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REVIEW ARTICLE

Nanotechnology applications in seed germination: Evolutionary and systematic perspectives

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Abstract

Agriculture faces challenges from limited arable land, climate change and population growth, threatening food security and requiring advanced solutions. Nanotechnology, including quantum dots and metal oxide nanoparticles, has shown promise in enhancing seed germination, seedling vigor and crop productivity by modulating key physiological and biochemical processes, thus supporting sustainable food production under these constraints. The integration of nanotechnology into agriculture holds significant promise for enhancing seed germination, crop yield and sustainable food production. Amid challenges such as shrinking arable land, climate variability and growing population demands, nanomaterials-particularly quantum dots (QDs) and metal oxide nanoparticles-have emerged as potent agents in improving seed physiological and biochemical traits. This review comprehensively examines the influence of various nanoparticles (e.g. CuO, Fe_2O_3, TiO_2, nanosilica and CNTs) on germination parameters across diverse plant species, highlighting their potential to penetrate seed coats, enhance water and nutrient uptake and activate key enzymes such as catalase, amylase and dehydrogenase. Additionally, we address the dual role of QDs in promoting early growth stages while acknowledging possible phytotoxic effects at higher concentrations. The review further examines antioxidant responses and the regulation of secondary metabolites in plants and it also assesses the biosafety of nanomaterials using model soil organisms such as earthworms. The review also explores antioxidant and secondary metabolite responses and evaluates biosafety using model soil organisms like earthworms. Overall, the study underscores the need for plant systematics-informed research on nanoparticle- plant interactions to optimize their safe and targeted application in seed technology and sustainable agriculture.

Keywords: antioxidant activity; nanoparticles; plant systematics; quantum dots; seed germination; seed priming

Introduction

Sustainable agriculture is a primary goal for agricultural scientists, aiming to eradicate the hunger, poverty and malnutrition. The current global population is 7.7 billion is projected to be nearly 9.8 billion by 2050 (1, 2). Environmental challenges including climate variability, erratic monsoons and soil degradation directly threaten agricultural productivity and sustainability. Socio-economic pressures such as population growth, urbanization and increased food demand, along with biotic and abiotic stresses like pests, diseases, drought and salinity, further compromise crop yields, emphasizing the urgent need for innovative solutions like nanotechnology to ensure resilient food production systems. Various bio- and nano- enabled techniques and strategies have been proposed and practiced improving food production and protection in order to meet the growing global food demand by supplying quality and adequate food. The applications of nanotechnology in agriculture are multidimensional: it includes (a) synthesis of nano-fertilizers to improve plant growth and yield, (b) invention of new pesticides formulations for pest and disease management and (c) nanosensors for monitoring soil quality and plant health (3). The collective aim of all these approaches is to enhance production efficiency and sustainability with fewer inputs and less waste. Seeds are the first and foremost basic input in agriculture. Viable seeds ensure uniform crop establishment, disease resistance and sustainable yield. Seeds are treated before sowing to improve the germination process and percentage. Currently, a number of conventional techniques are available to improve seed germination include soaking seeds in water to soften the seed coat and accelerate water uptake, scarification which involves physically or chemically breaking the seed coat and stratification where seeds are exposed to cold or alternating temperatures to simulate natural seasonal changes. Other widely used approaches are priming seeds with water or solutions followed by drying, using plant hormones such as gibberellic acid to overcome dormancy and even specific treatments like hot water immersion for a short duration. Traditional soil planting, as well as innovative practices like paper towel germination, are also employed, with the chosen method often depending on the particular characteristics of the seed species and their natural dormancy mechanisms (4-30). In last few years, quantum scientists have reported to improvements in seed physiological parameters by treating them with metal oxide quantum dots (31-36).

Copper (Cu) is a redox-active metal that is fundamental for plants as well as all living organisms. Cu participates in numerous physiological processes since it can exist in different oxidation states *in vivo* (37). CuO NPs are one of the most widely used engineered metal oxide NPs with critical industrial applications such as superconducting materials, thermoelectric materials, detecting materials, glass and ceramics (38). Nano-CuO has positive effects on the physiological parameters of seed quality. In regard to this, lower concentrations of copper oxide QDs did not affect the germination rate, germination potential and germination index of *Brassica pekinensis* (39). Iron is a fundamental micronutrient for practically all living organisms because it plays a critical role in metabolic processes such as DNA synthesis, respiration and photosynthesis. Further, numerous metabolic pathways are initiated by iron and it is a prosthetic group constituent of numerous enzymes. Iron is involved in the synthesis of chlorophyll and it is essential for the maintenance of chloroplast structure and function (40). To address iron deficiencies and improve plant growth, several biological and nanotechnology-based approaches and strategies have been proposed and applied to enhance nutrient delivery and utilization (21).

Nanotechnology offers significant advantages over traditional methods in seed germination by enhancing precision, efficiency and multifunctionality. Nanoparticles, with their high surface area-to-volume ratio, facilitate better seed interaction and nutrient delivery at low concentrations, improve water uptake, enzyme activity and metabolic processes and enable controlled release of bioactive compounds through nano-priming. Additionally, nanomaterials such as metal oxides, carbon dots and quantum dots induce beneficial physiological and biochemical changes including improved antioxidant defense, stress tolerance and enzyme activation, making nanotechnology-based seed treatments more effective, resource-efficient and environmentally sustainable for boosting germination and early plant growth. Since QDs have ultra-low size and greater surface area compared with NPs, they are more likely to penetrate seeds, thereby favouring seed germination and seedling vigor. Consequently, QDs boost seed vigor, promote uniform germination and support robust early seedling establishment, all while requiring relatively low input, making them valuable for sustainable agriculture. The potential of QDs and metal oxide NPs, including Cu, iron, zinc, manganese and titanium, lies in their ability to improve seed physiological and biochemical traits, thereby enhancing germination and early plant growth.

Role of nanoparticle in seed germination

Nano-priming with metal oxide QDs, such as iron oxide QDs primed at 150 rpm with 400 ppm, enhances seed germination by facilitating their entry into seeds either through weakening the seed coat or penetrating natural cracks. This infiltration promotes faster water uptake, which rapidly activates metabolic pathways by increasing hydrolytic enzymes like α-amylase and dehydrogenase, converting stored biomolecules into active forms necessary for germination. It is evident that the impact of nano-priming with metal oxide QDs improves germination in agricultural crops. Iron oxide QDs primed at 150 rpm with 400 ppm for a stipulated period may favor seed entry through penetration of the seed coat via physical damage or infusion through available cracks and crevices (41). The infiltration of nanomaterials or QDs may cause damage to the seed coat, thus favoring the entry of water into the seed. Hydration of the seed instantaneously triggers upregulation of enzymes such as catalase, dehydrogenase, alpha amylase, lipase and peroxidase, which in turn enhance sugar utilization, favor the above said reactions and initiates the conversion of biomolecules from an inactive state to an active state, ultimately promoting seed germination (42, 43).

Seeds treated with low concentrations show no effect, whereas optimum concentrations (30-50 nm, 0-500 mg L^{-1}) of activated carbon-based TiO_2 have been reported to enhance the germination percentage, seedling growth and the seedling vigor index in *Solanum lycopersicum* (44). Nano-silica has been shown to enhance germination parameters such as germination percentage, germination index, vigor index, mean germination time and average shoot length of tomato but not fresh or dry weight. The best results were found to be reported at 5 g/L nano-silica powder with increase over untreated control seeds was 22 % (germination percentage), 47 % (germination index), 92 % (vigor index) and 55 % (average shoot length). Similarly, nano-silica improved seed germination in tomato and it has a positive effect in seed germination overall. Application of nanoscale TiO_2 at optimum concentration 10 mg L^{-1} was appreciable under water scarcity conditions. At optimal concentrations, plants exhibited improved morphological and physiological characteristics, which led to enhanced overall growth and performance (45). The increased growth rate during critical germination period could be due to generation of reactive oxygen species (ROS) such as superoxide and hydroxide anions by nano-TiO_2, which enhanced seed stress resistance and improved seed coat permeability, facilitating water and oxygen uptake for rapid germination (46).

The increased growth rate during the critical germination phase may result from ROS generated by nano-TiO_2, such as superoxide and hydroxyl radicals. These ROS serve as signalling molecules that enhance seed stress resistance and improve capsule permeability, facilitating better water and oxygen uptake essential for rapid germination. CNTs are able to cause physical aberration by penetrating seed coats, thereby facilitating immediate water and oxygen uptake, which favors an increased rate of seed germination (47, 48). Fe_2O_3NPs enhanced the seed germination and plant growth in *Solanum lycopersicum* (tomato) compared with controls (49). The highest percentage of seed germination was observed to be 93 % at 50 mg/L and 97 % at 200 mg/L. However, treatment at higher concentrations (400-800 mg/L) of NPs, resulted in a decline in seed germination and all other parameters, approaching the growth rate of the control. This indicates that Fe_2O_3NPs in the range of 50-200 mg/L could be used to improve seed germination parameters in agriculture.

At low concentrations, nanoparticles can promote seed germination by improving water absorption, nutrient supply and activating enzymes. However, at higher concentrations, they may become toxic by generating excessive ROS, causing oxidative damage, impairing cell membranes and disrupting seed coat integrity, which together delay germination and hinder seedling growth. The enhanced germination might be further related to the particle's nanoscale size, which allows them to easily penetrate the seed coat, facilitating better absorption and usage by seeds (Fig. 1).

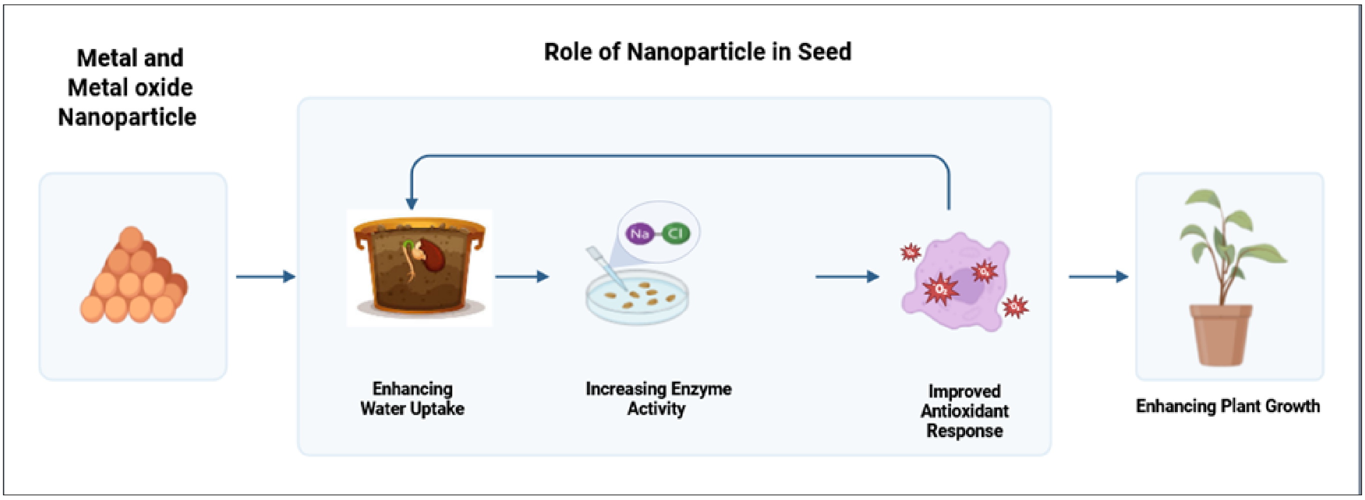

Fig. 1. Role of nanoparticle in enhancing the seed germination.

During germination, QDs may regulate redox processes by producing superoxide radicals that act as signalling molecules to boost antioxidant defenses. This controlled ROS signalling helps maintain redox balance and supports germination, but excessive ROS levels can lead to oxidative stress and cellular damage. As the soaking time increased, CuO QDs at higher concentrations greater than 300 ppm in black gram reduced the seed germination (50). QDs generally enhance or reduce seed germination, root and shoot growth, biomass production and physiological and biochemical activities. QDs priming or coating effect on seed germination are influenced not only by their size, composition and surface area but also by their coating properties, which affect their stability, absorption and translocation in germinating seeds (51). However, seed germination and root elongation studies have demonstrated the phytotoxicity of NPs, which increases with higher percentages of NPs and QDs (43, 52, 53).

Effect of nanoparticle in enzymatic activity

Free radical quenching is a natural phenomenon that occurs in all living organisms, including plants under oxidative stress. It has been reported that QD and NPs treatments increase the level of enzyme activity within the seed (54). Catalase (CAT) plays a critical role in decomposing H_2O_2 produced during photorespiration in peroxisomes, as well as H_2O_2 produced during β-oxidation of fatty acids in glyoxysomes, without energy expenditure. CAT expression is upregulated during the formation of higher concentrations of H_2O_2 as an adaptive reaction to counteract the damage induced by H_2O_2 generated during cell metabolism.

Treated seed exhibited an increase in α-amylase activity 23.8 % over the control (50). Treated seeds showed an enhancement of dehydrogenase activity by 16.2 % as compared to the control (50, 55). The highest CAT activity was recorded in treated seeds compared to the control. The highest increase in α-amylase activity indicates that seed treatment mainly stimulated starch breakdown, providing essential energy for germination. This enzyme activity supports carbohydrate mobilization, which is critical for seedling growth and development (56) (Table 1).

The highest increase in α-amylase activity indicates that seed treatment mainly stimulated starch breakdown, providing essential energy for germination. This enzyme's enhanced activity supports carbohydrate mobilization, which is critical for seedling growth and development. NPs or QDs treatment of seeds causes physical damage to the seed coat, resulting in increased water influx into the seeds and triggering ROS-generating and starch-degrading enzyme activity, which accelerates seed germination (43, 57). The main defense mechanism is the activation of secondary metabolism and the synthesis of phenolic compounds. Phenolic molecules are significant in the detoxification of ROS and their concentrations usually oscillate (58, 59). Increases in antioxidant activity in seeds exposed to QDs are mostly due to an increase in phenolic compounds, which are effective scavengers of ROS and can also inhibit free radical-producing enzymes. In *Brassica juncea* seed priming with gold nanoparticles at a concentration of 100 ppm enhanced antioxidant enzyme activity, which protected the seeds from ROS by detoxifying H_2O_2 (56). ZnO NPs at a concentration of 500 ppm has promoted catalase and peroxidase activity in cluster beans (60).

Table 1. Influence of nanoparticle in seed germination

Nanoparticle	Plant species	Effect on germination/enzyme activity	Optimum concentration	Reference
Copper oxide NPs	*Brassica pekinensis*	They can cause toxic effects by disrupting metal uptake and interfering with normal metabolic functions. Excessive accumulation may also amplify stress responses in the plant, leading to inhibited growth.	< 300 ppm	(39)
Iron oxide NPs	*Solanum lycopersicum*	Enhances the seedling parameters (seed germination, seedling vigor, chlorophyll, protein and sugar contents as well as on the activities of lipid peroxidation and antioxidant enzyme).	50-200 mg/L	(44)
Titanium dioxide NPs	Tomato	Enhances the growth under water stress.	-	(45)
Carbon nanotubes (CNTs)	*Brassica juncea*	Increase water uptake and helps in seed germination.	-	(48)
Gold NPs (AuNPs)	*Brassica juncea*	Enhance the physiological and biological activity.	100 ppm	(56)
Zinc oxide (ZnO) NPs	*Cyamopsis tetragonoloba*	Enhancing the biological activity (Chlorophyll content, total soluble leaf protein, rhizospheric microbial population, acid phosphatase, alkaline phosphatase and phytase).	500 ppm	(60)
Nanoparticles (Fe/Cu)	*Vigna mungo* (Blackgram)	Up to >300 ppm positive effect in seed germination.	≤ 300 ppm	(50)

Certain NPs have been reported to enhance seed germination, yet their influence on biomass accumulation remains inconsistent, reflecting gaps in the mechanistic understanding of stage-specific effects. The stimulation of germination is generally linked to improved water absorption, greater membrane permeability and the production of low concentrations of ROS, which serve as signals to activate reserve-utilizing enzymes such as amylases and proteases. These processes accelerate the breakdown and use of stored reserves, leading to faster and more uniform germination. In contrast, the same nanoparticles may fail to support later biomass production due to factors such as nutrient imbalances, impairment of photosynthetic function, or an excessive ROS shift from signaling activity to oxidative stress, thereby hindering root and shoot development. Additionally, the accelerated consumption of reserves during germination can deplete resources needed for sustained vegetative growth. Such inconsistencies underscore the importance of mechanistic studies that connect nanoparticle-seed interactions across developmental stages, rather than focusing narrowly on germination responses.

Biosafety studies of nanoparticle using earthworm

Earthworms are ubiquitous in almost all kinds of soil and may represent 60 %-80 % of the total soil biomass. A large amount of research on the potential applications of nanotechnology has been reported in recent years. Relatively modest studies have been done to assess the potential risks of NPs (61). Earthworms (*Esenia andrei*) exposed to the highest concentration tested (1000 mg kg^{-1}) showed no significant effect on their reproductive function (61). C-nZVI at a concentration of 3 g kg^{-1} soil showed no effect on the survival of *E. fetida* in the soil. However, varying effects such as concentration-dependent increase in tissue iron concentration, lipid peroxidation and damage to DNA molecules by C-nZVI were observed (62). Short-term experiments frequently show positive outcomes for germination or stress resistance, they seldom examine nanomaterial persistence in soils, bioaccumulation through trophic levels or long-term impacts on microbial ecosystems. Furthermore, most research neglects gradual, non-fatal consequences-including modifications to gene regulation, disruptions of plant-microorganism relationships, or persistent oxidative damage-that may not immediately affect growth but could undermine plant vitality, soil health or ecological balance in the long term. The biosafety of QDs was tested with earthworms using the soil-less filter paper method and the results revealed no significant mortality of earthworms at lower concentrations of QDs (1000 ppm), implying that the quantum dots were safe to handle and use (41).

Conclusion

Nanotechnology, particularly the use of QDs and metal oxide NPs, has shown great potential in enhancing seed germination and early plant growth, contributing to sustainable agriculture. These particles improve physiological and biochemical seed traits by enhancing water uptake, enzyme activity and antioxidant responses. Studies reveal that optimal concentrations of QDs promote higher germination percentages, seedling vigor and stress resistance across various plant species. Their small size allows them to penetrate seed coats easily, triggering metabolic activation and faster germination. However, higher concentrations can lead to phytotoxicity, indicating the importance of dose optimization. Biochemical analyses show increased activities of catalase, amylase and dehydrogenase in treated seeds, supporting their improved performance. Earthworm-based biosafety studies suggest minimal ecological risk at lower concentrations of QDs. Despite the promise, careful evaluation is essential to prevent adverse effects on plants and the environment. Future research should focus on crop-specific responses, safe dosage ranges and long-term impacts. Overall, nanoparticle-based seed treatments offer a novel, efficient approach for enhancing agricultural productivity.

Authors' contributions

JP and JSSD contributed to the conception of the review, performed information retrieval and analysis. DJ, HS and JM guided the manuscript writing and JP wrote the manuscript, created the tables and figures. PM and KP provided financial support. All authors contributed to manuscript and have read and approved the submitted version. 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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