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Agricultural nanotechnology for precision farming and controlled agrochemical delivery

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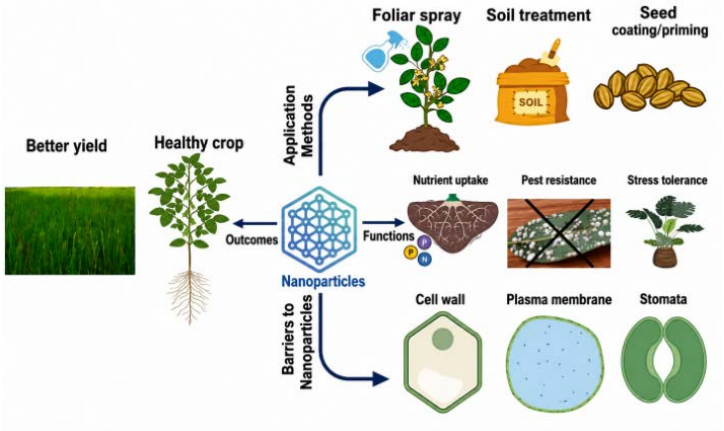
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Review

ABSTRACT

Nanotechnology has emerged as a transformative tool in agriculture, offering innovative solutions to enhance productivity, sustainability, and food security. Owing to their nanoscale size and unique physicochemical properties, nanoparticles (NPs) play crucial roles in improving seed germination, nutrient uptake, plant growth, and stress tolerance while minimizing the reliance on conventional chemical fertilizers and pesticides. Recent advancements highlight the use of nanofertilizers, nanopesticides, and nanobiosensors for precision farming, disease detection, and controlled agrochemical delivery. Additionally, nanomaterials contribute to soil and water remediation, food preservation, and packaging, reducing post-harvest losses. This review discusses diverse nanoparticles, emphasizing their synthesis, modes of application, and mechanisms of action in plants. It also addresses barriers such as nanoparticle uptake, plant physiological defenses, and concerns regarding toxicity, biosafety, and regulatory challenges. Overall, nanotechnology holds immense potential to revolutionize modern agriscience by promoting sustainable practices and improving global agricultural resilience.



Keywords: Nanotechnology, Nanoparticles, Sustainable agriculture, Agriscience, Plant-nanoparticle interactions

INTRODUCTION

Nanotechnology derives its name from the Greek word *nano*, meaning "dwarf," and refers to dimensions on the scale of a billionth of a meter (10^{-9} m). Nanoscience focuses on the study of materials and biological structures within the 1–100 nm range, while nanotechnology translates this knowledge into practical applications. As comparison, a strand of human hair is about 60,000 nm in diameter, whereas the double helix of DNA measures only around 1 nm in radius. The development of nanoscience can be traced from the time of the Greeks and Democritus in the 5th century B.C.[1] As a result of nanoparticles' small size and large surface-area-to-volume ratio, they can be reactive and bind, absorb, and carry compounds such as small-molecule drugs, DNA, RNA, proteins, and probes with high efficiency. Aside from surface area, nanoparticles differ in other properties when compared with their larger bulk equivalents.[2]

Agriculture is one of the main sources of income in many developed and developing countries. The agricultural sector suffers from low productivity due to conventional farming practices. The agricultural world is currently facing several challenges that include climate change, accumulation of fertilizers, pesticides, etc., in the land, to meet increasing population and demand, environmental issues, etc., Many technologies that have the greater potential have been employed to increase the productivity while causing no adverse effects to various factors such as soil, plant growth and nutrient protection, environment, economy, natural resources, human and animal health, etc.[2,3] With continued advancements, nanotechnology can drive sustainable agricultural development and global food security. However, current formulations often have low bioavailability, highlighting the need for improved NP design for effective agricultural applications.[4]

The green synthesis of NPs using plants offers an eco-friendly alternative, reducing environmental risks. Nanomaterials synthesized using green technology utilizing the extracts of plants

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and microorganisms, are found to have the same effect over the target, and also safeguard the environment, causing nil issues. Since it is produced using green materials, when applied to land or soil, it adds additional benefits by acting as a natural fertilizer or pesticide. Nano fertilizers and nano pesticides are also being developed nowadays using the method of green synthesis.[5] Understanding NP-plant interactions opens avenues for interdisciplinary research in agriculture, food science, and biomedicine.[6] Nanofertilizers, applied above or below ground, enhance plant growth, as seen in studies where ZnO NPs improve seed germination and promote plant growth by boosting chlorophyll content and root hormone production in Indian mustard and Bacillus siamensis-based NPs boosted rice growth.[7] Biologically synthesized NPs are preferred over chemical NPs due to their eco-friendliness, offering a sustainable approach to nanotechnology in agriculture.

Additionally, nanotechnology extends to biosensors and food packaging, further boosting agricultural productivity. However, concerns remain about NP toxicity, accumulation in edible plant parts, and effects on soil microbiota. Also, the challenges such as production costs, scalability and potential health risks must be addressed through further research and public awareness for widespread adoption. Despite the benefits, challenges like market adoption and regulatory concerns hinder widespread implementation. With continued research and innovation, nanotechnology holds immense potential for advancing modern agriculture while reducing environmental impact.[8,9]

Sustainable nanomaterial production is gaining attention, minimizing environmental impact. While nanotechnology holds immense potential, further research and strategic investment are needed to bring these innovations from the lab to the field. This review concentrates mainly on the application of various forms of nanotechnology in agricultural science and its unbound contribution in improving the sector.[10,11]

NANOTECHNOLOGY IN THE AGRICULTURAL SECTOR

The attention of nanotechnology towards the agricultural sector increased greatly in the 21st century (Figure 1). Nanotechnology finds its role in advanced agricultural fields such as in precision farming, a substantial role in suitable agriculture, conventional farming, etc., In the agriculture field, nanotechnology is used in the following areas: plant growth and germination, sensing of diseases, agrichemical applications, targeted genetic engineering, waste management, water management, Biochemical processes and microarray.[12,13] In addition to agriculture, its application in food processing and food packaging can improve food safety and quality.

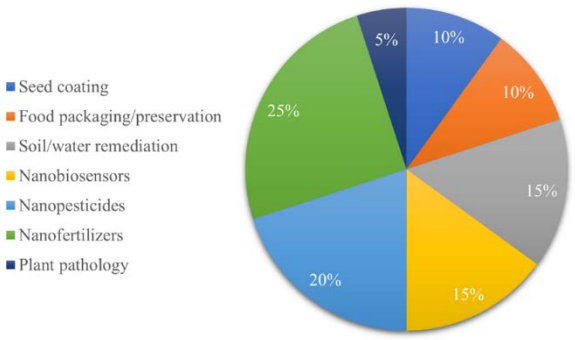


Figure 1. Applications of Nanotechnology in agriculture

Nanotechnology significantly influences agriculture by enhancing soil quality, increasing the yield of crops, encouraging nutrient absorption, functioning as antimicrobial agents and optimizing resource use. This technology is revolutionizing farming practices by utilizing nanofertilizers, which promote better nutrient uptake and lead to robust crops and increased yields, all with minimal environmental consequences. Nanopesticides offer targeted pest management, reducing the reliance on traditional chemical treatments. Furthermore, nanobiosensors assist farmers in effectively monitoring crop health. They contribute to sustainability by allowing for real-time tracking of soil and plant conditions, as well as identifying pathogens, thus supporting precision farming methods. Additionally, nanomaterials contribute to environmental remediation by removing contaminants from the soil.[14] By lowering input costs and reducing pesticide resistance, these advancements contribute to sustainable farming.[15]

Implementing nanotechnology in the agri sector is resource-efficient and enhances crop yields. Through advanced nanomaterial packaging and preservation techniques, post-harvest losses are minimized. Additionally, precise agrochemical application using nanomaterials benefits the environment, while global research interest in agricultural nanotechnology continues to rise [16,17]. It also serves an important function in environmental remediation by assisting in the detoxification of soil and water, while promoting sustainable farming practices. In the food industry, nanotechnology increases food quality, preserves food and extends shelf life [18]. It also plays a crucial role in food safety by aiding in detecting toxins and pathogens and also contributes a role in integrating with genome editing methods like CRISPR for creating better crop varieties.[19,20]

Furthermore, nanomaterials aid in soil restoration by eliminating pollutants and contaminants, resulting in enhanced crop quality. Nanoparticles and encapsulated nutrients increase fertilizer effectiveness, minimizing waste while promoting healthier plant growth.[21] By enhancing photosynthesis, targeted delivery of agrochemicals and disease detection in plants, nanoparticles are making farming more environmentally friendly and productive.[22]

Crop production is enhanced by nanotechnology, especially in stress conditions like salinity. Better plant protection and improved soil health result from the precise application of pesticides and fertilizers made possible by advanced nanotechnological delivery methods. Utilizing nanopesticides and nanofertilizers lowers chemical waste and promotes better crop health and output. Nanosensors aid in precision agriculture by tracking soil and plant conditions, allowing for more efficient resource management. In addition, nanotechnology aids genetic crop improvement, wastewater treatment for irrigation, and post-harvest food processing, addressing key environmental and food security challenges for sustainable agriculture.[23]

NANOMATERIAL UPTAKE AND INTERACTION IN PLANTS

Size is one of the major restrictions that plants possess while taking up nutrients and minerals. Nanoparticle traits will greatly influence the plants and they will be able to absorb them. Plants

primarily absorb nanomaterials through their roots and leaves via structures such as stomata, cuticles, and root junctions. Following their penetration into the plant, nanoparticles travel through the tissues primarily in two ways: the apoplast and the symplast. Once within, nanoparticles interact with cells, influencing overall physiological functions, stress tolerance and plant growth. Particle size, chemical makeup and application technique (soil, foliar spray, root treatment and seed treatment) determine how well the nanomaterials are absorbed[24]. Some nanoparticles enhance seed germination, nutrient absorption, and resilience against environmental stresses. Current studies and reports revealed that the nanoparticles of dimension 40-50 nm were allowed by the plants for smooth penetration and translocation.[8,25]

Through interactions with cuticle, stomata, leaf surface fissures and trichomes, nanoparticles (NPs) influence their uptake and their retention on the leaf surfaces. The degree to which NPs stay on leaves after being exposed to rain depends on factors like surface adhesion and rainfastness. Trichomes may accumulate or facilitate NP entrance, though their exact role remains unclear. After being metabolized, NPs have the ability to go to roots, seeds, fruits and flowers, changing the way nutrients are transported. Nanoparticles enter plants internally via diffusion, bulk flow and phloem loading. Some of the nanoparticle characteristics that influence the uptake efficiency are size, surface charge, hydrophobicity, concentration and exposure time. While studies confirm NP absorption, direct evidence of their transport to stems, roots, flowers, and fruits remains limited.[4,9]

A major factor in NP distribution is solubility. Nanoparticles can enter plants by a variety of mechanisms, such as endocytosis, passive diffusion, ion channels, aquaporins and carrier proteins. Certain crops like lettuce, cucumber, zucchini, and wheat show a higher uptake of nanoparticles due to their vascular system. Also, their uptake occurs through controlled mechanisms, with hydrophilic NPs showing high efficiency in foliar delivery. Environmental exposure through air, water and soil allows NPs to accumulate in plants, which raises the possibility of their entry into the food chain. Studies using hydroponic systems and nutrient media amendments confirm NP uptake and translocation, with some moving from leaves to roots via the phloem.[6,26]

NPs smaller than 20 nm (cotton) and 11 nm (maize) with a positive charge above 15 mV show efficient foliar absorption through stomata and cuticles. Coatings like PVP boost penetration, although they may limit the movement within the leaf. The translocation and uptake dynamics are impacted by the shape and composition of nanoparticles. Nanokinetic models guide nano-enabled agriculture by predicting the mobility of NPs in plants.[27,28]

The factors such as nanoparticle size, their coating and soil conditions, such as pH and organic matter content, influence the uptake of nanoparticles by plants. Metal nanoparticles such as silver (AgNPs) and gold nanoparticles (AuNPs) exhibit comparatively higher uptake efficiency in plants due to their smaller particle size and higher surface reactivity. Silver nanoparticles are readily absorbed through root tissues and leaf stomata and are effectively translocated through vascular tissues in crops such as wheat, rice and tomato.[29,30–32] AgNP accumulation patterns vary among plant species, with monocots and dicots displaying distinct absorption habits. Once inside the plants, AgNPs undergo biotransformation, which includes dissolution and complexation with organic materials, and that might impact their presence in edible plant tissues. Soil components like organic matter and clay also affect AgNP mobility, potentially altering uptake efficiency [31]. Gold nanoparticles, owing to their high biocompatibility and stability, have also demonstrated efficient movement through both apoplastic and symplastic pathways without causing major phytotoxicity at lower concentrations.[33]

Metal oxide nanoparticles including ZnO, TiO_2 and Fe_3O_4 nanoparticles are widely reported to exhibit enhanced uptake and accumulation in plants because of their partial solubility and ability

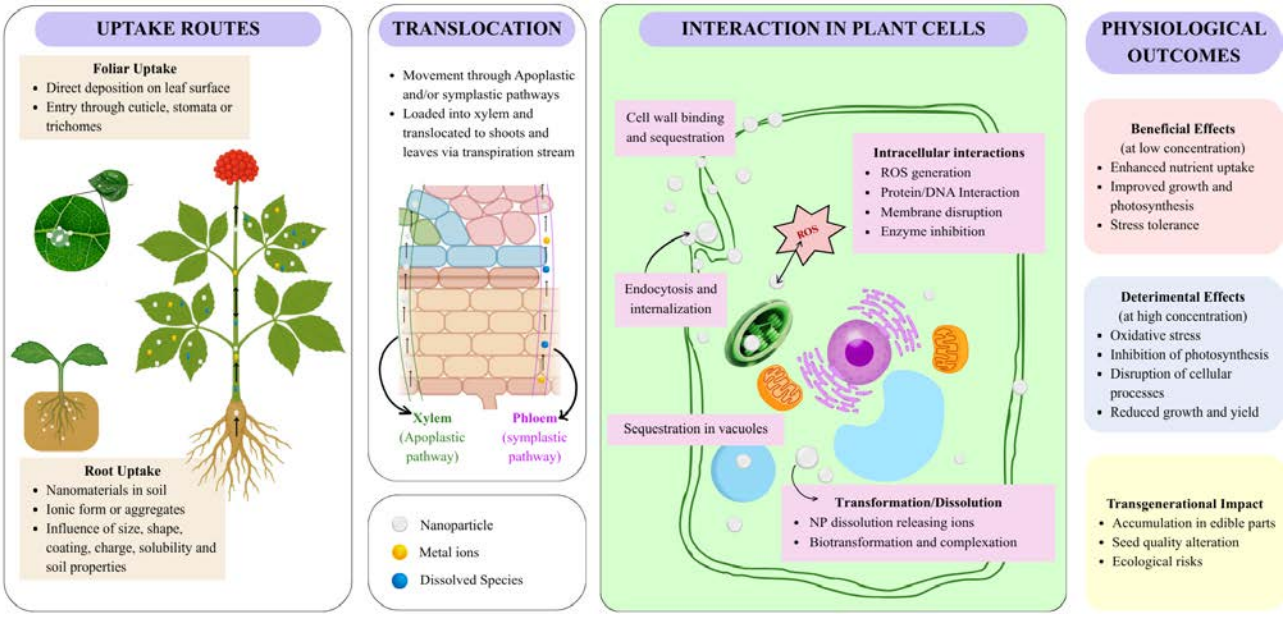


Figure 2. Nanomaterial interaction in plant system

to release beneficial metal ions. ZnO nanoparticles improve zinc bioavailability and are efficiently absorbed through roots, while TiO_2 nanoparticles enhance chloroplast activity and photosynthetic efficiency. In contrast, carbon-based nanomaterials such as carbon nanotubes and graphene oxide mainly facilitate water transport, seed germination and nutrient translocation by penetrating seed coats and vascular tissues.[34,35] In crops like chickpeas, carbon nanomaterials such as water-soluble carbon nanotubes (CNTs) stimulate water absorption and promote the growth of roots and shoots. Additionally, these substances promote capillary absorption, which could aid with molecular transport within plants. According to research on rice, carbon nanoparticles move to the leaves and raise the seed water content. Silica nanoparticles are also efficiently internalized due to their hydrophilic nature and play a significant role in improving stress tolerance and nutrient mobility within plant systems.[36,37] Interestingly, controlled nanomaterial-induced stress may boost the production of secondary metabolites, providing chances for phytochemical enhancement. It is essential to comprehend these relationships for applications in sustainable agriculture.[7,38,39]

Agriculturally important nanoparticles (Table 1) include silver nanoparticles, zinc oxide nanoparticles, titanium dioxide nanoparticles, silicon dioxide nanoparticles, copper-based nanoparticles.

Table 1. Nanoparticles, their mode of synthesis and their potential application in agriculture

	Mode of synthesis	Mode of application	Role	Action	Ref.
Silver Nanoparticles	Green synthesis, Microbial synthesis	Foliar spray, Soil treatment, Seed coating	Antimicrobial and antifungal properties serve as effective alternatives to chemical pesticides in combating plant diseases like powdery mildew and *Fusarium oxysporum*. They boost plant resilience to stress and improve nutrient uptake.	Pest control, Disease management, Crop protection, Plant growth	40,41
			Encourage the sprouting of seeds, the growth of roots, and the absorption of nutrients to enhance the overall well-being of the plant. Acts as nano-pesticides, which protect crops from bacterial and fungal pathogens and extend shelf life. Improves soil quality and water management.		42,43
			Antimicrobial properties help fight plant pathogens by disrupting cell membranes and generating reactive oxygen species (ROS), leading to cell death.		44,45
			Ensures targeted disease control. Enhance crop productivity and reduce the use of chemical pesticides.		46,47
			Functioning as antimicrobial substances, they help manage pathogens and boost agricultural output. Their use spans pest control, food safety, and environmental sustainability, positioning them as a valuable resource in modern farming.		48,49
Zinc Oxide nanoparticles	Green synthesis, Microbial synthesis	Foliar spray, Soil incorporation or amendment and seed treatment/seed priming	Enhance nutrient uptake. Act as nano-fertilizers, improving seed germination, crop yield and soil health while reducing the dependency on chemical fertilizers.	Plant-growth promoters. Support nutrient uptake and stress resistance. Reduce dependency on chemicals. Support soil and environmental health	50,51
	Biosynthesis, Sol-gel, hydrothermal, and Precipitation methods		Gradually releasing source of zinc enhances germination, photosynthesis, and overall yield. Their ability to combat microbes and contribute to stress tolerance makes them important for sustainable agriculture, fostering increased productivity while minimizing environmental effects.		52,53
	Biosynthesis and synthetic methods		Excellent solubility in water, essential for absorption by plants, functioning as both nano-fertilizers to enhance nutrient distribution and as antimicrobial solutions for safeguarding crops.		54,55
	Chemical, Physical and biological methods		Boost plant growth, improve crop yield and nutritional content. Enhancing resistance against pathogens through antimicrobial and enzyme-activating effects		56,57
	Green synthesis (Cow dung extract)		Low toxicity, better biocompatibility. Serves as a zinc supplement to combat soil deficiencies. Eco-safe nano-fertilizer		58,59

Titanium dioxide nanoparticles	Physico-chemical methods (Sol-gel, hydrothermal, precipitation) and green method	Root uptake, Foliar spray, Seed treatment and soil application	Improves seed germination, biomass and chlorophyll content. Also aids in phytoremediation.	Boost photosynthetic activity, Chlorophyll content and increase stress tolerance. Beneficial at low concentrations.	60,61
	Chemical methods (sol-gel and hydrothermal techniques) and green synthesis		Boosts chlorophyll content, promote root-shoot growth and improve yield. Help plants cope with drought and heavy metal stress		52,62
	Green synthesis		Stress tolerance against drought and salinity through ROS regulation and antioxidant activation. Possess antimicrobial properties		63,64
	-		Improve nutrient uptake, stimulate nitrogen metabolism, protect chloroplasts from oxidative damage and increase light absorption efficiency. Contribute to environmental sustainability by aiding pollutant removal and wastewater treatment.		65,66
	Hydrolysis of titanium salts or Chemical Vapor Deposition (CVD)		Enhance seed germination, stimulate root and shoot growth, improve nutrient uptake (such as K, P, Cu, Fe, Zn). Offers pesticidal action and aiding in pesticide degradation due to their photocatalytic nature.		67,68
Silicon dioxide nanoparticles	Green synthesis	Foliar spray, Soil supplementation, Soil irrigation, Seed priming, Hydroponics	Enhance germination, root and shoot growth and flowering. Improves stress tolerance against salinity, drought, heavy metals and UV-B exposure. Their mesoporous structure allows them to act as carriers for nutrients and pesticides, support controlled release, improve soil water retention, and offer antifungal, antibacterial and insecticidal benefits.	Promote growth and provide antimicrobial defense. Act as soil conditioners and contribute to agro-environmental remediation, offering a versatile, eco-conscious solution for boosting crop productivity.	37,69
	-		Supports plant growth and carotenoid levels. Suppresses bacterial and fungal diseases by forming a protective epidermal film. Activate key defense enzymes, increase proline accumulation for stress tolerance, and directly damage pathogens via cell wall disruption and reactive oxygen species generation.		70,71
	Physical, Chemical and Green synthesis		Protect plants from pests, pathogens, and harsh environmental conditions while improving antioxidant activity and reducing toxic metal accumulation. Their porous structure makes them effective nanocarriers for targeted delivery of fertilizers, pesticides, and bioactive compounds.		72,73
	-		Help plants withstand salinity, drought, heavy metal toxicity and UV stress by enhancing antioxidant activity, regulating ion balance and reducing toxic metal uptake.		69,74
	Green synthesis		Acts as antifungal agents, SiO_2 NPs effectively inhibit pathogens such as *Fusarium oxysporum* and *Aspergillus niger*, while boosting plant defense compounds like polyphenols. Improves nutrient uptake, water-use efficiency and resilience to environmental stress.		75,76

PURIFICATION OF WATER FOR IRRIGATION

Rather than adopting traditional and chemical-related methods, these nanotechnological methods provide efficient service and do not cause any harm to the environment. The nanofiltration method that is incorporated with nano filters is employed to purify the water intended for irrigation. Fused mech carbon nanotubes are utilized to eliminate waterborne pathogens.[3] Different kinds of nanomaterials are used in the process of water purification, including graphene, titanium dioxide, zero-valent iron and carbon

nanotubes. These materials, with their large surface area and unique reactive properties, efficiently remove pollutants, heavy metals and pathogens. a) Zero-valent iron nanoparticles and titanium dioxide are successful in eliminating heavy metals from water via adsorption, b) Functionalized nanoparticles can specifically target certain heavy metal pollutants, c) Nanostructured membranes with nanoscale pores enable selective elimination of contaminants while preserving minerals and nutrients. Techniques like nanoparticle functionalization and nanocomposites strengthen their stability and performance while lowering environmental risks [77,78]

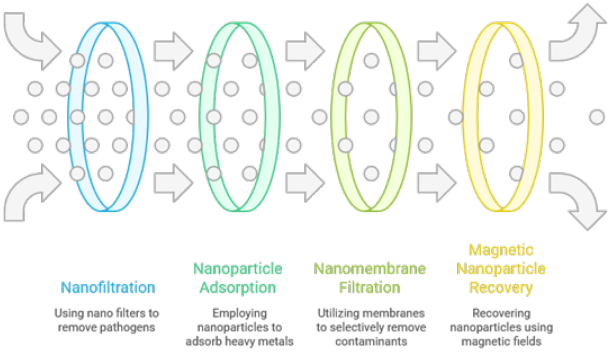


Figure 3. Nanoparticles for purification of water for irrigation

Magnetic nanoparticles are distinguished by their large surface area, efficient adsorption and convenient recovery using magnetic fields. Their performance is influenced by variables such as particle size, surface charge and water chemistry. The adsorption mechanism is fundamental in using magnetic nanoparticles, where contaminants like heavy metals adhere to the nanoparticle surface via interactions like hydrogen bonding and ion exchange. To boost their effectiveness, these iron oxide-based nanoparticles are often functionalized, enhancing their capacity to trap pollutants (Figure 3). They are easily retrieved using a magnetic field after treatment, streamlining separation without the need for additional filtration. A major advantage is their reusability; with proper regeneration, they can sustain up to 90% efficiency over multiple cycles. Additionally, their effectiveness within an optimal pH range (5-7) improves both sustainability and practicality in modern water treatment systems.[79]

Nanomembrane filtration technologies are emphasized as cutting-edge methods that aid in the recycling of water for agricultural purposes. These systems are designed to efficiently eliminate contaminants, enabling the safe reuse of drained water, municipal wastewater and industrial discharges. This capability is essential for boosting water sustainability in farming practices, as it allows previously discarded water sources to be utilized for irrigation and other agricultural functions. Nano-enabled solutions, such as nanocatalysts and nano-engineered methods, are presented as innovative strategies to address agricultural pollution and waste management. These technologies can help mitigate greenhouse gas emissions and improve the overall quality of water used in agricultural contexts. Cleaner water sources and more sustainable farming practices are made possible by nanocatalysts that promote chemical reactions effective in breaking down pollutants.[29,80]

Advanced filtration systems, like carbon nanofilms, are highly effective at removing heavy metals, pesticides and organic pollutants. Carbon nanofilms consist of layers of carbon nanotubes combined with nanoscale silver, zinc and copper, providing an efficient and versatile filtration solution. These membranes effectively filter out bacteria, viruses, organic pollutants and salts, while allowing water molecules to pass through. Their self-cleaning properties reduce energy consumption and maintenance requirements, while the embedded silver improves pathogen removal. Tailored nanoparticles can target specific contaminants, and integrating nanosystems with conventional methods like reverse osmosis boosts overall purification efficiency.[81,82]

NANOPARTICLES IN PLANT PATHOLOGY

Nanoparticles serve an important function in plant pathology by acting as antimicrobial agents, making it more difficult for pathogens to build resistance against them. They also enhance the plant's innate immunity by triggering antioxidant production, defense enzyme activity and cell wall strengthening. Their distinct features enable them to inhibit pathogen cellular activities while also increasing plant resilience [83,84]. Various forms of nanoparticles such as metal, metal oxide and non-metal are employed in resisting diseases and pathogens that cause diseases. Carbon nanomaterials, nanotubes (Single-walled and multi-walled), fullerenes, liposomes, dendrimers, nanoshells, quantum dots, nano biosensors, etc., are used as diagnostics, research tools, nano vehicles or nano drug carriers.[85]

The high surface area of nanoparticles augments their antimicrobial activity by allowing better interaction with pathogens, leading to their destruction. Upon contact, nanoparticles can disrupt microbial cell membranes, resulting in the leakage of cellular contents and ultimately causing cell death. They also generate Reactive Oxygen Species (ROS) like hydrogen peroxide and superoxide radicals, causing oxidative stress that damages vital biomolecules within pathogens. Also, nanoparticles hinder biofilm formation, making pathogens more susceptible to treatment, and their ability to release toxic metal ions like Zn^{2+} further boosts antimicrobial effects (Figure 4). Certain nanoparticles interfere with bacterial quorum sensing, resisting communication that promotes biofilm development and virulence. Beyond treatment, nanoparticles are used to develop sensitive biosensors, enabling early and accurate detection of plant diseases, ultimately supporting more effective disease management in agriculture.[86,87]

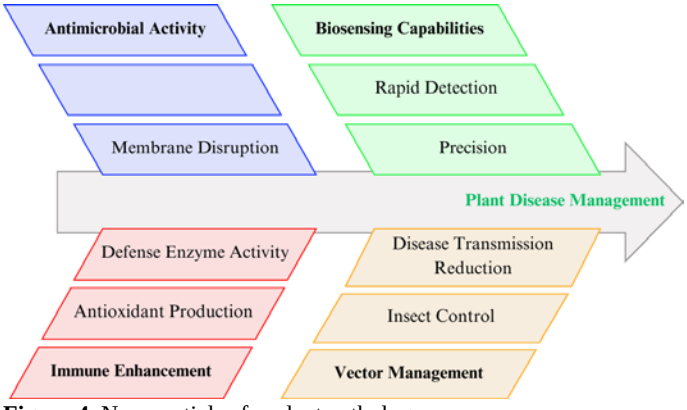


Figure 4. Nanoparticles for plant pathology

Gold nanoparticles (AuNPs) have been effectively used in rapid biosensing systems, like colorimetric assays and lateral flow tests, for quick virus detection in crops. They demonstrate direct antiviral properties by disrupting viral particles, as evidenced in studies involving the barley yellow mosaic virus and the tobacco mosaic virus. Nanoparticles also help manage insect vectors that carry viruses, thus reducing disease transmission. The advancement of nanobiosensors using materials like graphene oxide and quantum dots has greatly improved the precision of virus detection.[88,89] Bimetallic nanoparticles such as Ag-Cu and Au-Ag nanoparticles have recently gained attention in plant disease management due to their synergistic antimicrobial activity. These nanoparticles exhibit stronger inhibition against phytopathogenic fungi and bacteria compared to monometallic nanoparticles by simultaneously disrupting microbial membranes and inducing oxidative stress.[90]

Chitosan nanoparticles significantly raise plant defense by activating defense genes (PR1–PR5, PR10) and boosting the activity of key enzymes like peroxidase and catalase, that leading to stronger systemic resistance. They induce more effective and quicker protection against diseases like wheat leaf rust, compared to traditional treatments like salicylic acid. In addition to boosting immune responses, chitosan nanoparticles directly damage fungal membranes, prevent the growth of pathogens, enhance nutritional absorption and fortify the structure of plant tissue, all of which together contribute to the development of a strong defense barrier. They are positioned as an effective and sustainable substitute for chemical fungicides due to their multifunctional action.[91,92]

Metal oxide nanoparticles, particularly ZnO and CuO, are showing great promise in managing phytopathogenic fungi, often outperforming traditional agrochemicals. The production process determines the effectiveness of nanoparticles. With biologically produced nanoparticles, such as titanium oxide from plant extracts, exhibit stronger antifungal action. These nanoparticles damage the membranes of fungal cells, generate reactive oxygen species, and disrupt metabolic processes, ultimately resulting in the death of the pathogens.[93]

NANOPARTICLES IN SEED COATINGS

Seed coating technologies play a critical role in supplying nutrients and biostimulants to the seeds uniformly and recent advances suggest that incorporating nanoparticles could further elevate this process. Nanoparticles can also serve as markers for seed tracking and security. Using equipment like rotary pans and powder applicators, these nano-infused coatings could be applied efficiently to boost germination, seedling vigor, and resilience against both biotic and abiotic stresses in agriculture [94]. Seed coating is a technique where physical, chemical or biological materials are applied to seeds to boost their germination, protect against pests and improve early growth (Figure 5). The use of agrochemicals directly and periodically in the field has varied negative impacts due to uncontrolled discharge into the environment resulting in plant and soil degradation. To overcome this, nano polymers are used in seed coatings wherein biodegradable and biocompatible polymers are coated. They are sustained with growth regulators, nutrient supplements, plant development hormones and materials that protect against pests, pathogens, etc., [95]. Traditionally, organic materials, such as powdered moringa leaf, have been utilized over time, while nanoparticles present new opportunities due to their smaller size, greater surface area and distinctive features. Nanoparticles can facilitate water retention, boost early plant growth, improve nutrient delivery and form a barrier that keeps pathogens apart. They are ideal for improving seed performance due to their capacity to regulate nutrient delivery and foster the growth of solid root systems, especially in harsh environmental conditions.[96]



Figure 5. Nanoparticles in seed coatings

Mesoporous silica nanoparticles and chitosan-based nanoparticles are increasingly utilized in nano-seed coatings because of their controlled release properties and biocompatibility. These nanomaterials gradually release nutrients and bioactive compounds, thereby enhancing seed vigor, moisture retention and early seedling establishment under abiotic stress conditions.[97,98] Zinc oxide nanoparticles (ZnONPs) have demonstrated immense potential in enhancing plant growth, yield and fiber quality, especially in maize. The concentration of 20 mg/L outperforms conventional treatments like bulk $ZnSO_4$ coatings. Beyond improving vegetative metrics, ZnO NPs boosted soil microbial activity, improved soil enzyme functions and increased zinc nutrient uptake, all of which correlate with healthier soil ecosystems. Methods included seed priming with sonicated ZnO NP suspensions and polymer-based coatings that ensured uniform distribution and gradual nutrient release. Treated plants exhibited higher chlorophyll content, reflecting better photosynthesis [99]. Seed coating with zinc oxide (ZnO) nanoparticles has shown remarkable improvements in germination rates and development of soybean plants (*Glycine max*). In the study, ZnO-coated seeds demonstrated a nearly 40% increase in germination rates compared to untreated seeds, while also producing seedlings with stronger root and shoot architecture. Unlike conventional $ZnSO_4$ coatings, which were found to be toxic and suppressed growth, ZnO nanoparticles promoted healthier early development by facilitating gradual zinc release. Most zinc was transferred to the soil post-sowing and a fraction was successfully taken up by seedlings, boosting early growth. The nanoparticles also altered the seed cuticle, enhancing soil interaction and water retention.[100]

Seed coating improves crop establishment, as seen in dry direct-seeded rice, where treatments like calcium peroxide and *Bacillus sp.* KS-54 markedly improved field emergence, seedling vigor and weed suppression. Coated seeds exhibited larger reducing sugar levels and boosted antioxidant enzyme activity, promoting

resilience under stress. Seed coatings increased the vigor of early seedlings, enabling crops to naturally outcompete weeds.[101]

BARRIERS TO NANOPARTICLES IN PLANTS

Plants naturally obstruct the penetration of nanoparticles (NPs) through a series of structural and biochemical barriers (Figure 6). The initial hurdle is the cell wall, which has pores that are about 13 nm in size, that restricts bigger NPs from passing through. It has a negative surface charge, which repels the similarly charged particles. Even if NPs get past this barrier, the tightly packed lipids that make up the plasma membrane limit further entry. Therefore, NPs often rely on processes like lipid exchange rather than chemical endocytosis.[33,102]

Organelle membranes present another level of restriction inside the cell. To improve uptake, researchers are tailoring NP size, charge and surface chemistry, aiming to bypass or interact more effectively with these plant defenses for successful delivery. While the smaller nanoparticles dissolve more quickly and promote ion uptake, the exact interaction pathways remain unclear.[103]

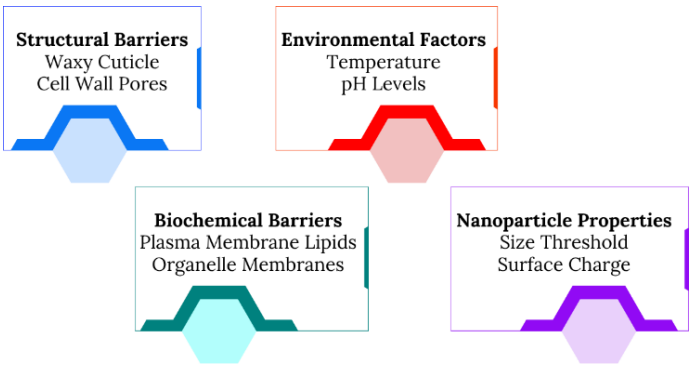


Figure 6. Barriers to nanoparticles in plants

Numerous environmental and natural obstacles can limit the absorption and functionality of nanoparticles in plants. One of the primary barriers is the plant's physical defense; its waxy cuticle and tightly regulated stomata, retaining big particles from penetrating the leaf surfaces. Overuse of NPs can block stomata, diminishing gas exchange and impeding photosynthesis. Nanoparticle size is a crucial aspect, as only those below a specific threshold can flow through absorption channels. In addition, the chemical composition and surface charge of the nanoparticles affect how well they interact with plant tissues. NP behavior is also influenced by environmental factors, including pH, temperature, and ion presence. These factors collectively determine whether NPs reach their target sites and carry out their intended agricultural benefits.[9,104]

The plant cell wall acts as a primary filter, only allowing very small particles to pass through, typically under 100 nm. Stomatal pores, with diameters around 0.6–0.8 nm, also pose a size limitation, permitting only extremely small or properly structured particles. The plant's waxy cuticle acts as an extra barrier of defense, and the absorption of nanoparticles differs according to whether the particles are hydrophilic or lipophilic in nature. Following penetration, nanoparticles move through the plant through phloem transport, typically with the help of certain transporters or carrier proteins like Lsi1. The effectiveness of this entire process is influenced by the plant species, the size, and surface properties of the nanoparticles.[105] The surface hydrophobicity of NPs also influences uptake; for example, amphiphilic particles can traverse leaf cells more effectively than purely hydrophilic ones. To overcome these challenges, biorecognition motifs like transit peptides to guide NPs to specific targets such as chloroplasts, significantly improve delivery rates.[106]

The cell wall of a plant, composed of cellulose, hemicellulose, and pectin, functions as a gatekeeper, selectively permitting nanoparticles based on their size and charge. Stomata offer another entry route, with openings wider than cell wall pores, although the accessibility still relies on the characteristics of the particles. The vascular system governs the internal transport and distribution, whereas root structures, especially lateral roots create physical fissures that could allow NP access. Chemical traits like surface charge and hydrophilicity influence the interaction between the particles and the plant tissues. Positively charged NPs often show better uptake due to their affinity for the negatively charged cell wall.[37,107] Recent studies indicate that surface-functionalized nanoparticles coated with polymers such as polyethylene glycol (PEG) and polyvinylpyrrolidone (PVP) exhibit improved penetration across plant barriers by reducing aggregation and enhancing colloidal stability. Such surface modifications significantly influence nanoparticle mobility, retention and intracellular transport within plant tissues.[24]

It is challenging to guarantee constant NP behavior in plants due to their complex tissues, varying absorption patterns, and unpredictable reactions. Beyond biology, the adoption of new nanoagritechnologies is slowed down by stringent regulatory scrutiny and safety concerns. Their usage is further restricted by the difficulty in scaling up NP manufacturing and inconsistent reproducibility in laboratory results. Moreover, the lack of reliable predictive models makes it hard to forecast NP performance in real field conditions [108,109]. Understanding these complex barriers is crucial for improving the use of nanoparticles in enhancing plant growth and resilience.

CONCLUSION

Nanotechnology has emerged as a pivotal innovation in modern agriculture, addressing global challenges such as low crop productivity, excessive use of agrochemicals, soil degradation, and climate stress. With their unique nanoscale properties, nanoparticles offer novel solutions for enhancing plant growth, improving nutrient uptake, boosting stress tolerance, and ensuring sustainable food production. The application of nanofertilizers and nanopesticides reduces the dependency on conventional chemical inputs while enhancing efficiency through targeted and controlled release. Nanobiosensors and nano-enabled delivery systems further strengthen precision farming, enabling real-time monitoring of soil health, pathogen detection, and optimized resource management. Moreover, the integration of nanomaterials in water purification, food packaging, and post-harvest technologies minimizes losses and promotes food safety, contributing to a more resilient agricultural system. Despite their immense potential, challenges such as nanoparticle uptake barriers, toxicity concerns, environmental persistence, scalability of production, and lack of

regulatory clarity remain critical. The interactions of nanoparticles within plant systems, including their absorption, translocation, and impact on physiological functions, require further in-depth investigation to ensure safety and sustainability. Additionally, awareness among farmers, coupled with policies supporting eco-friendly nanomaterials and green synthesis methods, will be vital for large-scale adoption. Overall, nanotechnology stands at the frontier of agricultural innovation, bridging the gap between sustainability and productivity. By addressing current limitations through interdisciplinary research, eco-conscious design, and regulatory frameworks, nano-enabled agriculture can significantly contribute to global food security while minimizing environmental impact. As research advances from laboratory studies to field-scale applications, nanotechnology has the potential to revolutionize agriscience, offering a pathway to a sustainable and resource-efficient agricultural future.

CREDIT - AUTHORS CONTRIBUTION STATEMENT

Priyavashini Prakash: Formal analysis, Investigation, Software, Writing – Original draft, Writing – review and editing

Rajamehala Murugan: Conceptualization, Methodology, Resources, Supervision, Writing – Original draft, Writing – review and editing

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CONFLICT OF INTEREST STATEMENT

Authors declare no conflict of interest.

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