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REVIEW ARTICLE

Integrating nanotechnology into seed production and management for future ready agriculture

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Abstract

Food and agriculture are directly related to human life. Traditional farming methods restrict the utilization of available farmlands up to their potential. Nanotechnology has emerged as one of the most promising solutions for overcoming the shortcomings of traditional agricultural practices. At every stage of agriculture (starting from seed germination until the resultant seed quality), nanotechnology promises to improve crop productivity and quality. The application of nanoparticles with unique physicochemical and biological properties in agriculture to improve seed germination is the initial step in increasing crop yield. Recently, nanotechnology has been recognized as a promising and emerging approach for enhancing crop productivity through seed treatment for improved germination and seedling vigour, foliar application for improved nutrient uptake by plants and nanofertilizers for balanced crop nutrition with reduced chemical inputs and environmental impacts. Additionally, nanoherbicides and nanoinsecticides facilitates targeted and efficient pest and weed control that reduces chemical residues in the ecosystem and improves crop health. Further, applying various nanosensors in the early detection of plant diseases and nutrient deficiencies helps in timely intervention for improved crop management practices. Thus, the aim of this review article is to provide a comprehensive overview of the role of nanotechnology in seed quality enhancement of different crops, highlighting its potential to address the food security issues in an eco-friendly and sustainable manner.

Keywords: nanoparticles; seed enhancement; seed germination; stress management

Introduction

Food security is a major concern nowadays. Eliminating the “hidden hunger” has become the primary objective in modern agriculture. Because of the growing population, climate change, environmental pollution and other factors, the need for basic resources also increases, limiting essential needs such as food, water and energy (1). According to FAO, the population is expected to reach around 10 billion by 2050 (2). Considering this situation, adopting a more precise farming system to improve crop productivity becomes necessary. Agriculture is driven by a combination of inputs such as seeds, fertilizers, machinery and crop protection chemicals, but among these inputs, seeds serve as a basic and prime input. There is a proverb that says “you reap what you sow”, which denotes that if good quality seeds are sown, it will result in a bountiful harvest of good quality seeds. This highlights the direct impact of seed quality on yield. To enhance the quality of seeds, methods such as seed priming, coating and pelleting have been applied with the incorporation of various growth regulators, endophytes, biocontrol agents, nanoparticles, etc., and the extensive use of these resources during the Green Revolution has led to an imbalance in the ecosystem (3).

In conventional farming, fertilizers, pesticides and other agricultural inputs, which were applied in large quantities, often result in nutrient runoff and eutrophication, as excess nutrients leach into the soil and water systems and non-specific materials may harm beneficial organisms such as birds, insects and microbes. They also lack the ability to target specific issues at the cellular or molecular level because the nutrients or chemicals may not be fully absorbed by the targeted organisms, resulting in the overuse of resources, more production costs and long-term environmental degradation and causing potential threats to agricultural sustainability (4). To restore the ecosystem, the technologies that address these problems with limited resources are the need of the hour.

One such approach is the intervention of nanotechnology in agriculture. Nanotechnology revolves around nanomaterials that have a size ranging from 1 - 100 nm but with more benefits. Nanoparticles exhibit remarkable physical and chemical properties, mainly higher surface area to volume ratio, enhanced functionality, surface bioactivity and biocompatibility, which distinguish them from their bulk counterparts. Nanomaterials can be classified based on different criteria, *viz.,* size, origin (natural or engineered), shape (spheres, tubes, rods, dots, cones or fibres), form (amorphous or crystalline), metallic (Au, Ag), non-metallic (carbon) or semiconductor (Cd, Se). Apart from this, it includes a significant classification based on the dimensions of the materials, i.e., zero-dimensional (0-D), e.g., nanomaterials and nanoparticles; one-dimensional (1-D), e.g., nanotubes, nanorods and nanowires; two-dimensional (2-D), e.g., nanofilms, nanolayers and nanocoatings and three-dimensional (3-D), e.g., dispersions of nanoparticles, bundles of nanowires and nanotubes and multi nanolayers (5). These nanomaterials are pretty different from bulk materials due to their nanoscale dimensions and also possess excellent optical (more fluorescence and plasmonic effects due to quantum confinement), electronic (possess electrical conductivity) and physiochemical properties (enhanced reactivity and interaction with other materials due to high surface area to volume ratio) (6).

The benefits of nanotechnology include the targeted delivery of nutrients, pesticides, or other inputs directly to plant cells or targeted pests, which minimizes resource over-exploitation and environmental impacts. Nanoparticles have higher efficiency and effectiveness and lower application rates compared to bulk materials because of their higher surface area to volume ratio and smaller size (7). Many nanotechnological inventions have already started to revolutionize agriculture and some of the technologies that hold hands with seed science and technology are discussed in the following sections. Examples of such technologies include nanofertilizers, nanopesticides, nanoencapsulation, seed coating with nanohydrogels, nanobiostimulants, etc. and all these technologies are most commonly adapted for improving the quality of seeds both directly and indirectly (8). In addition, nanoparticles can also be used in the genome editing of plant genes and as a carrier material to deliver specific genes, potentially enabling the development of crops with desired traits (9). Nanotechnology offers a wealth of potential applications in seed science, holding the key for improved seed quality, enhanced crop yields and more sustainable agricultural practices (10).

This comprehensive review explores recent advancements in nanotechnology for seed quality enhancement, summarizing key findings, synthesis methods and future prospects for sustainable agricultural practices.

Synthesis of nanomaterials

Nanomaterials or nanoparticles can be synthesized using top-down and bottom-up approaches. The top-down approach starts large and breaks down, while the bottom-up approach starts small and builds up. In the top-down approach, techniques such as etching and ball milling progressively reduce the material dimensions, yielding isolated nanoparticles. In contrast, the bottom-up approach involves the aggregation of atoms and results in the formation of nanoparticles (11). Both approaches have their advantages and disadvantages, which are presented in Table 1.

Based on the nature of the energy source, the chemical reactions involved and the other two follow a bottom-up approach for the nanomaterial synthesis. The origin of the raw materials and the methods of nanomaterial synthesis can be classified as physical, chemical and biological. Among the 3 methods, the physical method involves a top-down approach and the other two follow a bottom-up approach for the nanomaterial synthesis.

Synthesis by physical approaches

Physicals method leverage various forms of physical energy to synthesize nanoparticles, which typically involves (i) Mechanical energy, which serve as the principle force in instruments such as ball milling and sonication to break down more extensive materials into nanosized particles; (ii) High-energy radiation, which is employed in methods such as laser ablation and gamma irradiation to induce ablation or fragmentation of bulk materials; (iii) Thermal energy, which is adopted in thermal decomposition and evaporation-condensation methods that employ heat to melt or vaporize materials, followed by recondensation into nanoparticles under controlled conditions and (iv) Electrical energy which is used in electrospraying and electrochemical methods to create charged droplets or induce reactions at electrodes, ultimately leading to nanoparticle formation. By manipulating these physical forces, we can control the size, shape and surface properties of synthesized nanoparticles (12).

Synthesis by chemical approaches

The chemical synthesis process mainly involves the reduction and decomposition of the precursors. Nanocrystals formation is primarily influenced by important processes namely nucleation and growth of the nanocrystals, both of which occur during the precipitation reaction. Chemical methods

Table 1. Advantages and disadvantages of top-down and bottom-up approaches

Approaches	Advantages	Disadvantages
Top-down	•Bulk production of nanomaterials is possible •Particles can be synthesized in small span of time •Free of solvent contamination •Size of the particles can be fine tuned by adjusting the energy force	•Particles obtained are non homogeneous and have an imperfection in surface structure •Involves high machine costs •Cross contamination and production of abundant waste materials
Bottom-up	•Homogeneous particles can be synthesized •High purity •Less production cost •Particle size can be adjusted by altering the reaction environment	•Bulk production of nanomaterials is not possible •Synthesis process takes more time

possess great advantages, such as simple equipment, uniform shapes and sizes of resultant nanoparticles and the synthesis of large quantities of particles at low cost in a short time. Chemical methods also pose a significant threat to both the environment and human health (13).

The major drawbacks of physical and chemical methods of synthesis include the use of expensive equipment, hazardous chemicals, no standard protocol and skilled personnel and not well-developed laboratories. Therefore, at present, biological synthesis has attracted more attention among researchers seeking to develop eco-friendly, non-toxic and safer nanoparticles (14).

Synthesis by biological approaches

This approach was mainly based on using plants, biomass waste, bacteria, fungi and viruses for nanoparticle synthesis. To date, numerous metal and metal oxide-based nanomaterials have been synthesized using biological methods (15). Some of the examples include silver (Ag), gold (Au), selenium (Se), tellurium (Te), palladium (Pd), silica (SiO_2) and copper (Cu). In the green synthesis process, plant extracts serve as both reducing and stabilizing agents, negating the need for chemical agents to stabilize the synthesis. In addition, the presence of hydroxyl, carboxyl groups and primary and secondary metabolites in the plant also helps to facilitate the synthesis process (16). Additionally, various microbes such as *Bacillus subtilis*, *Lactobacillus* sp., *Verticillium* sp., *Trichoderma viride* and *Fusarium oxysporum* are also involved in the synthesis of gold, cadmium and silver nanoparticles (17, 18). In addition to its numerous benefits, it also possesses certain drawbacks, such as limited nanoparticle production, microbial culture, biomass harvesting, purification procedures and increased time consumption. Hence, the choice of synthesis procedure should be mainly based on the type of nanoparticles to be synthesized and their final application. There are different methods in each category for producing nanoparticles and they are listed below in Table 2.

After the synthesis of materials from the precursor, it is important to perform characterization. Advanced nanoscale techniques such as UV - visible Spectroscopy (UV - Vis), X-ray Diffraction (XRD), Fourier-Transform Infrared (FTIR) Spectroscopy, High Resolution Transmission Electron Microscope (HRTEM), Brunauer-Emmett-Teller (BET), Zeta Potential, Raman Spectroscopy, Atomic Force Microscopy (AFM) and Energy-Dispersive X-ray Analysis (EDAX), capable of measuring or imaging materials at the nanometer scale (up to 1 nm) can be utilised for the confirmation of optical and physiochemical properties of synthesized nanomaterials (19).

Recent advances in seed production and management

Soil health management

Soil health refers to the capacity of soil to function as a vital component of the ecosystem, thereby contributing to biological productivity, maintaining air and water quality and supporting plant, animal and human health. Soil's physical, chemical and biological characteristics directly influence the quality and quantity of seeds produced by providing optimal conditions for seed germination, crop growth and development (20).

Soil is the primary source of both macronutrients and micronutrients essential for plant growth. The availability of these mineral nutrients is influenced by various soil characteristics such as pH, soil texture and organic matter content and environmental factors like temperature and moisture levels. Macronutrients, mainly nitrogen (N), phosphorus (P) and potassium (K), as well as micronutrients such as zinc (Zn), copper (Cu) and manganese (Mn), undergo various transformations namely precipitation, immobilization, adsorption, leaching, volatilization, etc., making them unavailable to plants. This results in low quality and low vigour seeds, poor and delayed crop growth and maturity, increased susceptibility to pest and disease attacks and a need for additional nutritional supplements (21). Due to the increasing population and the intensification of agriculture through modern technology, the soil's capacity to sustain its functions has been compromised, leading to long-term productivity loss, more soil residues and chemical toxicity and reduced soil organic matter and beneficial organism activities (22). It is, therefore, important to develop innovative strategies that can overcome these deficiencies with limited resources.

One potential solution is the application of nanotechnology, which can address these challenges. Nanoparticles possess a greater surface area and sorption capacity, which enables them to exert biological effects and enhance the efficiency of macro and micronutrient use through controlled release, thereby reducing fertilizer waste

Table 2. Different methods used for the synthesis of nanoparticles

Physical methods	Chemical methods	Biological methods
•Laser ablation •Electro spraying •Inert gas condensation •Physical vapour deposition •Laser pyrolysis •Flash spray pyrolysis •Molecular beam epitaxy •High energy ball milling •Melt mixing	•Chemical vapour deposition •Co-precipitation •Sol-gel •Polyol •Microemulsion •Microwave assisted synthesis •Photoreduction using gamma rays •Ultrasonic waves •Liquid plasma •Spray drying •Solvothermal synthesis •Electrospinning	•Using plant parts and plant extracts •Using biomass waste •Microbial synthesis

caused by leaching, degradation and volatilization (23). Nanofertilizers characterized by their small particle size, provide a solution by enhancing plant nutrient uptake efficiency and reducing nutrient runoff (24). The use of Cu as a nanofertilizer positively impacted the growth and development of the cowpea cultivar in terms of its morphological attributes. Additionally, it enhanced plant chlorophyll content and antioxidant activity through its involvement in various physiological processes, such as respiration, photosynthesis, oxidative stress protection, carbon and nitrogen metabolism and electron transport in the photosynthetic and respiratory chains (25). The use of controlled-release urea (CRU) as a nanofertilizer resulted in improved plant growth, yield and fruit quality in tomato plants, possibly due to the ability of the encapsulated nano-urea to conserve and provide nitrogen throughout the crop growing season (26). As a foliar spray, nano-urea (2 %) improved the plant growth and yield of bhendi, which might be attributed to its enhanced ability to transport and deliver nutrients more efficiently through plasmodesmata (27).

Molybdenum disulfide nanoparticles increased soybean biological nitrogen fixation and grain yield, protected nodules against reactive oxygen species (ROS) damage, delayed nodule ageing and enhanced tolerance to abiotic stress (28). ZnO nanoparticles at 0.5 % exhibited the maximum efficacy in nutrient release (N and Zn), grain yield, root biomass and biological yield (29). Fe_2O_3 nanoparticles were observed to decrease CO_2 emissions by up to 30 %, suggesting reduced decomposition of soil organic matter (SOM) by applying nano materials to the soil. These nanoparticles can store organic carbon in soil, potentially contributing to carbon-nitrogen metabolism and lowering global warming (30).

The application of nanochitosan and bioinoculants, improved soil physicochemical properties by increasing total bacterial count, as well as the phosphate and potassium solubilizing microorganisms. Additionally, it enhanced soil enzyme activities, namely dehydrogenase, fluorescein diacetate and alkaline phosphatase, compared to untreated plants in the maize rhizosphere region. Metagenomic analysis also confirmed that nanochitosan stimulated the plant growth-promoting bacteria, contributed to nutrient assimilation and various growth-promoting activities (31).

Seed quality enhancement

In commercial agriculture, the successful establishment of stands and the productivity of crop plants largely depend on rapid and uniform seed germination and initial seedling emergence. Various seed invigoration techniques namely seed priming, seed coating, seed pelleting and designer seed technology are employed to enhance germination and seedling vigour and prolong storage life (3).

Nanotechnology is an emerging field in seed science, where some metal-based nanoparticles (e.g., Ag, Cu, Fe, TiO_2, Zn and ZnO) and carbon-based nanoparticles (e.g., carbon nanotubes) are used as seed pretreatment agents to improve seed quality by altering the morphological, physiological and molecular attributes associated with seeds (32). Silicon nanoparticles, which are hydrophilic, decrease the mean germination time and enhance seed germination and seedling vigour in tomato plants. Additionally, they improved bacterial colonization (*Bacillus* sp.) around the seeds and reduced the hairy structure on the seed surface (33). Priming of finger millet seeds with ZnO nanoparticles at concentrations of 100 and 500 ppm led to a significant increase in germination rate, seedling vigour and various growth parameters namely, seedling length, fresh and dry weight of the seedlings, as well as the root-shoot ratio of the seedlings due to the upregulation of GA_3 and the down regulation of ABA (34). The priming of wheat seeds with iron oxide nanoparticles at relatively high concentrations (200 and 500 mg/L) enhanced plant growth, photosynthesis and respiration and increased the content of photosynthetic pigments. Additionally, these nanoparticles led to increased stress tolerance due to increased ascorbate peroxidase and reduced malondialdehyde (MDA) content in roots and leaves (35). Likewise, in watermelon seeds, priming with turmeric oil nano emulsions (TNE) and silver nanoparticles led to improved seed germination, growth and yield, while maintaining fruit quality. Moreover, the treated seeds exhibited a reduced mean germination time and sucrose content, which was attributed to the conversion of disaccharides (such as sucrose) into monosaccharides (such as glucose and fructose), which serve as a fuel for the seedlings (36). The different effects of nanoparticles on seed quality enhancement in different crops are presented in Table 3.

Biotic stress management

The stress caused by any living organism that affects plants normal growth and development is called biotic stress. This may be caused by various organisms such as fungi, bacteria, viruses, nematodes, insects and animals. The effects of biotic stress can be categorized as direct or indirect effects. The direct effects include physical damage that affects photosynthesis, nutrient uptake, water transport, respiration, hormone signalling, plant growth, yield and quality of economic produce. Some of the important crops in which the occurrence of biotic stress causes complete loss of yield are rice (*Magnaporthe oryzae*), maize (*Spodoptera frugiperda*), cotton (*Helicoverpa armigera*), sugarcane (*Colletotrichum falcatum*), brinjal (*Leucinodes orbonalis*), tomato (Tomato leaf curl virus), okra (Yellow vein mosaic virus) and cucumber (Cucumber mosaic virus). On the other hand, it indirectly increases the susceptibility of plants to other stresses such as drought, temperature and salinity (50). To overcome these stress effects, plants have their own defense mechanisms, such as physical barriers, chemical defences, hypersensitive reactions and various signalling pathways that trigger defensive responses (51). Nanotechnology offers a promising new approach for managing biotic stress in plants. Nano-phytopathology is an emerging field that applies the principles of nanotechnology to the study and control plant diseases (52). Various forms of nano based approaches *viz.,* nanopesticides made of silver, copper, zinc oxide; nano delivery systems for the targeted delivery of biocontrol agents or beneficial microbes; nanoparticles to stimulate plant growth and defense mechanisms that trigger stress signalling pathways and nanosensors for the early detection and diagnosis of specific pathogens or pests at an early stage of infection have been developed (53–55).

Table 3. Applications of different nanoparticles for enhancing seed quality in different crops

S. No	Nano particle	Crop	Method of application and concentration	Effects	Reference
1.	Zinc oxide	Bitter gourd	Seed priming at 100 ppm	Improved germination and crop quality	(37)
2.	GA_3 infused nano formulation	Groundnut	Seed coating at 15 mL / kg	Reduced mean germination time and improved seed quality	(38)
3.	Iron	Lucerne	Seed priming and foliar spray at 10 ppm	Improved plant growth and nitrogen fixation capability	(39)
4.	Calcium oxide	Mung Bean	Seed treatment at 20 ppm	Improved physiological and biochemical attributes of seed	(40)
5.	Zinc oxide	Mustard	Seed treatment at 10 ppm	Improved germination and seedling length	(41)
6.	Calcium oxide	Tomato	Seed treatment at 20 ppm	Improved seedling length and dry weight of seedlings	(42)
7.	Calcium oxide	Bengal gram	Seed treatment at 150 ppm	Improved germination and biochemical attributes	(43)
8.	Zinc oxide	Paddy	Seed priming at 10 ppm	Improved germination and seedling length	(44)
9.	Peanut shell derived carbon dots	Blackgram	Seed priming at 200 ppm and foliar spray at 50 ppm	Improved physiological, photosynthetic and yield attributes	(45)
10.	Plastic derived carbon dots	Pea	Seed priming at 2 ppm	Improved germination, seedling length, seed coat rupture and chlorophyll content	(46)
11.	Selenium	Maize	Seed priming at 10 ppm	Improved germination, seedling vigour and total antioxidant capacity	(47)
12.	Strontium hexaferrite	Pulses	Seed priming at 30 ppm	Improved seed germination and vigour	(48)
13.	ZnO-CuO hybrid nanoparticles	Maize	Seed treatment at 125 ppm	Improved germination, shoot and root ratio	(49)

Plants can benefit from nanoparticles in 2 ways: (i) they can act directly as a protective barrier against threats and (ii) they can serve as efficient carriers for delivering targeted pesticides (56). The use of encapsulated pesticides represents a significant advancement over traditional formulations. Various inorganic nanoparticles such as ZnO, Cu, SiO_2, TiO_2, CaO, MgO, MnO and Ag effectively control microbes in plants (57). Additionally, nanopesticides have a broad-spectrum insecticidal activity against field and stored grain pests (58). Moreover, combining chitosan alginate with paraquat in a nano formulation reduces the toxicity of the herbicide. At the same time, copper nanoparticles have been shown to be effective against diverse plant pathogens such as bacteria, yeasts and fungi. It was also confirmed that sucking or chewing insects can be controlled with SiO_2 nano formulations that can improve the penetration of insecticides into plant tissues and access cell sap (59). Some microbes, such as *Ralstonia solanacearum*, *Fusarium oxysporum*, *Verticillium dahliae*, *Fusarium solani*, *Monilinia fructicola*, *Colletotrichum gloeosporioides*, *Botrytis cinerea* and *Alternaria alternata,* which are considered the prime causes of soil-borne diseases, were controlled when metallic oxide NPs were used as treatments (60). The protective role of silver nanoparticles was confirmed by their antifungal activity against *Candida albicans*, which is resistant to fluconazole (61). The antifungal activity of various nanoparticles has also been reported by various authors, including silver nanoparticles for controlling *Stromatinia cepivora*, graphene oxide for *Fusarium graminearum* and *Sclerotinia sclerotiorum*, titanium for the management of *Alternaria alternata* and selenium for *Aspergillus niger* and *Aspergillus fumigatus* (62–65). In tomato, when chitosan-based nanocarriers were impregnated along with biocontrol agents, they efficiently managed Fusarium wilt disease (66). Nano-based biosensors were found to be more helpful in the early and rapid detection of plant diseases and disease management (67). This phenomenon was experimentally validated using a nano biosensor combined with gold nanoparticles to detect the potato late blight fungus and the citrus greening bacterium (68, 69). The effects of the nanoparticles on the induction of stress tolerance against different pests and diseases are presented in Table 4.

Abiotic stress management

Abiotic stress refers to the negative impact of non-living environmental factors such as extreme weather and soil conditions on living organisms, specifically affecting their growth, development and survival. The impact of abiotic stress on seed quality can be complex and can vary depending on the plant species, developmental stage of the seed and type and severity of the stress (81). Some plants have developed mechanisms to tolerate or resist abiotic stress, but in most cases, these mechanisms must be managed through various external agricultural practices. Understanding the specific impacts of different types of stress on different crops is crucial for developing strategies to mitigate their effects and ensure food security (82).

One such mitigation strategy includes the incorporation of nanotechnology. Various nanoparticles and nanomaterials have gained importance in enhancing plant resilience against abiotic stress. The size of these nanoparticles ranges from 1 to 100 nm and possess diverse physiochemical properties and a large surface area (83). Because of these advantages, plants are subjected to seed treatments, foliar sprays, soil application and hydroponic treatment with these nanoparticles. Applying TiO_2 nanoparticles enhanced the photosynthetic and enzyme activities of the plants. Above all, the key mechanism that governs the impact of titanium dioxide nanoparticles on plants is their interaction with chloroplasts, which are the site of ROS signalling, affecting reactive oxygen species (ROS) levels and influencing nitrogen metabolism under UV light. It can convert nitrogen to nitrate, which boosts nitrate reductase activity, which is important for nitrogen assimilation (84).

Table 4. Applications of different nanoparticles for biotic stress tolerance

S. No.	Nano particle	Crop	Method of application and concentration	Effect	Reference
1.	Silver and Copper	Chilli	Seed priming at 100 ppm	Resistant against *Scirtothrips dorsalis*	(70)
2.	Silicon, Copper and Iron	Lettuce	Seed treatment at 200 ppm	Resistant against root rot	(71)
3.	Selenium dioxide	Wheat	Foliar spray at 100 ppm	Antifungal activity against *Ustilago tritici*	(72)
4.	Chloroacetamide-loaded alginate-based nanogel	Tobacco	Foliar spray	Tobacco mosaic virus resistance	(73)
5.	Silicon	Brinjal	Seed treatment at 100 ppm	Resistant against *Meloidogyne incognita*	(74)
6.	Zinc oxide	Castor	Foliar spray	Resistant against *Spodoptera litera*	(75)
7.	Copper	Wheat	Seed treatment	Resistant against *Trifolium castoreum*	(76)
8.	Sulfur	Mango	Foliar spray at 100 ppm	Resistance against powdery mildew	(77)
9.	Zinc oxide	Wheat	Foliar spray at 50 ppm	Resistance against *Bipolaris sorokiniana*	(78)
10.	Cerium oxide	Alfalfa	Foliar spray at 100 ppm	Resistance against alfalfa mosaic virus	(79)
11.	Silver	Jute	Foliar spray at 100 ppm	Protection against *Spilosoma obliqua*	(80)

The incorporation of nanomaterials can alleviate salinity, UV- radiation, drought and extreme temperature in various crops (85–88). Nanomaterials have been shown to modulate plant responses by influencing various aspects of plant development such as seed germination, plant growth and stress tolerance. Additionally, they can manipulate the endogenous levels of a wide range of phytohormones, including auxin, cytokinin, gibberellin, ethylene, salicylic acid, jasmonic acid, nitric oxide and melatonin, thereby affecting plant signalling pathways and physiological processes (89).

In addition, researchers have developed "smart" delivery systems by encapsulating plant growth hormones within the nanoparticles. These nano-formulations will provide optimal properties for gradual release inside plant cells, potentially improving their effectiveness compared to conventional methods (90). By influencing specific genes linked to stress responses, nanoparticles enable plants to handle harsh environments. This includes stimulating the production of anti-stress molecules, enhancing antioxidant enzyme activity and even optimizing photosynthesis (91). Silver nanoparticles pose a triple threat against abiotic stress in crops. Nanoparticles can reduce nutrient deficiencies, enhance the activity of beneficial enzymes and promote the attachment of plant growth-promoting bacteria to plant roots (92). Another study suggested that adapting Cu nanoparticles increased photosynthetic activity, plant antioxidant mechanisms, plant growth and biomass production without any toxic effects (93). Specifically, iron-based nanoparticles (e.g., Fe_3O_4 nanoparticles) showed greater potential for helping plants cope with drought stress. These nanoparticles act as a protective shield for the iron within them, making them safe for plants because of their unique properties, such as light absorption, catalytic effects and resistance to breakdown. Studies have shown that lower doses of these nanoparticles can enhance plant growth, antioxidant systems and photosynthesis and ultimately increase nutrient uptake in *Brassica napus* and rice compared to those in untreated plants under drought conditions (94, 95). The mechanism of the nanoparticles and their effects under different stress conditions are depicted below (Fig. 1 and Table 5).

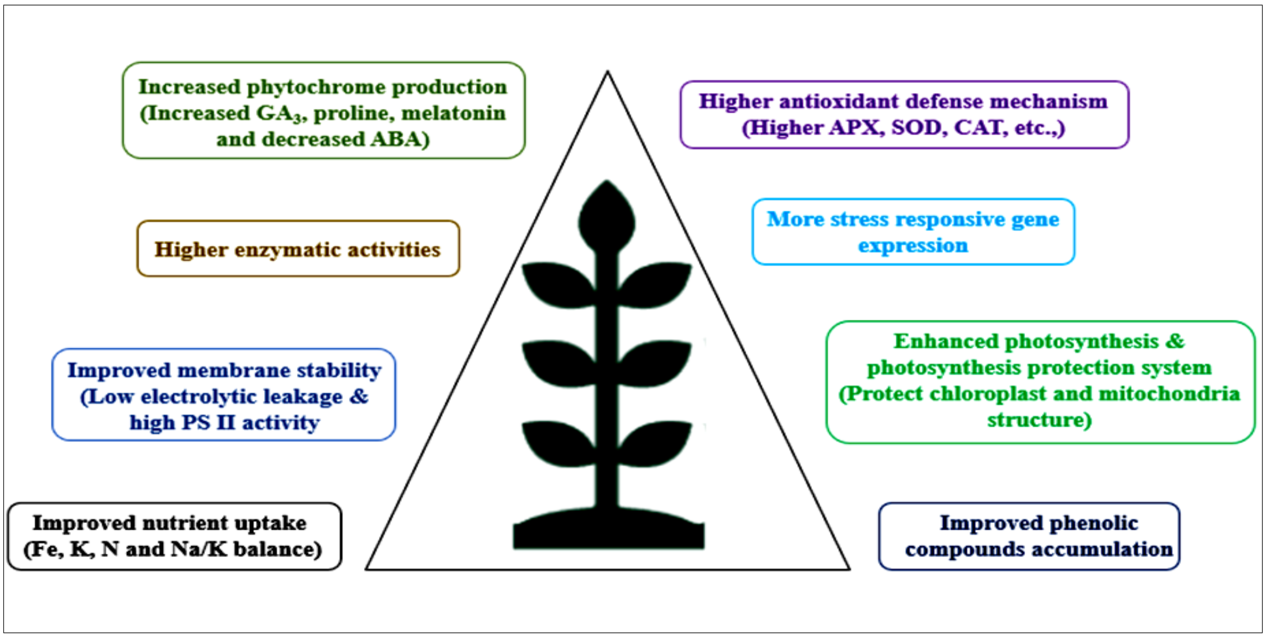

Fig. 1. Physiological mechanism of nanoparticle-induced stress tolerance in plants.

Table 5. Applications of different nanoparticles for abiotic stress tolerance

S. No	Nano particle	Crop	Concentration and method of application	Effect	Reference
1.	Silicon dioxide	Rapeseed	Foliar spray at 100 µM	Resistance against heavy metal stress	(96)
2.	Titanium dioxide	Safflower	Seed priming	Induced heat and salt tolerance	(97)
3.	Vanadium and Selenium	Paddy	Foliar Spray	Boosted plant height and resistant against heavy metal	(98)
4.	Silicon	Coriander	Foliar spray	Improved plant growth and yield under drought stress	(99)
5.	Silicon and Selenium	Paddy	Seed priming	Resistance against salt stress	(100)
6.	Titanium dioxide	Maize	Foliar Spray at 250 ppm	Resistance against heavy metal	(101)
7.	Silver	Pearl millet	Seed priming at 20 ppm	Increased salt stress resistance	(102)
8.	Tannic acid-derived carbon dots embedded gelatin hydrogels	Maize	Seed coating at 10 ppm	Improved germination, seedling length and photosynthetic parameters under drought stress	(103)
9.	Iron nanoparticles	Maize	Seed priming at 20 ppm	Improved germination ratio, seedling vigour index, root and shoot length stress tolerance index under saline condition	(104)
10.	Silica	Cucumber	Seed priming at 40 ppm	Improved drought tolerance and upregulation of sugars, amino acids, signalling molecules, antioxidants and desiccation tolerance genes	(105)
11.	Peanut shell carbon dots	Blackgram	Seed priming at 200 ppm followed by foliar spray at 50 ppm	Tolerance against drought stress and enhanced gas exchange and antioxidant properties	(106)

As a carrier for gene transfer

In recent decades, gene transformation has been extensively applied to breeding new crop varieties with high yield, quality and stress resistance traits.

Pollen magnetoception technology utilizes Fe_3O_4 magnetic nanoparticles loaded with foreign DNA, which penetrate cotton pollen grains before pollination through the pores (apertures) in the pollen under the influence of a magnetic field. This method helps in producing genotype-independent transgenic cotton plant (9). Similarly, in maize, magnetic nanoparticles coated with DNA penetrate maize pollen grains through their aperture, facilitating the establishment of a genotype-independent pollen transfection system (107).

Seed preservation

Secured seed storage has become vital because seeds carry the genetic legacy of plant species, connecting the next generation and ensuring their survival. Seed storage is primarily important for the regeneration of extinct species, distribution during extreme calamities and saving seeds for subsequent sowing. Biotic and abiotic threats such as insects, fungi, rodents and environmental conditions play a significant role in determining the longevity and viability of seeds during storage. Hence, to understand the impacts of environmental and biological threats, selecting management strategies has become an essential step for maintaining the germination, viability and vigour of seeds during storage. Various methods have been employed to maintain seed quality during storage.

Nanotechnology has emerged as a promising tool for revolutionizing seed preservation, offering a range of exciting possibilities across various stages during seed storage. Priming chickpea seeds with silver nanoparticles at 100 ppm enhanced germination and seedling vigour, attributed to increased α-amylase activity. Additionally, nanopriming stimulated the upregulation of aquaporin genes and the production of reactive oxygen species (ROS), crucial factors in enhancing seed germination (108). Nanopriming of cotton seeds with zinc oxide (ZnO) and titanium dioxide (TiO_2) nanoparticles improved seed longevity and other seed quality traits, namely germination rates, seedling length and seedling dry weight compared to untreated seeds. Additionally, the treated seeds recorded lower electrical conductivity and MDA contents with higher dehydrogenase and an enhanced level of antioxidant enzyme activity (109).

Conclusion

Nanotechnology has shown immense benefits in all aspects of seed science and technology with the help of various advanced techniques such as nanocoating, nanopriming, nanosensors and nanobarcoding. While hurdles exist, nanotechnology provides an exciting solution for critical issues such as food security, climate change and environmental sustainability. Through proper utilization, nanotechnology can create a future where agriculture thrives with low inputs but with increased productivity, efficiency and environmental harmony. Although the potential of nanotechnology in seed science is vast, ensuring long-term safety, assessing the environmental impacts, ensuring toxic effects on living organisms and ensuring equitable access for small-scale farmers remain crucial concerns. Addressing these challenges and taking up more research related to seed preservation, seed tracking, etc., will pave the way for a nano-driven future in seed science and technology that empowers farmers with innovative tools for a more productive, sustainable and food-secure world.

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Authors' contributions

GJ wrote the review article conceptualized by RU and GJ under the supervision of RU. KNN, TA, CI and MD reviewed the manuscript and edited by RU and GJ. All authors read and approved the final manuscript

Compliance with ethical standards

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Ethical issues: None

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