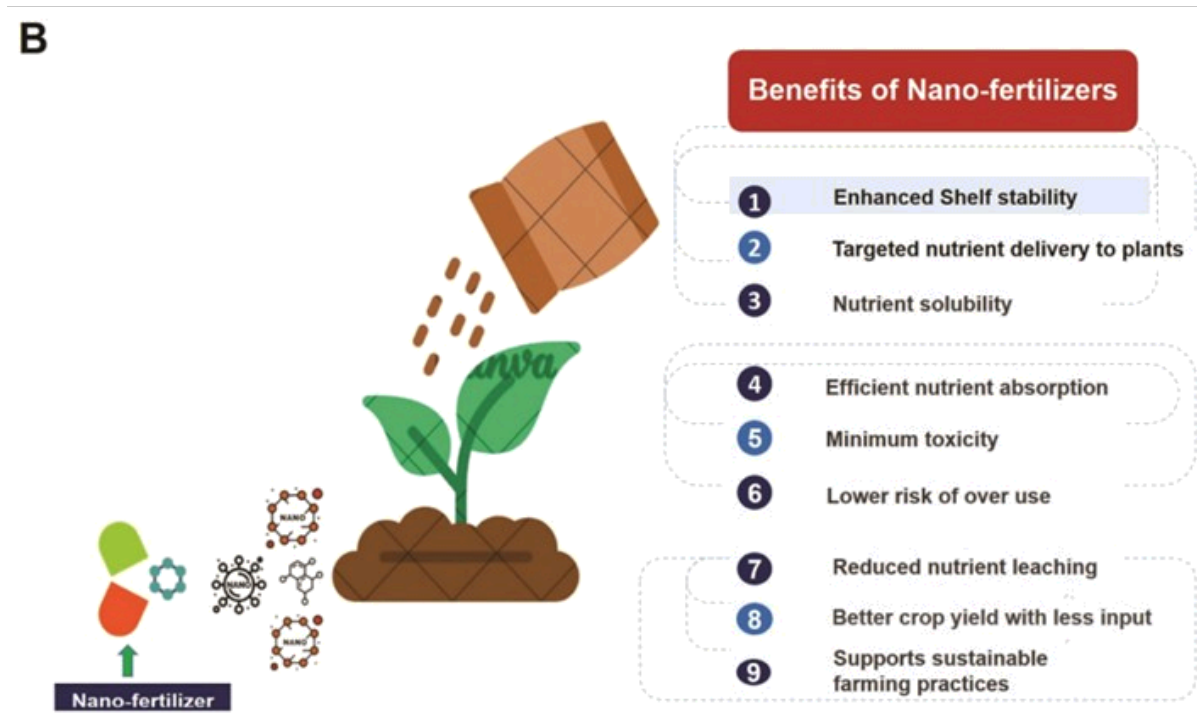


Figure 2. Categories of nanoparticles and their characterization. Jabran *et al.* (2024) [13] and Kalu *et al.* (2026) [13, 11].

The top-down approach involves converting a bulk material into nanosized particles by progressively reducing its size. (Tanwar *et al.*, 2024; Wadhwa *et al.*, 2022) [21, 19] In this method, larger materials are broken down using physical or chemical techniques. (Tanwar *et al.*, 2024; Wadhwa *et al.*, 2022) [21, 19] Common techniques include milling, grinding, lithography, laser ablation, etching, and mechanical attrition. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] The major advantage of the top-down method is that it can produce nanoparticles di-

rectly from bulk materials. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] However, it has several limitations. The process can require high energy consumption, specialized equipment, and longer processing times. It may also produce particles with a broad size distribution and irregular shapes. Furthermore, mechanical processes can introduce impurities or structural defects into the nanoparticles. Thus, achieving highly uniform nanoparticles can be challenging using this approach. (Ali *et al.*, 2020; Yadav *et al.*, 2018) [1, 20]

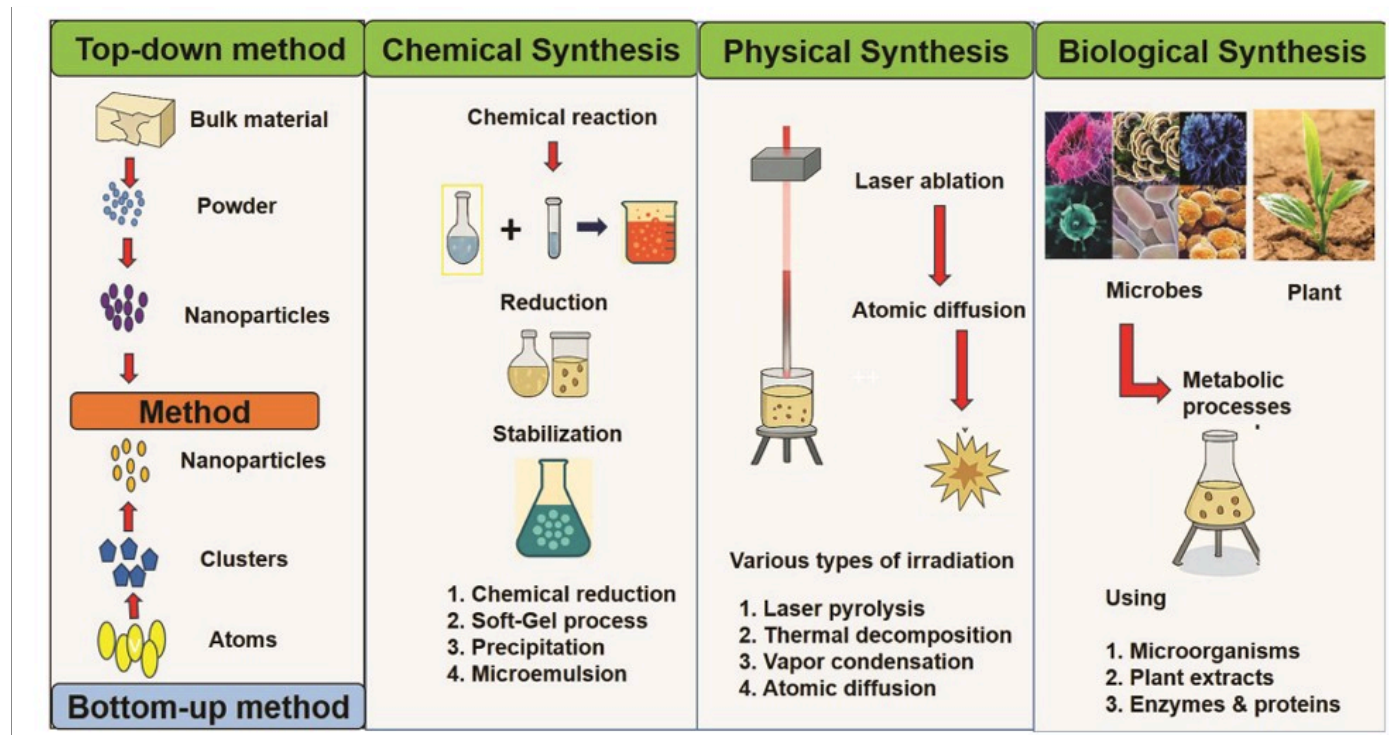


Figure 3. Nanoparticle synthesis approaches. Tanwar *et al.* (2024) [21] and Ali *et al.* (2020) [21, 1].

2. Bottom-up approach

The bottom-up approach is based on the construction of nanoparticles from smaller building blocks such as atoms, ions, molecules, or molecular clusters. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] These components gradually assemble through processes such as nucleation,

growth, precipitation, reduction, condensation, and self assembly to form nanoparticles. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] Examples of bottom-up techniques include chemical reduction, sol gel synthesis, precipitation, hydrothermal synthesis, biological synthesis, and microbial or plant-mediated synthesis. (Nandini *et al.*,

2023; Wadhwa *et al.*, 2022) [2, 19] Compared with top-down methods, bottom-up techniques generally provide better control over particle size, morphology, composition, and size distribution. (Nandini *et al.*, 2023; Wadhwa *et al.*, 2022) [2, 19] They can also require less energy and may be more economical and suitable for large scale production. (Ali *et al.*, 2020; Yadav *et al.*, 2018) [1, 20]

Characterization of nanoparticles

Comprehensive characterization of nanoparticles (NPs) is essential for determining their size, shape, structure, composition, surface properties, stability, and functional characteristics. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] After synthesis, nanoparticles must be carefully analyzed to confirm that they possess the desired properties and are suitable for their intended applications. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] Important parameters include particle size and size distribution, morphology, crystallinity, chemical composition, surface area, optical properties, dispersibility, and thermal stability. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Zhang *et al.*, 2024) [11, 13, 23]

Several analytical techniques are commonly used for nanoparticle characterization. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17]

1. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] UV–Visible (UV–Vis) spectroscopy is mainly used to confirm nanoparticle formation and evaluate their optical properties and stability by detecting characteristic absorption peaks. (Tanwar *et al.*, 2024; Wadhwa *et al.*, 2022) [21, 19] X-ray diffraction (XRD) provides information about the crystalline structure, crystal size, and phase composition of nanoparticles. (Tanwar *et al.*, 2024; Wadhwa *et al.*, 2022) [21, 19] Dynamic light scattering (DLS) and particle size analysis (PSA) are used to determine particle size distribution and assess the stability of nanoparticle suspensions. (Jabran *et al.*, 2024; Zhang *et al.*, 2024; Cardoso *et al.*, 2022) [13, 23, 24]
2. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] Fourier transform infrared spectroscopy (FTIR) is used to identify functional groups present on the nanoparticle surface and to determine their possible involvement in nanoparticle synthesis and surface modification. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed information about nanoparticle morphology, size, shape, surface structure, and aggregation. (Tanwar *et al.*, 2024; Nandini *et al.*, 2023) [21, 2] TEM generally provides higher resolution visualization of individual nanoparticles. (Jabran *et al.*, 2024; Zhang *et al.*, 2024) [13, 23]
3. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5] Energy dispersive X-ray spectroscopy (EDS) is often coupled with SEM or TEM to determine the elemental composition of nanoparticles and confirm the presence of desired elements and their purity. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5] Thermogravimetric analysis (TGA) evaluates thermal stability by measuring changes in nanoparticle weight during controlled heating. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6] It can also help determine moisture content, organic coatings, and decomposition temperatures. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6]
4. Advanced techniques provide additional information about nanoparticle surfaces and structures. Atomic force microscopy (AFM) provides nanoscale surface topography, while Raman spectroscopy helps investigate molecular structure and chemical interactions. X-ray photoelectron spectroscopy (XPS) provides detailed information about surface elemental composition and chemical states.

Thus, no single technique can provide complete information about nanoparticles. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] The combined use of UV–Vis, XRD, DLS/PSA, FTIR, SEM, TEM, EDS, TGA, AFM, Raman spectroscopy, and XPS provides a comprehensive understanding of their physicochemical characteristics. (Wadhwa *et al.*, 2022; Zhang *et al.*, 2024) [19, 17] Such characterization is particularly important for agricultural nanoparticles because their size, morphology, surface chemistry, stability, and composition directly influence their interaction with plants, pathogens, soil, and agrochemicals. (Jabran *et al.*, 2024; Zhang *et al.*, 2024) [13, 23]

Biosynthesis of nanoparticles using biological agents

Nanoparticles (NPs) can be synthesized through physical, chemical, and biological methods. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5] Physical methods are often energy intensive and may require specialized equipment, whereas chemical methods can involve toxic reducing and stabilizing agents that may pose environmental and health risks. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5] Therefore, biological or green synthesis has gained considerable attention as a safer, cost effective, and environmentally sustainable alternative. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6] In biological synthesis, plants, bacteria, fungi, algae, and plant viruses use their natural biomolecules, enzymes, and metabolites to reduce metal ions and stabilize the resulting nanoparticles. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6] This approach can produce a wide range of nanoparticles, including silver (Ag), gold (Au), selenium (Se), platinum (Pt), iron oxide, copper oxide, and zinc oxide nanoparticles, with potential applications in agriculture and plant disease management. (Ali *et al.*, 2020; Wasule *et al.*, 2024; Chauhan *et al.*, 2023) [1, 5, 15]

1. Plant mediated nanoparticle synthesis

Plant mediated synthesis is one of the simplest and most widely studied green approaches. (Chauhan *et al.*, 2023; Tanwar *et al.*, 2024) [15, 21] Leaves, fruits, roots, stems, flowers, seeds, peels, and other plant materials can be used to prepare extracts containing phytochemicals such as phenolics, flavonoids, proteins, carbohydrates, alkaloids, and terpenoids. (Chauhan *et al.*, 2023; Tanwar *et al.*, 2024) [15, 21] These compounds act as natural reducing and capping/stabilizing agents, converting metal ions into stable nanoparticles while limiting the need for hazardous chemicals. (Ali *et al.*, 2020; Nandini *et al.*, 2023) [1, 2] Generally, plant material is washed, dried, ground, and extracted in water. (Ali *et al.*, 2020; Nandini *et al.*, 2023) [1, 2] The extract is filtered and mixed with an appropriate metal salt solution. A visible change in colour often indicates nanoparticle formation. Plants such as *Ocimum tenuiflorum*, *Azadirachta indica*, *Aloe barbadensis*, *Curcuma longa*, *Citrus sinensis*, and *Mangifera indica* have been successfully used for the synthesis of different metallic and metal oxide nanoparticles. Plant derived NPs are particularly attractive because of their low toxicity, simplicity, low cost, scalability, and environmental compatibility. (Ali *et al.*, 2020; Wasule *et al.*, 2024; Chauhan *et al.*, 2023) [1, 5, 15]

2. Bacteria mediated synthesis

Bacteria can synthesize nanoparticles through intracellular or extracellular mechanisms. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] Their enzymes, proteins, and other cellular metabolites facilitate the reduction of metal ions and stabilization of the nanoparticles. (Ali *et al.*, 2020; Bora *et al.*, 2022) [1, 6] Factors such as pH, temperature, incubation conditions, and bacterial cell-wall functional groups influence nanoparticle formation, size, and morphology. (Tanwar *et al.*, 2024; Nandini *et al.*, 2023) [21, 2] Bacterial species such as *Pseudomonas*, *Bacillus*, *Escherichia*, *Clostridium*, and *Rhodococcus* have been reported for the synthesis of silver, gold, iron sulfide, and magnetite nanoparticles. (Tanwar *et al.*, 2024; Nandini *et al.*, 2023) [21, 2] Although bacterial synthesis is environmentally friendly and can produce biocompatible nanoparticles, limitations include labour intensive processing, downstream purification requirements, and difficulties in precisely controlling particle size and shape. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5]

3. Fungal assisted synthesis

Fungi are considered effective biological nanofactories because they produce large amounts of extracellular enzymes and metabolites capable of reducing and stabilizing metal ions. [1, 15] Nanoparticle synthesis can occur either inside fungal cells or extracellularly, with extracellular synthesis being more advantageous because it simplifies nanoparticle recovery and purification. (Ali *et al.*, 2020; Chauhan *et al.*, 2023) [1, 15] Fungi such as *Fusarium oxysporum*, *Aspergillus fumigatus*, *Penicillium spp.*, and *Verticillium spp.* have demonstrated the ability to synthesize metallic and metal sulfide nanoparticles. (Bora *et al.*, 2022; Nandini *et al.*, 2023) [6, 2] Compared with bacteria, fungi generally offer higher biomass production, efficient secretion of biomolecules, easier cultivation, and better suitability for large-scale production. (Bora *et al.*, 2022; Nandini *et al.*, 2023) [6, 2] These characteristics make fungal mediated synthesis a promising route for sustainable nanoparticle production. (Ali *et al.*, 2020; Wasule *et al.*, 2024; Chauhan *et al.*, 2023) [1, 5, 15]

4. Algae mediated synthesis

Algae, including microalgae, macroalgae (seaweeds), and cyanobacteria, are another important source for green nanoparticle synthesis. (Ali *et al.*, 2020; Chauhan *et al.*, 2023) [1, 15] Algal cells contain proteins, polysaccharides, pigments, lipids, antioxidants, and other bioactive compounds that can function as natural reducing and stabilizing agents. (Ali *et al.*, 2020; Chauhan *et al.*, 2023) [1, 15] Species belonging to Cyanophyceae, Chlorophyceae, Phaeophyceae, and Rhodophyceae have been used to synthesize metallic and metal oxide nanoparticles, particularly silver and gold NPs. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6] Algae offer advantages such as rapid growth, easy harvesting, metal accumulation ability, scalability, and low environmental impact. (Nandini *et al.*, 2023; Bora *et al.*, 2022) [2, 6] Nanoparticles synthesized using *Chlorella* and *Sargassum* species have also shown promising antimicrobial activity. (Ali *et al.*, 2020; Wasule *et al.*, 2024; Chauhan *et al.*, 2023) [1, 5, 15]

5. Plant virus based nanoparticles

Plant virus-based nanoparticles (PVNPs) represent an emerging biological approach in nanotechnology. (Young *et al.*, 2008; Xue *et al.*, 2023) [25, 26] Plant viruses and virus-like particles possess highly organized and uniform structures that can serve as natural nanoscale scaffolds. (Young *et al.*, 2008; Xue *et al.*, 2023) [25, 26] Their biocompatibility, biodegradability, structural uniformity, and ability to encapsulate or deliver biological molecules make them useful for advanced applications in agriculture and biotechnology. (Avila-Quezada *et al.*, 2022; Zhang *et al.*, 2024) [4, 17] Viral particles can also be genetically modified or produced through plant based molecular farming and other scalable systems. (Avila-Quezada *et al.*, 2022; Zhang *et al.*, 2024) [4, 17] Although this technology is still developing, PVNPs have considerable potential as precision delivery and nanobiotechnology platforms. (Ali *et al.*, 2020; Wasule *et al.*, 2024) [1, 5]

Nanoparticles synthesized from chitosan and other biopolymers and metallic nanoparticles

Chitosan nanoparticles

Chitosan nanoparticles (CNPs) are biodegradable and biocompatible nanomaterials derived from chitosan, a natural polysaccharide obtained by deacetylation of chitin, which is abundantly present in crustacean exoskeletons. (Chouhan *et al.*, 2021; Moussa *et al.*, 2013) [27, 28] Chitosan is considered an environmentally friendly material because of its low toxicity, biodegradability, antimicrobial properties, and biocompatibility. (Chouhan *et al.*, 2021; Moussa *et al.*, 2013) [27, 28] When converted into nanoparticles, its surface area and biological activity increase, resulting in enhanced antifungal and antimicrobial effects. (Wasule *et al.*, 2024; Chouhan *et al.*, 2021) [5, 27] CNPs have therefore attracted considerable attention as sustainable alternatives to conventional chemical fungicides. (Wasule *et al.*, 2024; Chouhan *et al.*, 2021) [5, 27] For example, CNP application has been shown to substantially reduce gray mold severity in strawberry, while chitosan based nanoparticles have also been reported to enhance plant growth, secondary metabolite accumulation, and disease resistance in

Capsicum species. Furthermore, combining CNPs with beneficial microorganisms such as *Trichoderma longibrachiatum* and *Penicillium polonicum* has demonstrated strong inhibitory activity against *Fusarium equiseti*. Thus, CNPs have considerable potential as eco friendly antifungal agents and plant defense enhancers, although their precise molecular mechanisms and optimal field application conditions require further investigation. (Worrall *et al.*, 2018; Wasule *et al.*, 2024) [12, 5]

Metallic nanoparticles

Metallic nanoparticles (MNPs), including silver, zinc oxide, silica, copper, iron oxide, titanium dioxide, and selenium nanoparticles, are increasingly being explored for plant disease management. (Worrall *et al.*, 2018; Khan *et al.*, 2022) [12, 14] Their effectiveness is associated with their high surface area to volume ratio, strong redox activity, and ability to interact with microbial cells. (Worrall *et al.*, 2018; Khan *et al.*, 2022) [12, 14] Depending on their composition, MNPs can damage pathogen cell membranes, generate reactive oxygen species (ROS), interfere with enzymes and DNA, and inhibit spore germination and mycelial growth. (Avila-Quezada *et al.*, 2022; Tariq *et al.*, 2022) [4, 29] Consequently, they can act against a broad range of fungal, bacterial, and viral phytopathogens and may provide an alternative or complementary strategy to conventional pesticides. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Worrall *et al.*, 2018; Wasule *et al.*, 2024) [11, 13, 12, 5]

Silver nanoparticles

Silver nanoparticles ($AgNPs$) are among the most extensively studied nanomaterials for plant disease management because of their broad-spectrum antibacterial and antifungal activity. (Tariq *et al.*, 2022; Avila-Quezada *et al.*, 2022) [29, 4] Their antimicrobial action is largely associated with the release of Ag^+ ions, which interact with microbial cell membranes and proteins, increase membrane permeability, disturb enzymatic functions, and cause cellular and DNA damage. (Tariq *et al.*, 2022; Avila-Quezada *et al.*, 2022) [29, 4] $AgNPs$ have demonstrated activity against important pathogens such as *Fusarium*, *Colletotrichum*, *Sclerotinia*, *Rhizoctonia*, *Bipolaris*, and *Ralstonia*. (Ameen *et al.*, 2021; El-Shetehy *et al.*, 2021) [3, 30] They have also shown potential against plant viruses, with studies reporting reduced viral concentration and disease severity following $AgNP$ application. (Ameen *et al.*, 2021; El-Shetehy *et al.*, 2021) [3, 30] Green-synthesized $AgNPs$, particularly those produced using plant extracts, are gaining attention because they may reduce dependence on hazardous chemical synthesis. (Tariq *et al.*, 2022; El-Shetehy *et al.*, 2021) [29, 30] However, concerns regarding silver toxicity, environmental persistence, and accumulation highlight the need for careful dose optimization and assessment of their environmental safety. (Kalu *et al.*, 2026; Worrall *et al.*, 2018; Wasule *et al.*, 2024) [11, 12, 5]

Zinc oxide nanoparticles

Zinc oxide nanoparticles ($ZnO-NPs$) are promising alternatives for disease management because they combine antimicrobial activity with the nutritional importance of zinc. (Daniel *et al.*, 2023; Avila-Quezada *et al.*, 2022) [22, 4] Their antifungal effects are associated with disruption of fungal hyphae, inhibition of spore and conidia formation, ROS generation, DNA damage, and disturbance of cellular redox balance. (Daniel *et al.*, 2023; Avila-Quezada *et al.*, 2022) [22, 4] $ZnO-NPs$ have demonstrated activity against pathogens including *Fusarium oxysporum*, *Penicillium expansum*, *Botrytis cinerea*, and *Xanthomonas oryzae*. (Daniel *et al.*, 2023; Nandini *et al.*, 2023) [22, 2] They have also shown potential in controlling diseases such as rice blast and bacterial leaf blight. (Daniel *et al.*, 2023; Nandini *et al.*, 2023) [22, 2] Green synthesized $ZnO-NPs$ prepared using plant extracts provide an additional sustainable approach. (Ameen *et al.*, 2021) [3] Because $ZnO-NP$ toxicity depends on particle properties, concentration, exposure conditions, soil chemistry, and plant species, their use requires dose optimization and environmental assessment. Their antimicrobial activity and role as a zinc source nevertheless make them promising candidates for integrated crop protection. (Kalu

et al., 2026; Jabran *et al.*, 2024; Worrall *et al.*, 2018; Daniel *et al.*, 2023; Ameen *et al.*, 2021; Cox *et al.*, 2016) [11, 13, 12, 22, 3, 31]

Silica nanoparticles

Silica nanoparticles (SiO₂-NPs) can enhance plant resistance against both biotic and abiotic stresses. (El-Shetehy *et al.*, 2021; Khan *et al.*, 2022) [30, 14] Their protective effects involve strengthening plant cell walls and cuticles, creating physical barriers against pathogens, stimulating defense-related enzymes and activating defense signalling, including salicylic acid associated responses. (El-Shetehy *et al.*, 2021; Khan *et al.*, 2022) [30, 14] SiO₂-NPs can also promote the production of defensive compounds such as phenolics and flavonoids. (El-Shetehy *et al.*, 2021; Nandini *et al.*, 2023) [30, 2] Recent research indicates that low concentrations of SiO₂-NPs can activate SA-dependent immune responses and improve resistance against bacterial pathogens. (El-Shetehy *et al.*, 2021; Nandini *et al.*, 2023) [30, 2] In addition to disease protection, mesoporous silica nanoparticles can function as nanocarriers for the controlled delivery of DNA and other bioactive molecules, making them valuable tools for plant biotechnology and precision agriculture. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Zhang *et al.*, 2024; El-Shetehy *et al.*, 2021) [11, 13, 23, 30]

Copper nanoparticles

Copper nanoparticles (CuNPs) possess strong antibacterial and antifungal properties and have considerable potential in agricultural disease management. (Worrall *et al.*, 2018; Avila-Quezada *et al.*, 2022) [12, 4] Their antimicrobial activity is associated with the generation of reactive species, particularly hydroxyl radicals, which can damage essential cellular components such as proteins, membranes, and DNA. (Worrall *et al.*, 2018; Avila-Quezada *et al.*, 2022) [12, 4] CuNPs have demonstrated broad spectrum activity against pathogens including *Alternaria alternata*, *Curvularia lunata*, *Fusarium oxysporum*, *Phoma destructiva*, *Xanthomonas campestris*, *Botrytis cinerea*, and *Fusarium kuroshium*. (Khan *et al.*, 2022; Tariq *et al.*, 2022) [14, 29] In some studies, CuNPs have shown greater pathogen inhibition than conventional copper formulations. (Khan *et al.*, 2022; Tariq *et al.*, 2022) [14, 29] Moreover, incorporating Cu-based compounds into nanohydrogels can enable controlled and targeted delivery, potentially improving fungicide efficiency while reducing unnecessary chemical application. (Kalu *et al.*, 2026; Worrall *et al.*, 2018; Wasule *et al.*, 2024) [11, 12, 5]

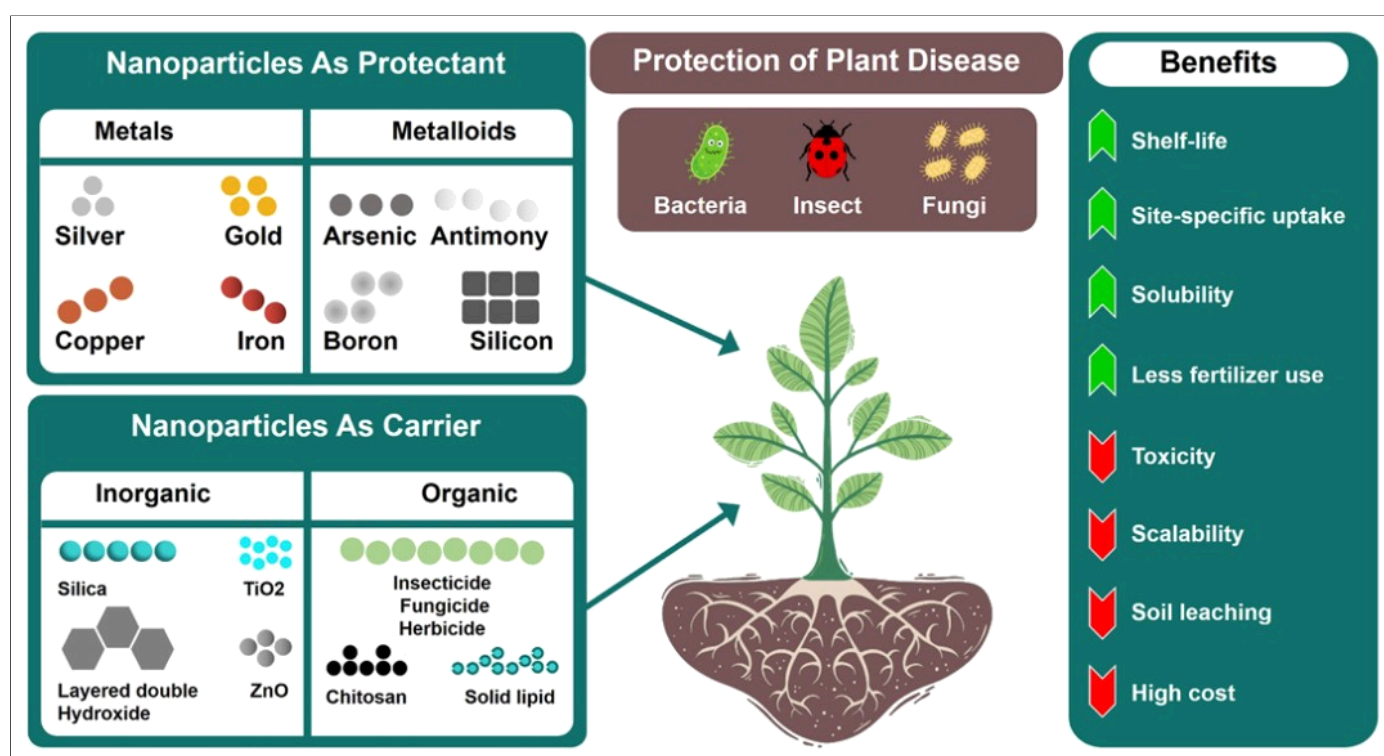


Figure 4. Nanomaterials as protectants/carriers for crop protection. Worrall *et al.* (2018) [12], *Agronomy* 8:285 [12].

Detection of plant pathogens

Early detection of plant diseases is essential for reducing crop losses and enabling timely disease management. (Cardoso *et al.*, 2022; Shivashakarappa *et al.*, 2022) [7, 8] Nanotechnology based tools such as nanosensors, nanochips, quantum dots, and nanobiosensors provide rapid, sensitive, and accurate detection of plant pathogens. (Cardoso *et al.*, 2022; Shivashakarappa *et al.*, 2022) [7, 8] Nanosensors can identify viruses and other pathogens at early infection stages using specific biological recognition molecules. (Khan *et al.*, 2022; Zhang *et al.*, 2024) [14, 17] Nanochips detect pathogen-specific genetic sequences with high sensitivity and specificity, while quantum dots and gold nanoparticles provide strong optical signals for pathogen identification. (Khan *et al.*, 2022; Zhang *et al.*, 2024) [14, 17] These technologies have been applied to detect important pathogens such as *Phytophthora infestans* and *Xanthomonas campestris*. (Cardoso *et al.*, 2022) [7] When combined with molecular diagnostics and smartphone based systems, nano based detection offers a portable, rapid, and reli-

able approach for field level disease monitoring and precision crop protection. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Zhang *et al.*, 2024; Cardoso *et al.*, 2022) [11, 13, 23, 24]

Plant disease management using nanoparticles

Effective management of plant diseases is essential for protecting crops and agricultural products both before and after harvest. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] Fungal, bacterial, and viral pathogens are major causes of crop losses, and conventional disease control methods often face limitations. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] Host plant resistance through conventional breeding is an important strategy, but it is time consuming because resistant genes must be identified and selected over several generations. (Avila-Quezada *et al.*, 2022; Khan *et al.*, 2022) [4, 14] Transgenic approaches can provide broader and longer lasting resistance by introducing useful resistance genes into crops. (Avila-Quezada *et al.*, 2022; Khan *et al.*, 2022) [4, 14] However, the development and adoption of such approaches can also involve technical, regulatory, and

public-acceptance challenges. (Kalu *et al.*, 2026) [11] Nanotechnology offers a promising complementary approach to conventional disease management. (Kalu *et al.*, 2026) [11] Traditional pesticide application

can result in spray drift, runoff, photodegradation, off target deposition, and environmental contamination. (Kalu *et al.*, 2026; Dutta *et al.*, 2023; Worrall *et al.*, 2018) [11, 18, 12]

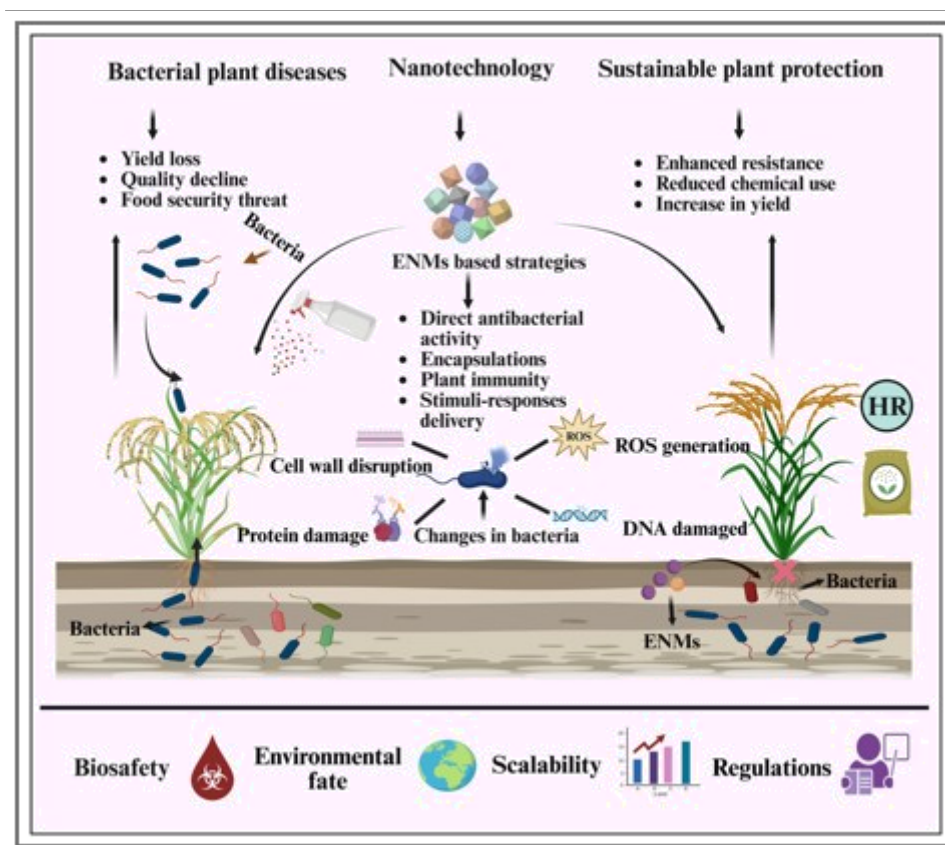


Figure 5. Nanotechnology-based strategies for sustainable management of bacterial plant diseases. Malook *et al.* (2026) [32], Environmental Science: Nano (Malook *et al.*, 2026) [32].

Nanoparticles (NPs) can overcome some of these limitations because their small size and modifiable surface properties allow controlled, targeted, and efficient delivery of active compounds. (Worrall *et al.*, 2018; Qiao *et al.*, 2024) [12, 16] NPs can be used directly as antimicrobial agents or as nanocarriers for pesticides, fungicides, insecticides, and RNA-interference (RNAi) molecules. (Worrall *et al.*, 2018; Qiao *et al.*, 2024) [12, 16] Nanoparticles can act through different mechanisms, including disruption of pathogen cell membranes, generation of reactive oxygen species (ROS), inhibition of enzymes, damage to nucleic acids, and interference with pathogen growth and reproduction. (Qiao *et al.*, 2024; Avila-Quezada *et al.*, 2022) [16, 4] Their nanoscale size may also facilitate better interaction with plant surfaces and, for suitable formulations, movement within plant tissues. (Qiao *et al.*, 2024; Avila-Quezada *et al.*, 2022) [16, 4] In particular, NPs have shown potential for targeting plant viruses and reducing pathogen multiplication, making them an emerging tool for viral disease management. (Zhang *et al.*, 2024) [17] An important advantage of nanotechnology is its potential for precision crop protection. (Zhang *et al.*, 2024) [17] Nanocarriers can protect active ingredients from premature degradation and release them gradually or at specific sites, potentially reducing the quantity of pesticide required and minimizing environmental losses. NPs can also be combined with RNA-based technologies, enabling targeted delivery of molecules that suppress pathogen genes or interfere with infection processes. In addition to disease control, nanoparticles can improve plant tolerance to abiotic stresses such as drought, salinity, heat, cold, and heavy metal stress. For example, Fe, ZnO, Se, TiO₂, Si, Ag, and Fe₃O₄ nanoparticles have been reported to improve plant growth, photosynthetic activity, antioxidant defense, nutrient uptake, and stress related biochemical responses. These effects may involve increased antioxidant enzyme activity, reduced oxidative damage, improved water and nutrient balance, and modulation of stress responsive genes. (Kalu *et al.*, 2026;

Dutta *et al.*, 2023; Worrall *et al.*, 2018; Wasule *et al.*, 2024) [11, 18, 12, 5]

Concluding remarks and future perspectives

Agricultural nanotechnology offers promising opportunities for sustainable and efficient crop production through applications such as nanofertilizers, nanopesticides, targeted delivery systems, nanosensors, and stress management technologies. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] Nanoparticles can improve nutrient use efficiency, enhance plant resilience, reduce agrochemical losses, and support effective control of pests and plant diseases. (Worrall *et al.*, 2018; Nandini *et al.*, 2023) [12, 2] However, their widespread adoption is still limited by concerns regarding environmental persistence, bioaccumulation, toxicity, effects on beneficial soil microorganisms, production costs, and large scale consistency. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Wasule *et al.*, 2024; Zhang *et al.*, 2024; Ameen *et al.*, 2021; Cox *et al.*, 2016) [11, 13, 5, 23, 3, 31]

Future research should focus on developing biodegradable and eco friendly nanoparticles, improving targeted delivery systems, and conducting long term laboratory and field studies to evaluate their effectiveness and safety. (Wasule *et al.*, 2024; Ameen *et al.*, 2021; Cox *et al.*, 2016) [5, 3, 31] Clear regulatory frameworks, standardized risk assessments, cost effective production, and evaluation of socioeconomic factors are also essential for successful commercialization. (Wasule *et al.*, 2024; Ameen *et al.*, 2021; Cox *et al.*, 2016) [5, 3, 31] Greater collaboration among researchers, farmers, industries, and policymakers will be necessary to build confidence and facilitate responsible adoption. (Qiao *et al.*, 2024; Mgadi *et al.*, 2024) [16, 10] Overall, with appropriate safety assessment and sustainable development, nanotechnology has significant potential to contribute to precision agriculture, food security, environmental sustainability, and climate resilient farm

ing. (Kalu *et al.*, 2026; Jabran *et al.*, 2024; Wasule *et al.*, 2024; Malook *et al.*, 2026; Khan *et al.*, 2025) [11, 13, 5, 32, 33]

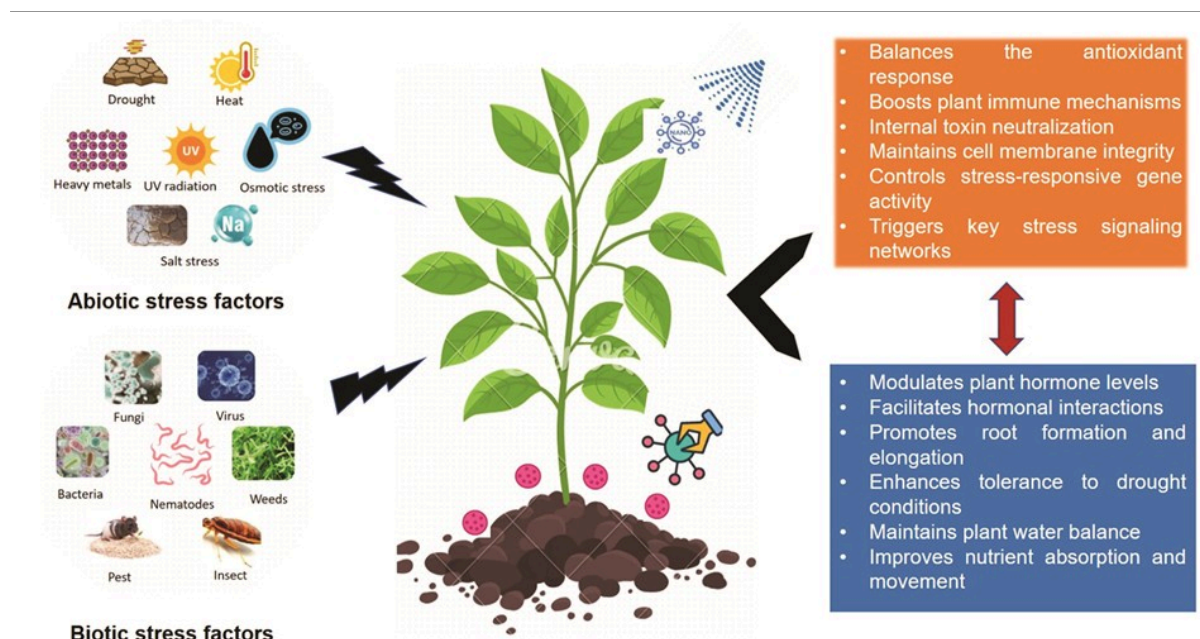


Figure 6. Nanoparticle-mediated responses to biotic and abiotic stress. Khan *et al.* (2025) [33].

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