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REVIEW ARTICLE

Role of nanoparticles in alleviation of biotic and abiotic stress in crops a review

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Abstract

Difficulties such as drought, salt and high temperatures caused by environmental problems reduce worldwide crop yields and greatly prevent seeds from sprouting. Because of what they are made of nanoparticles (NPs) are getting a lot of attention as a method to boost plant growth in tough conditions. The review covers information on how various NPs are affected by abiotic conditions and in turn influence the process of seed germination and the early stages of plant growth. Metallic, carbon-based and biopolymer nanoparticles modulate water uptake, activate germination-related enzymes (e.g., amylase, protease) and enhance antioxidant defense (e.g., superoxide dismutase, catalase), thereby improving seed vigour under stress. This is done because these interactions save cellular balance, which results in less oxidative stress and greater resistance to outside problems. The study also investigates the ways NPs get into seed cells and what impacts they have on cellular organelles. Topics related to NPs like their toxicity, the possibility that they last in nature for a long time and the many regulations are mentioned too. It is highlighted that when it comes to using nanotechnology in agriculture, emphasis ought to be placed on making sure things are environmentally friendly and sustainable and that nanoparticles are properly adjusted to encourage seed germination under stressful conditions.

Keywords: drought; heavy metals; high temperatures; nanoparticles; salinity; seed germination; stress mitigation

Introduction to nanoparticles and abiotic Stress

Global agriculture is seriously threatened by climate change, which is typified by increasing temperatures, changed precipitation patterns and decreased water availability. Communities in developing nations, where farming is a major source of food security and livelihood, should be especially concerned about these developments. Issues like food insecurity and hunger are getting worse as climate change intensifies and the world's population keeps expanding. In response to these challenges, researchers are increasingly exploring advanced technologies. Among them, nanotechnology has emerged as a promising strategy for enhancing plant tolerance and productivity under adverse environmental conditions. NPs have distinct physical and chemical characteristics that set them apart from their bulk counterparts because of their minuscule size. They are fascinating from a scientific and technological standpoint because they reside at the boundary between individual molecules and large-scale materials. Currently, agriculture is using a wide range of engineered nanomaterials to address environmental stress, including metals (Zn, Cu, Ag, Fe), metal oxides (TiO_2, ZnO, Fe_2O_3/Fe_3O_4, SiO_2, Al_2O_3, MgO), metalloids (Si) and carbon nanomaterials (e.g., carbon nanotubes).

In order to sense and react swiftly to external stressors, plants have developed sophisticated mechanisms. These adaptive responses can be strengthened by NPs, making plants more resistant to abiotic stress. By increasing their capacity to endure and function in challenging growth environments, crops may be able to increase yields by nanotechnological treatments (1-5) (Fig. 1).

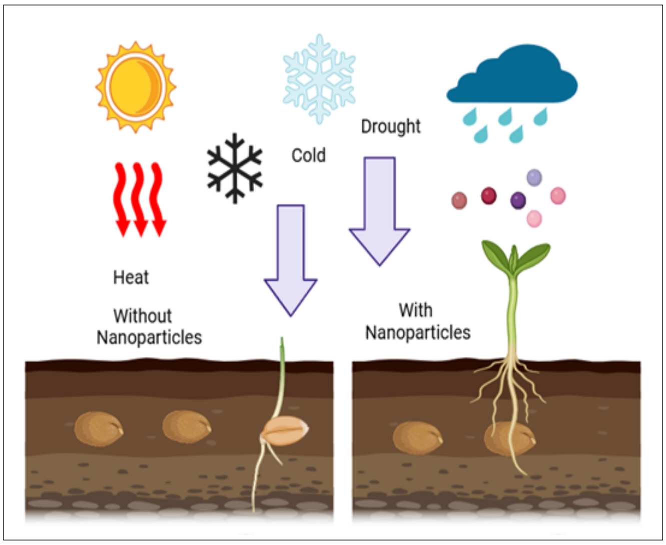

Fig. 1. The impact of abiotic stress on seed germination, the image contrasts untreated seedlings with those enhanced by nanoparticles, showing enhanced development and resilience.

Uptake, translocation and mechanistic interactions of nanoparticles in plant systems

NPs, due to their minuscule size, can enter plant tissues through both belowground and aboveground structures. They penetrate roots via tips, lateral roots, the cortex, or damaged areas and aboveground parts through features like the cuticle, epidermis, stomata, hydathodes and other natural openings. NPs reach plant roots through the soil matrix via bulk flow and diffusion, influenced by their size, charge, solubility and surface coatings. Once near the root surface, they interact with root exudates and penetrate through two main pathways: the apoplastic and symplastic routes. In the apoplastic pathway, NPs move passively between cell walls and intercellular spaces until they are blocked by the casparian strip in the endodermis. To move further, they must enter the cells. The symplastic pathway involves active uptake through endocytosis, where the plasma membrane engulfs NPs into vesicles. From there, they move cell-to-cell via plasmodesmata (6).

Root hairs and sites of lateral root emergence are key zones for NPs entry due to thinner cell walls and higher permeability. Internalized NPs may undergo changes like dissolution or binding with biomolecules, influencing their behavior inside the plant. Once past the cortex, they can access the xylem for upward translocation. The surface properties of NPs, such as positive charge or biocompatible coatings, enhance their adhesion and uptake. Understanding these processes is vital for optimizing the application of NPs in agriculture, ensuring efficient root uptake and minimal toxicity while enhancing nutrient delivery and stress tolerance (7).

The extent and nature of NPs' impact on plants largely depend on various factors including plant species, growth stage, type of NP, method of application, dosage and duration of exposure (8,9). According to the mass flow or pressure flow hypothesis, NPs that enter through the stomata are transported within the plant via the phloem, driven by pressure differences between the root and shoot systems (10). The pathway taken by NPs significantly influences essential physiological processes such as seed germination, antioxidant activity, nutrient absorption (macro and micronutrients), chlorophyll synthesis, chloroplast formation and overall photosynthesis (11). In *Arabidopsis*, for instance, NPs have been shown to alter intra-root signaling by modifying ethylene production (12). After penetrating the cell wall and membrane, NPs can migrate to internal tissues like the epidermis, xylem, central cylinder and ultimately the leaves (13). Before reaching the central cylinder, NPs are passively transported through the endodermis (14). Transport occurs via both the symplastic route (through plasmodesmata) and apoplastic or active pathways, driven by osmotic pressure, capillary action and interactions with pores in the cell wall (15). NPs may also breach the plasma membrane by forming pores or binding to transport proteins and they can enter cells through mechanisms like ion channels, aquaporins, or endocytosis. The ability of NPs to penetrate plant tissues is largely determined by their size (16). Larger NPs typically move through structures like stomata, stigma and hydathodes, while smaller particles especially those between 15-40 nm can pass directly through the cell wall (17,18). Once inside, smaller NPs (<~40 nm) can move symplastically and enter the translocation stream (xylem/phloem), facilitating systemic distribution to aerial tissues (19), as illustrated in Fig. 2.

Researchers believe that nanotechnology can bring big improvements to agriculture. Today, scientists are coming up with new approaches that rely on nanotechnology to boost the quality of seeds, increase germination and yield more crops. As a result of these advancements, it will be possible to overcome difficulties from changes in the environment and continue providing enough food (20). At present, the wide use of nanotechnology in farming is greatly restricted due to the difficulty of dealing with agricultural ecosystems. At the same time, nanotechnology has a promising role in boosting different aspects of plant growth, such as seed germination, strength and output. If nanomaterials are combined with seeds, they could advance different processes in plants. With this method, the chance of seeds germinating well, the vigor of seedlings and total plant health may all improve under great conditions (21). Even though nanotechnology could bring great benefits, there are more concerns about its possible harm to the environment and people. Some researchers have brought up issues with the unknown dangers of nanomaterials on the ecosystem when they are introduced (22,23), Nanomaterials can be harmful to living and non-living parts of nature due to their potential toxicity, persistence in the environment and ability to accumulate in biological systems, leading to adverse effects on organisms, ecosystems and natural resources. They can either harm the bacteria in the soil (24) or lessen the number of nutrients available (25), which also negatively affects arthropods (26) and annelids (27). The reason for this is that pests may cause the crops to produce less and ecological problems may follow as well. Using nanomaterials on seeds has brought about some beneficial and some negative changes for their germination. The effects of nanomaterials on seed germination are covered in different studies and have been presented (Table 1 and Fig. 3).

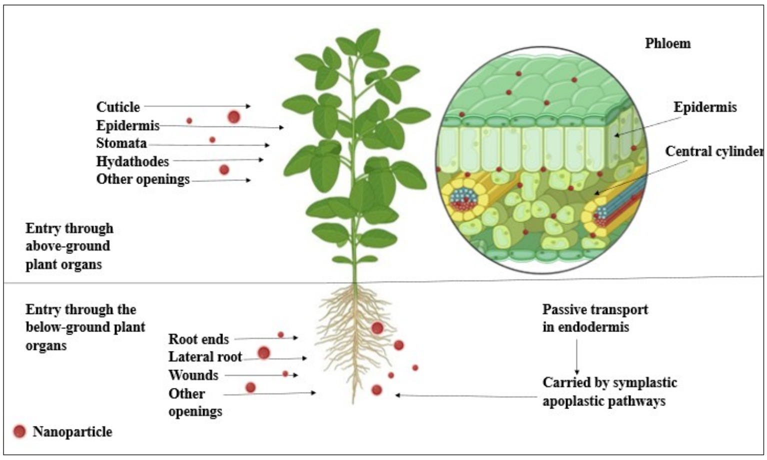

Fig. 2. Above ground and below ground mechanisms by showing multiple entry locations and transport channels of nanoparticles in plants.

Table 1. Influence of various nanoparticles on seed germination

S.no.	Particle used	Seed type	Remarks	Physiological process	References
1.	Fe_2O_3	*Vigna mungo*	Seeds primed 120 min with Fe_2O_3 quantum dots attains maximum germination percentage @500 ppm (93 %).	Enhanced enzyme activity (amylase), ROS balance and hormonal signaling	(30)
2.	Silver	*Lolium multiflorum, Panicum vigatum*	Ag NPs coated with gum Arabic considerably slowed the growth of *Juncus effusus* and *Scirpus Cyprinus.*	Allelopathic suppression, interference in cell division	(31)
3.	TiO_2	*Linum usitatissiumum, Solanum lycopersicum* and *Vigna radiata*	Treatment with TiO_2 with sizes corresponding to 25 and 32 nm indicated stimulatory effect on root growth and seed germination.	Increased photosynthesis, ROS scavenging, nutrient uptake	(32)
4.	TiO_2	*Triticum aestivum*	Lower concentrations of TiO shortened the germination durations, while larger concentrations repressed the germination of seeds.	Hormonal regulation (ABA/GA balance), oxidative stress	(33)
5.	TiO_2	Switch grass [*Panicum virgatum*]	When compared to control sets, the mean seed germination was reduced by around 50 % at a concentration of 2.5 % TiO; however, germination was not adversely affected by concentrations lower than 2.5 %.	Toxicity induced oxidative stress, membrane damage	(34)
6.	CuO	*Hordeum sativum*	When compared to control seeds, NPS reduced seed germination by 23 %.	Disruption of mitochondrial respiration, membrane integrity	(35)
7.	Al_2O_3, CuO	*Solanum lycoperscion*	After receiving NPs, there was no impact on seed germination. When compared to control sets.	No significant physiological alteration	(36)
8.	Amine-modified polystyrene and TiO_2	Lettuce	Following exposure to TiO_2 and amine-modified polystyrene, there were notable reduction in both length of the plant (root, shoot) sulfate-modulated polystyrene did not have any inhibitory effects.	Interference with auxin signaling, cell elongation	(37)
9.	Ag, Cu, Au	*Eruca sativa*	The optimal positive response for Ag NP was demonstrated by the 42 day seed germination. Ag NPs were the only ones that showed complete seed germination.	Ag enhances antimicrobial action, hormonal activity	(38)
10.	Multiwalled carbon nanotube, Al, Al_2O_3, Zn and ZnO	*Raphanus sativus, Brassica napus, Lolium multiflorum, Lactuca sativa, Zea mays* and *Cucumis sativus*	*Zea mays* and *Lolium multiflorum* seed germination were only impacted by Zn-based nanoparticles.	Zn influences protein synthesis, enzyme activation	(39)
11.	TiO_2	*Foeniculum vulgare*	After being treated with NPs at low concentration, the seed germination index increased; the germination of the seeds was improved; at 40 ppm of NPs, the germination was improved. length up to 31.8 % in comparison to the control group.	Enhanced water uptake, hormonal balance	(40)
12.	SiO_2	*Lycopersicum esculentum*	Applying NPs had stimulatory effects on the characteristics of seed germination; the time for seedling emergence and the optimal concentration for enhancing seed germination were found to be at 8 gL.	Improved cell wall loosening, water uptake	(41)
13.	Chitosan	*Oryza sativa*	Chitosan nanoparticle treatment increased rice seed germination and was thought to be a germination elicitor; in a conclusive test, fewer seeds germinated at higher concentrations of the nanoparticle.	Modulated immune response, seed enzyme activation	(42)
14.	Cu_2O	*Lycopersicum esculentum*	Seed germination was stimulated by low concentrations (20 ppm); higher concentrations were found to inhibit seed germination.	Cu influences ROS detoxification, energy metabolism	(43)
15.	Hydroxyapatite	*Solanum lycopersicum*	There was no discernible inhibitory effect on seed germination when hydroxyapatite concentration increased (2-2000 ppm).	Acts as phosphorus source, no stress response triggered	(44)
16.	TiO_2, ZnO, Al_2O_3, CuO	*Raphanus sativus, Cicumis sativus, Solanum lycopersicon* and *Medicago sativa*	Different NP treatments resulted in inhibition of seed germination; TiO treatment, up to a specific dosage, increased root and shoot growth; and ZnO and CuO NP treatments showed results. inhibiting the length of the roots and shoots	Variable effects: growth regulation, ROS balance, enzyme activity	(45)
17.	ZnO, TiO_2, CuO, Ag	*Avena sativa* and *Trifolium alexandrinum*	nanoparticle treatment increased rice seed germination and was thought to be a germination elicitor.	Synergistic enhancement of antioxidant defense and nutrient availability	(46)
18.	Monometallic and bimetallic nanoparticles	*Silybum marianum*	The application of nanoparticle therapy greatly accelerated germination; the highest positive effect was observed when silver nanoparticles were suspended; the average germination rate of every seed tested exceeded 85 %.	Ag-induced microbial inhibition, protein synthesis	(47)
19.	Nano zero-valent iron and Ag	*Genus Lolium, Hordeum vulgare, Linum usitatissimum*	The germination of seeds was completely suppressed at 1000-2000 ppm of nZVI.	Induced oxidative stress, iron toxicity, DNA damage	(48)
20.	ZnO	Peanut	Favorable impact on the seed sprouting.	Zn boosts enzyme systems like dehydrogenase, membrane integrity	(49)

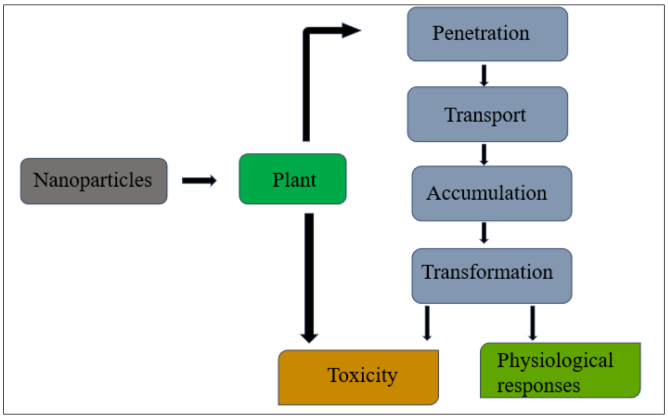

Fig. 3. The flow chat gives about the penetration of NPs in plants.

Role of NPs in modifying seed germination

With staples like grains, legumes and nuts making up a sizable amount of the world's caloric intake, seeds are an essential source of nutrition in the human diet (28). Particularly for species that do not reproduce vegetatively, seeds are essential to plant reproduction. They maintain the genetic diversity and continuity of plant populations by acting as biological carriers of genetic information. Through its ability to interact with various physiological processes, nanotechnology has become a promising tool for improving seed germination. Improved germination rates, seedling vigor and overall plant performance may result from the modulation of water intake, enzyme activation and metabolic activities by NPs, especially in harsh climatic circumstances (29).

Specific effects of abiotic stress

Agricultural crops are subject to a wide range of stresses, which can be classified as either biotic (originating from living things) or abiotic (originating from environmental variables that are not living). Since abiotic stresses are mostly unpredictable and inevitable in nature, they are very important. These include drought, salinity, high temperatures (cold and heat) and heavy metal contamination. Because plant responses are diverse and dynamic, it is challenging to accurately measure the effect of abiotic stress on crop output. These responses may be elastic (reversible adaptations) or plastic (permanent changes), depending on the intensity and duration of the stress.

Plants cope with abiotic stress through two primary strategies: avoidance and tolerance. Avoidance mechanisms involve the plant's ability to evade stress by altering growth or development patterns. For example, some plants exhibit escape strategies, where they accelerate their life cycle and complete reproduction before the onset of severe stress. This includes utilizing available soil moisture efficiently and enhancing gas exchange rates through rapid growth. Plants may also adjust morphologically and physiologically to avoid damage by shedding leaves to reduce water loss, delaying or reducing seed germination, closing stomata during the night to conserve water and adopting a compact growth form, which minimizes the surface area exposed to adverse conditions. These adaptive responses are crucial for plant survival and productivity in fluctuating environments (Table 2a, Table 2b). In the table spell out if some of the above processes are affected in plants.

Effects of NPs on seed germination under salinity stress

NPs plays a key role in mitigating the adverse effects of salinity stress on plants. For instance, treatment with silver NPs (Ag NPs) in *Lathyrus sativus* under salt stress improves germination rate, shoot and root lengths, as well as seedling fresh and dry weights by enhancing osmotic regulation and reducing the harmful impact of salinity (65, 66). Similarly, adding Cu NPs to the soil significantly promotes growth and yield in wheat, while decreasing oxidative stress caused by salinity (67). Pre-treatment of wheat seeds with Ag NPs modulates antioxidant enzyme activities, reduces oxidative damage and enhances tolerance to salt stress during germination (68). Moreover, ZnO NPs have been found to increase dry weight in sunflowers exposed to saline conditions (69). The physiological responses of *Brassica napus* under salt stress are enhanced by cerium oxide (CeO) NPs at concentrations of 100 and 200 mg/kg (70). In basil plants exposed to salt stress, the application of Ag NPs also promotes seed germination (71,72). By reducing adverse effects on germination percentage and shoot

Table 2a. Impact in enhancing crop tolerance to salinity stress

Type of particle used	Treatment	Crop	Stress induced	Effects	References
Aluminum oxide	Seed soaking	*Glycine max*	Salinity	Controlled the activity of the tricarboxylic acid cycle, membrane permeability and the ascorbate-glutathione pathway.	(50)
Mn_3O_4	Foliar application	Cucumber	Salinity	Enhanced luminescence concentration, net transpiration and yield each have an impact on metabolomics.	(51)
Mn	Foliar application	sweet peppers	Saltiness	improved sprouting of seeds and root growth.	(52)
Fe	In nutrient media	Grape	Salinity	Reduced levels of H_2O_2, antioxidant enzymatic activity.	(53)
Fe	Foliar application	Moldavian balm	Salinity	Increased TAT, RAS and RA gene expression.	(54)
Fe	Seed soaking	Jowar	Saltiness	Increased lipid peroxidation, photosynthetic rate	(55)
Fe	50% of the pots were filled with nano-zinc oxide suspension.	Mineral nutrient	Saltiness	decreased the amount of MDA and began the plant's growth.	(56)
CeO_2	Spraying	Mouse-ear cress	Salinity	Enhanced photosynthesis, biomass, chlorophyll concentration and mesophyll K + retention in leaves	(57)
CeO_2	Within the ground	*Brassica napus*	Saltiness	Enhanced photosynthetic equipment efficiency and biomass in plants	(58)

Table 2b. Impact in enhancing crop tolerance to drought stress

Type of particle	Treatment	Crop	Stress induced	Effects	References
Si	Added to nutrient solution of seedling	Hawthorn	Drought	Enhanced plant tolerance through the preservation of vital metabolic and biological processes	(59)
Titanium dioxide (TiO2)	Seed priming	*Zea mays* (Maize)	Drought	Improved seed germination, enhanced photosynthetic activity and better water use efficiency under drought stress.	(60)
Silver nanoparticles (AgNPs)	Foliar spray	*Triticum aestivum* (Wheat)	Drought	Reduced oxidative damage, increased antioxidant enzyme activity and improved plant biomass.	(61)
Silicon dioxide (SiO2)	Soil application	*Oryza sativa* (Rice)	Drought	Enhanced root development, membrane stability and relative water content under drought stress.	(62)
Carbon nanotubes	Seed treatment	*Vigna radiata* (Mung bean)	Drought	Increased water retention, accelerated germination and improved stress resistance.	(63,64)

length under salt stress, Ag NPs increase plant resilience in *Satureja hortensis* (73). When sprayed to cumin plants, Ag NPs greatly increased their ability to withstand salty conditions (74). Finally, high concentrations of NaCl (75) can induce oxidative damage to mint plants, but FeO_4 NPs shield them from this harm.

NPs effects on drought-stressed seed germination. Abiotic stressors like drought severely reduce agricultural yield (76,77). Applying NPs can improve physiological characteristics, boost antioxidant enzyme activity and increase phytohormone levels, all of which can mitigate the impacts of drought. Analcite NPs, for instance, have been demonstrated to enhance wheat germination and growth when applied to hot, dry soil (78). Furthermore, the application of ZnO NPs to dried soybean seeds promotes germination rates (79). Cu and Zn NPs help wheat plants survive drought by increasing relative moisture content and antioxidant enzyme activity, decreasing Thio barbituric acid concentrations, controlling reagent precipitation, preserving the amount of photosynthetic pigment in leaves and reducing stress damage (80). Across different abiotic stresses, NPs consistently promote seedling vigor by enhancing antioxidant activity, modulating hormonal pathways and improving osmotic balance. While the specific mechanisms vary, the overarching trend indicates that nanomaterials can bolster early stage plant resilience under both drought and salinity stress (81). Furthermore, SiO_2 NPs applied to barley under drought conditions improve shoot length and relative water content (RWC), while decreasing superoxide radical production and membrane injury (82).

Effects of NPs on seed germination under heavy metal stress

Treating plants with NPs either through soil or foliar application can reduce toxicity caused by oxidative stress, enhance plant growth and photosynthesis and mitigate the harmful effects of heavy metal stress. As a result, NPs also contribute to the remediation of environments contaminated with heavy metals. When plants face heavy metal exposure, applying NPs decreases the heavy metal concentration in the soil, regulates the expression of genes involved in metal transport, strengthens the plant's antioxidant defenses, improves physiological functions and encourages the production of protective substances such as organic acids, phytochelatin and root exudates (83). Phytoremediation is an environmentally friendly and cost effective technique that uses green plants to clean up heavy metal-contaminated soils and water bodies. This method relies on the natural ability of certain plants to uptake, accumulate and detoxify heavy metals through various mechanisms. One of the most common methods is phyto extraction, where plants absorb heavy metals from the soil and translocate them to the aerial parts, which can then be harvested and safely disposed of. Phyto stabilization involves the immobilization of heavy metals in the root zone through root exudates or precipitation, thereby reducing their mobility and bioavailability in the soil (84). Rhizofiltration utilizes plant roots, especially from aquatic or hydroponically grown plants, to absorb or adsorb heavy metals from polluted water. Phytovolatilization is another process where plants take up specific heavy metals like mercury or selenium, convert them into volatile forms and release them into the atmosphere. Although not effective for all types of metals, phytodegradation, which primarily addresses organic contaminants, can support metal remediation indirectly by enhancing soil health (85). The success of phytoremediation depends on plant species, pollutant type and environmental factors. Overall, phytoremediation offers a sustainable and non-invasive approach for restoring ecosystems impacted by heavy metal pollution (86). For example, under arsenic stress, Si NPs applied to maize reduce negative effects on maximum quantum efficiency, photochemical quenching and non-photochemical quenching of photosystem II, while also decreasing total chlorophyll, carotenoid and protein content (87). Titanium dioxide (TiO_2) NPs play a critical role in alleviating heavy metal-induced oxidative stress by limiting cadmium toxicity and improving physiological traits and photosynthesis rates in soybean plants (88). In pea seedlings subjected to chromium stress, treatment with Si NPs increases activities of antioxidant enzymes like ascorbate peroxidase (APX) and superoxide dismutase (SOD), thereby reducing oxidative damage (89). Additionally, Si NPs have been found to reduce aluminum toxicity in maize by activating antioxidant defense mechanisms (90).

Future prospects and Conclusion

Interactions between plants and NPs lead to both physiological and structural changes in plants. However, the effectiveness of NPs application depends on several factors, including the chemical composition, size, surface charge, reactivity, dosage, frequency of application, plant species and the specific plant part treated. A notable area in this context is nanoparticle-based plant delivery systems. Thanks to nanotechnology, it is now possible to precisely alter genes and regulate their expression by delivering tailored DNA into plant cells. The introduction of desirable features into genetically distinct organisms is accelerated by this method. A wide range of characteristics, including different hues, increased yields and changing growing seasons, can be incorporated into seeds. Nanomaterials offer dual application modes internally for genetic transformation and externally for precise nutrient or pesticide delivery both aimed at improving stress tolerance and productivity. Additionally, NPs can be utilized to precisely administer herbicides and nutrients, providing a novel way to improve crop protection while lessening the impact on the environment.

The integration of NPs into plant systems not only enhances genetic transformation but also revolutionizes precision agriculture. By facilitating targeted delivery of agrochemicals, NPs minimize off-target effects and reduce the required quantity of inputs, thereby lowering environmental contamination. For instance, nanoformulations of fertilizers ensure slow and sustained nutrient release, improving nutrient use efficiency and promoting healthier plant growth. Similarly, NPs based herbicide delivery enables precise weed control without harming the crop. Moreover, the unique physicochemical properties of NPs allow them to penetrate plant tissues efficiently, including through stomata or root absorption, making them highly effective carriers. This targeted approach also reduces the likelihood of resistance development in pests and pathogens. With continuous advancements, nanoparticles are being engineered to respond to specific biological signals, paving the way for smart delivery systems that release their cargo only under certain environmental or physiological conditions. As a result, nanotechnology holds immense potential to transform traditional farming into a more sustainable, efficient and responsive system, aligning agricultural practices with environmental stewardship and food security goals.

Priming seeds with NPs has been shown to enhance germination and growth, particularly in medicinal and fodder plants, indicating the possibility of higher agricultural productivity. As a conclusion it can be said that combining green synthesis with the remediation potential of NPs working with microorganisms presents viable ways to clear agricultural waste and contaminated soils, tackling environmental issues in farming. In summary, nanotechnology represents a transformative approach for agricultural sustainability, but realizing its full potential will require responsible innovation, robust regulation and coordinated efforts across scientific disciplines. Numerous studies have demonstrated that the application of NPs in agriculture can significantly enhance crop yield, thereby justifying their use. For instance, seed priming with ZnO NPs in wheat has been shown to improve yield by 20-30 % through enhanced germination and nutrient uptake. In rice, the application of nano-silica and nano-iron has led to yield increases of 15-25 % due to improved stress tolerance and photosynthetic efficiency. Similarly, maize treated with NPs based priming agents such as Ag or Si NPs exhibited a 15-20 % increase in grain yield compared to conventional methods. In tomato cultivation, foliar application of nanofertilizers has resulted in a 20-35 % increase in fruit yield along with improved quality. Even in medicinal plants like *Withania somnifera*, seed treatment with NPs enhanced biomass and secondary metabolite content by up to 30 %. These quantified improvements clearly highlight the effectiveness of nanotechnology in boosting crop productivity, supporting sustainable agriculture and addressing global food security challenges. Despite promising outcomes, inconsistent results across plant species and environments highlight the need for standardized formulations and rigorous safety assessments. Future research must prioritize interdisciplinary collaboration, integrating plant physiology, materials science and environmental toxicology to develop safe and scalable nanotechnological applications in agriculture.

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Authors' contributions

All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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