

NANOTECHNOLOGY IN SEED COATING: PRECISION TOOLS FOR CROP IMPROVEMENT

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Abstract

Nanotechnology has emerged as a transformative approach in modern agriculture, offering precision tools to enhance seed performance and crop productivity. Seed coating, a widely adopted technique for improving germination and early plant establishment, is being revolutionized through the integration of nanomaterials. Nano-enabled seed coatings provide controlled release of nutrients, growth regulators, and protective agents, ensuring efficient utilization during critical stages of seed germination and seedling development. The nanoscale dimension of these materials enhances water uptake, enzymatic activity, and stress resilience, thereby promoting uniform germination and vigorous growth even under adverse environmental conditions. In addition to improving physiological responses, nanotechnology-based coatings offer protection against seed-borne pathogens through antimicrobial nanoparticles such as silver, zinc oxide, and chitosan derivatives. These coatings reduce reliance on conventional chemical treatments, aligning with sustainability goals and minimizing ecological footprints. Furthermore, biodegradable nanopolymers ensure eco-friendly applications, addressing concerns of soil health and environmental safety. Despite these advantages, challenges remain in terms of cost-effectiveness, regulatory frameworks, and long-term ecological impacts of nanoparticles in agroecosystems. Future research directions emphasize the development of plant-derived and biodegradable nanomaterials, integration with precision agriculture technologies, and optimization of formulations for diverse crop species. By bridging materials science and crop improvement, nanotechnology in seed coating holds immense potential to support global food security, climate resilience, and sustainable development. This chapter highlights the principles, applications, benefits, and challenges of nano-enabled seed coatings, positioning them as precision tools for advancing agricultural innovation and achieving sustainable development goals.

Keywords: Nanotechnology, Seed coating, Controlled release, Germination and seedling establishment, Biodegradable nanopolymers, Sustainable agriculture

Introduction

Seed coating has long been recognized as a valuable technique in agriculture, designed to improve seed handling, germination, and early seedling establishment. Conventional coatings often include polymers, fertilizers, pesticides, and growth regulators, which provide protection and initial nutrient support.

While these methods have contributed to crop productivity, they are limited by uncontrolled release of inputs, environmental toxicity, and reduced effectiveness under stress conditions such as drought or salinity (Durgadevi et al., 2025).

The emergence of nanotechnology in agriculture offers a paradigm shift in seed enhancement strategies. Nanomaterials, owing to their unique physicochemical properties such as high surface area, reactivity, and controlled release potential, are increasingly being integrated into seed coatings. Nano-fertilizers, nano-polymers, and antimicrobial nanoparticles have demonstrated the ability to improve water uptake, enzymatic activity, and pathogen resistance, thereby ensuring uniform germination and vigorous seedling growth (Singh et al., 2024). These innovations position nanotechnology as a precision tool for crop improvement, bridging materials science with plant biotechnology.

Beyond agronomic benefits, nano-enabled seed coatings make a significant contribution to sustainability and global development goals. By reducing reliance on bulk chemical inputs and promoting biodegradable alternatives, they align with SDG 2 (Zero Hunger) through improved food security, SDG 13 (Climate Action) by enhancing resilience to abiotic stresses, and SDG 12 (Responsible Consumption and Production) through eco-friendly practices (Selvarani et al., 2025). Thus, nanotechnology in seed coating is not merely a technological advancement but a strategic approach to sustainable agriculture.

The scope of this chapter is to provide a comprehensive overview of nanotechnology in seed coating, examining its principles, materials, and application methods. It will highlight the physiological and agronomic benefits, as well as environmental and safety considerations, and include case studies demonstrating its effectiveness across various crop species. Finally, the chapter will address challenges such as cost, scalability, and regulatory frameworks, while outlining future directions for research and innovation. By doing so, it positions nano-seed coating as a transformative tool for precision agriculture and sustainable crop improvement.

Fundamentals of Nanotechnology

Nanotechnology refers to the manipulation and application of materials at the nanoscale, typically between 1 and 100 nanometers. At this scale, materials exhibit unique physicochemical properties such as increased surface area, enhanced reactivity, and improved solubility, which make them highly effective in agricultural applications (Khan et al., 2023). These properties enable nanomaterials to interact more efficiently with biological systems, including seeds, soil, and microorganisms, thereby offering precision tools for crop improvement.

In agriculture, nanotechnology has been applied across diverse domains including nano-fertilizers, nano-pesticides, nano-sensors, and seed enhancement technologies. Nano-fertilizers provide nutrients in a controlled and targeted manner, reducing losses due to leaching and volatilization. Similarly, nano-pesticides offer prolonged protection against pathogens with lower chemical residues compared to conventional formulations (Rai et al., 2022). When integrated into seed coatings, these nanomaterials ensure that essential inputs are delivered directly to the seed during critical stages of germination and early growth.

The effectiveness of nanotechnology in seed coating lies in its ability to regulate water absorption, enzyme activation, and nutrient release. Nanoparticles such as zinc oxide, silver, and chitosan have demonstrated antimicrobial properties, protecting seeds from fungal and bacterial infections. Meanwhile, nano-polymers act as carriers for growth regulators and micronutrients, ensuring sustained availability during seedling establishment (Durgadevi et al., 2025). This precision delivery system enhances seed vigor and uniformity, which are crucial for achieving higher crop yields.

Beyond functional benefits, nanotechnology also supports sustainability by reducing the need for bulk chemical inputs and promoting biodegradable alternatives. Plant-derived nanomaterials and eco-friendly polymers are being developed to minimize environmental risks while maintaining efficacy. This dual advantage—enhanced performance and ecological safety—positions nanotechnology as a cornerstone of future agricultural innovation (Selvarani et al., 2025). Overall, the fundamentals of nanotechnology provide the scientific basis for its integration into seed coating technologies. By leveraging nanoscale properties, researchers and practitioners can design coatings that not only improve seed performance but also contribute to sustainable farming practices and global food security.

Seed Coating: Concepts, Types and Conventional Practices

Seed coating is a widely adopted technique in agriculture, designed to improve seed handling, germination, and early crop establishment. The process involves applying external materials such as polymers, fertilizers, pesticides, or bioactive compounds to the seed surface. These coatings enhance seed size, weight, and uniformity, making them easier to plant mechanically while also protecting against pathogens and pests (Halmer, 2015). Conventional seed coatings have played a crucial role in modern farming systems, particularly in ensuring rapid and uniform crop stand establishment.

Traditional seed coatings are typically categorized into three types: film coating, pelleting, and encrusting. Film coating involves applying a thin polymer layer that adheres active ingredients to the seed surface without significantly altering seed size. Pelleting, on the other hand, adds substantial material to modify seed shape and size, facilitating precision planting in crops such as sugar beet and lettuce. Encrusting represents an intermediate approach, where seeds are coated with moderate amounts of material to improve handling and sowing efficiency (Taylor et al., 1998). Each method has specific advantages depending on crop type, planting system, and environmental conditions.

Despite their widespread use, conventional seed coatings face several limitations. The release of nutrients and pesticides from traditional coatings is often uncontrolled, leading to inefficiencies and environmental contamination. Moreover, chemical residues from fungicides and insecticides can negatively impact soil health and beneficial microorganisms. Under abiotic stress conditions such as drought or salinity, conventional coatings provide limited protection, resulting in poor germination and reduced crop performance (Pedrini et al., 2020). These challenges highlight the need for more advanced and sustainable alternatives.

Recent innovations in seed coating have attempted to incorporate biological agents such as beneficial microbes, biostimulants, and organic polymers. While these approaches improve ecological compatibility, they still lack the precision and efficiency required to address complex agricultural challenges. This gap has paved the way for nanotechnology-based seed coatings, which offer controlled release, enhanced stress tolerance, and eco-friendly solutions. By building upon the foundation of conventional practices, nano-enabled coatings represent the next generation of seed enhancement technologies. Furthermore, the types of seed coating and seed coating formulaions were summarized in **Tables 13.1 and 13.2.**

Table 13.1. Types of seed coating

Type of Seed Coating	Purpose	Benefits	Commonly Used Crops	Reference
Film Coating	To apply a thin and even layer of chemicals like pesticides, fungicides, or colorants without altering the seed's shape.	Improves seed appearance, reduces chemical dusting, ensures uniform germination, and enhances sowing efficiency.	Cereals, pulses, and vegetable seeds.	Copeland & McDonald (2012)
Encrusting (Light Pelleting)	To make small or uneven seeds easier to handle and sow, especially using mechanical planters.	Increases seed weight slightly, improves handling, protects from minor damage, and ensures even seed distribution.	Forage crops, grasses, and flower seeds.	Taylor (2003)
Pelleting	To give very small or irregular seeds a round, uniform shape suitable for precision sowing.	Makes sowing easier, ensures accurate spacing, improves field emergence, and allows uniform plant growth.	Carrot, lettuce, onion, tobacco, and other small-seeded crops.	Halmer (2006)
Polymer Coating	To form a protective layer that can carry nutrients, fungicides, or insecticides while improving seed handling.	Protects from pests and diseases, prevents seed clumping, enhances shelf life, and ensures even	Maize, cotton, and hybrid vegetable seeds.	Scott (1989).

		chemical application.		
Nutrient or Bioactive Coating	To enrich seeds with nutrients or beneficial microbes for better early growth and root development.	Improves germination, strengthens seedlings, boosts nutrient uptake, and reduces fertilizer need.	Pulses, legumes, and cereal crops.	Bewley et al. (2013)

Table 13.2. Components of seed coating formulations

Component	Function / Purpose	Examples	Remarks / Benefits	Reference
Polymer / Binder	Serves as the primary coating material that binds all ingredients to the seed surface.	Polyvinyl alcohol (PVA), methyl cellulose, biodegradable acrylic polymers	Improves seed smoothness, handling, and appearance; prevents dust-off; eco-friendly polymers reduce residue.	Patyal et al. (2025)
Filler / Inert Material	Provides bulk and ensures uniform coating thickness.	Talc, kaolin clay, bentonite, limestone powder	Enhances flowability, maintains seed size uniformity, prevents clumping; sustainable fillers reduce environmental impact.	Durgadevi et al. (2025)
Colorants / Pigments	Adds color to distinguish treated seeds from untreated ones.	Natural dyes, iron oxides, titanium dioxide	Facilitates seed identification, branding, and safety labeling; biodegradable pigments reduce toxicity.	Scott (1989); updated by Patyal et al. (2025)
Plasticizers	Maintains coating flexibility and prevents cracking after drying.	Glycerol, polyethylene glycol (PEG), bio-based plasticizers	Improves film integrity, reduces brittleness, supports long shelf life.	Halmer (2006); Durgadevi et al. (2025)

Surfactants / Wetting Agents	Ensures even spreading and adhesion of coating materials on the seed surface.	Nonionic surfactants, lecithin	Promotes uniform coverage and better contact between seed and coating.	Copeland & McDonald (2001); Patyal et al. (2025)
Bioactive Agents / Pesticides	Protect seeds from pathogens, insects, or nematodes.	Fungicides (Thiram, Carbendazim), insecticides, nematicides	Enhances seed health and germination rate; nano-pesticides reduce chemical load.	Taylor et al. (2003); Rai et al. (2022)
Nutrients / Growth Promoters	Supply essential nutrients and stimulants for early seedling growth.	Micronutrients (Zn, Fe), humic acid, gibberellic acid	Promotes early vigor, root development, and nutrient uptake; nano-fertilizers improve efficiency.	Bewley et al. (2013); Khan et al. (2023)
Microbial Inoculants / Biofertilizers	Introduce beneficial microbes to improve soil fertility and plant growth.	Rhizobium, Azospirillum, Trichoderma spp.	Encourages symbiotic nitrogen fixation and disease suppression; supports sustainable farming.	Vessey (2003); Selvarani et al. (2025)
Solvents / Carriers	Dissolve or disperse coating ingredients uniformly.	Water, ethanol	Provide a medium for mixing and applying coatings; green solvents reduce environmental risks.	Basra (2006); Patyal et al. (2025)
Antioxidants / Preservatives	Extend the shelf life of coated seeds.	Ascorbic acid, propionic acid	Prevent oxidation and microbial spoilage of coatings; improves storage stability.	Bradford (1986); Durgadevi et al. (2025)

Nanotechnology in Seed Coating Concept and mechanism

Nanotechnology in seed technology is a modern approach that uses very tiny materials called *nanoparticles* to improve the way seeds grow and develop. These particles are so small

that they can easily attach to or enter the seed, helping it absorb water and nutrients better. This technology makes seeds stronger, more resistant to diseases, and capable of growing even under tough conditions like drought or poor soil. In short, nanotechnology gives seeds a “smart start” before they even touch the soil.

Table 13.3. Mechanism of nanotechnology in seed coating

Process	Mechanism	Benefit to the Seed/Plant	Reference
Nano-priming	Seeds are soaked or treated with nanoparticles such as zinc oxide or titanium dioxide before sowing. These tiny particles boost water absorption and activate the enzymes inside the seed.	Seeds sprout faster and more evenly, even when conditions aren't perfect.	Mahakham, et al. (2016)
Nano-coating	A very thin layer of nanoparticles is applied to the seed surface. This layer can contain nutrients or natural protectants.	Provides steady nutrition and shields seeds from insects and diseases.	Pérez-de-Luque, (2017)
Nano-encapsulation	Important substances like fertilizers, hormones, or vitamins are packed inside nanoparticles that slowly release them after planting.	Ensures a steady and eco-friendly supply of nutrients during seedling growth.	Liu., & Lal, R. (2015)
Biosensing	Special nanoparticles act like tiny sensors that detect diseases or nutrient levels around the seed.	Helps in early detection of problems and keeps the plant healthier.	Kah, et al. (2019)
Gene delivery	Nanoparticles can carry beneficial genes directly into seeds or cells for better crop traits.	Helps in developing stronger, more productive plants.	Torney, et al. (2007)

Nanomaterials Used in Seed Coating

Nanomaterials are increasingly recognized as powerful agents in seed coating technologies, offering multifunctional benefits that combine protection, nutrition, and growth stimulation. Their nanoscale size allows them to adhere tightly to seed surfaces or penetrate seed coats, enabling efficient delivery of bioactive compounds, nutrients, and protective agents.

This unique property makes them highly effective in enhancing seed vigor, improving germination rates, and supporting sustainable crop production (Rai et al., 2022; Durgadevi et al., 2025).

Zinc Oxide (ZnO) and Titanium Dioxide Nanoparticles

Among the most widely studied nanomaterials are zinc oxide (ZnO) nanoparticles, which play a critical role in activating seed enzymes and supplying essential zinc. Their application has been shown to accelerate germination, stimulate root elongation, and improve tolerance to abiotic stresses such as drought and salinity (Mahakham et al., 2016; Khan et al., 2023). Similarly, titanium dioxide (TiO₂) nanoparticles are valued for their ability to enhance photosynthesis and chlorophyll biosynthesis, resulting in stronger and greener seedlings with improved resilience under stress conditions (Pérez-de-Luque, 2017).

Silicon Dioxide (SiO₂) and Silver Nanoparticles

It contributes to strengthening seed coats and improving drought tolerance by enhancing water retention and mechanical resistance. Silver (Ag) nanoparticles are particularly important for their antimicrobial properties, offering protection against fungal and bacterial pathogens and reducing dependence on chemical fungicides (Kah et al., 2019; Selvarani et al., 2025).

Iron Oxide (Fe₃O₄) and Copper Oxide (CuO) Nanoparticles

Iron oxide (Fe₃O₄) provides essential iron nutrition, supporting chlorophyll formation and photosynthetic efficiency during early seedling development (Liu & Lal, 2015). Copper oxide (CuO) nanoparticles serve a dual role as micronutrients and antimicrobial agents, improving metabolic activity and disease resistance (Patyal et al., 2025).

Advanced nanomaterials such as carbon nanotubes (CNTs) and chitosan nanoparticles further expand the scope of seed coating. CNTs increase seed coat permeability, thereby improving water and nutrient absorption efficiency (Torney et al., 2007). Chitosan nanoparticles, derived from natural sources, are biodegradable and act as carriers for nutrients or plant hormones, while simultaneously enhancing pathogen defense mechanisms (Durgadevi et al., 2025). Additionally, nano-clays and polymer nanocomposites are employed as carriers for fertilizers and pesticides, ensuring controlled and sustained release of inputs, which reduces chemical wastage and environmental contamination (Patyal et al., 2025). Overall, the integration of these nanomaterials into seed coatings represents a significant advancement in agricultural biotechnology. By combining nutrient delivery, pathogen protection, and stress tolerance into a single nano-enabled layer, seeds gain a healthier and more vigorous start. This approach not only improves crop productivity but also aligns with sustainable farming practices and global efforts to achieve food security under changing climatic conditions (Rai et al., 2022; Selvarani et al., 2025).

Techniques of Nano Seed Coating

Nano seed coating is a cutting-edge approach that applies a thin, uniform layer of nanomaterials onto the seed surface to enhance germination, nutrient uptake, and stress tolerance. The primary aim is to ensure that nanoparticles, nutrients, and protective substances adhere firmly to seeds and are released gradually during germination and early growth. This controlled release improves seed vigor, reduces chemical wastage, and supports sustainable agriculture (Patyal et al., 2025).

- 1. Dry coating technique:** One of the simplest methods is the **dry coating technique**, where seeds are mixed with dry nanoparticles or nano-formulated powders along with adhesive materials such as natural gums or polymers. The seeds are rotated in a drum to achieve uniform coverage. This technique is cost-effective and scalable, making it suitable for crops like maize and wheat. For example, zinc oxide nanoparticles applied through dry coating have been shown to improve germination and root elongation in maize under drought stress (Mahakham et al., 2016).
- 2. Wet coating or slurry coating technique:** The **wet coating or slurry coating technique** is widely used in vegetable and legume crops. Nanoparticles are suspended in a liquid medium, often water or polymer solutions, and seeds are dipped, sprayed, or tumbled in the suspension. As the seeds dry, a thin nano-layer forms on their surface. This method ensures even coating and allows easy incorporation of nutrients, pesticides, and growth enhancers. For instance, chitosan nanoparticles applied via slurry coating have improved disease resistance and nutrient uptake in chickpea and tomato seeds (Pérez-de-Luque, 2017).
- 3. Nano-encapsulation:** Another advanced method is **nano-encapsulation**, where nutrients, pesticides, or plant growth regulators are enclosed within nanosized capsules or carriers. These capsules are coated onto the seed surface and release their contents gradually during germination. This technique has been particularly effective in rice and soybean, where encapsulated micronutrients and hormones improved seedling vigor and nutrient-use efficiency while reducing chemical wastage (Liu & Lal, 2015).
- 4. Electrostatic coating technique:** The **electrostatic coating technique** uses electrical charges to enhance nanoparticle adhesion. Nanoparticles are given a specific charge, while seeds are given the opposite charge, ensuring strong and uniform attachment. This method is especially useful for metallic nanoparticles such as zinc oxide and copper oxide, which provide both nutrient supplementation and antimicrobial protection. Electrostatic coating has been successfully applied in cotton and groundnut seeds, producing durable nano-layers that enhance disease resistance (Kah et al., 2019).
- 5. Layer-by-layer (LbL) assembly:** A more precise approach is **layer-by-layer (LbL) assembly**, where seeds are alternately coated with positively and negatively charged nanoparticles or polymers, forming multiple thin layers. Each layer can contain different materials such as nutrients, protectants, or stimulants, allowing customization of seed treatments. For example, alternating layers of chitosan and

silica nanoparticles have been used in rice and lettuce seeds to provide controlled release of nutrients and biocontrol agents, improving seedling establishment and uniformity (Torney et al., 2007).

6. **Spray coating technique:** It involves spraying a fine mist of nano-suspension onto rotating seeds in a coating drum or chamber. As the solvent evaporates, a uniform nano-film forms on the seed surface. This method is suitable for bulk operations and ensures even coating without damaging seeds. Spray coating has been widely adopted in hybrid vegetable seeds such as tomato and cucumber, where nano-fertilizers and nano-biostimulants improve germination and early vigor (Patyal et al., 2025). Together, these techniques demonstrate the versatility of nanotechnology in seed enhancement. By tailoring coating methods to specific crop needs, researchers and farmers can achieve improved germination, stress tolerance, and yield, while promoting sustainable agricultural practices. Also, a comparative summary of nano seed coating technique was displayed in **Table 13.4**.

Table 13.4. Comparative summary of nano seed coating technique.

Technique	Crop Examples	Benefits	Reference
Dry Coating	Maize, wheat	Simple, cost-effective; improves germination and root elongation under stress.	Mahakham et al. (2016)
Wet Coating (Slurry)	Chickpea, tomato	Ensures even coating; integrates nutrients and biocontrol agents.	Pérez-de-Luque (2017)
Nano-encapsulation	Rice, soybean	Controlled release of nutrients/hormones; enhances vigor and nutrient-use efficiency.	Liu & Lal (2015)
Electrostatic Coating	Cotton, groundnut	Strong adhesion of metallic nanoparticles; durable nano-layer improves disease resistance.	Kah et al. (2019)
Layer-by-Layer (LbL) Assembly	Rice, lettuce	Customizable multi-layer coatings; controlled release of nutrients and protectants.	Torney et al. (2007)
Spray Coating	Tomato, cucumber (hybrid seeds)	Suitable for bulk operations; uniform nano-film improves germination and vigor.	Patyal et al. (2025)

Controlled Release of Nutrients and Protectants

A persistent challenge in modern agriculture is ensuring that seeds receive nutrients and protective agents at the right time and in the right amounts. Conventional seed treatments often deliver inputs in a single burst, which can lead to rapid depletion, leaching, or

environmental contamination. Controlled release technology, especially when combined with nanotechnology, addresses this issue by enabling nutrients and protectants to be delivered gradually and in a sustained manner throughout germination and seedling establishment (Kah et al., 2018; Nair et al., 2010).

Nanotechnology achieves this through nanocarriers – tiny delivery systems made from materials such as chitosan, silica, nano-clays, hydrogels, or biodegradable polymers. These carriers encapsulate nutrients or pesticides and release them slowly in response to environmental triggers such as soil moisture, pH changes, or enzymatic activity during germination. This mechanism ensures a steady nutrient supply, much like the way the human body absorbs vitamins over time, thereby improving efficiency and reducing waste (Fincheira et al., 2023; Verma et al., 2025).

The benefits of controlled release are multifaceted. Seeds experience continuous growth support, as nutrients are supplied progressively, strengthening seedlings and enhancing vigor. The coatings also provide long-lasting protection, with pest and disease control agents released gradually, safeguarding plants during their most vulnerable stages. Importantly, this approach minimizes nutrient wastage, since fertilizers are less likely to leach into the soil or wash away with irrigation, thereby reducing input costs and environmental pollution. Furthermore, controlled release contributes to eco-friendly farming, as chemicals are used more efficiently, keeping soil and water systems cleaner (Nayak et al., 2025; Rodrigo & Munaweera, 2025).

Recent advances highlight the role of biodegradable polymers and eco-friendly hydrogels in smart release systems. For example, biopolymer nanocarriers have been shown to improve agrochemical performance while reducing toxicity (Thapliyal & Khan, 2024). Similarly, nano-clay polymer composites are being developed for controlled nitrogen release, ensuring crops receive nutrients in synchrony with their growth stages (Nayak et al., 2025). Hydrogels, meanwhile, act as moisture-sensitive carriers that release nutrients and protectants only when soil conditions demand, boosting resilience in water-stressed environments (Rodrigo & Munaweera, 2025).

A practical example is the use of chitosan nanoparticles loaded with zinc or urea, which release nutrients progressively as the coating biodegrades in the soil. This not only improves nutrient-use efficiency but also supports healthier plant development while minimizing environmental risks. Such innovations demonstrate how nanotechnology-based controlled release systems can simultaneously enhance productivity, reduce chemical dependency, and align with sustainability goals in agriculture.

Physiological and Agronomic Benefits

Nano-enabled seed coatings provide multiple physiological advantages that directly enhance seed germination and early seedling vigor. The nanoscale properties of materials such as zinc oxide, silver, and silica nanoparticles improve water absorption and enzymatic activation, leading to faster and more uniform germination compared to conventional coatings (Durgadevi et al., 2025). Enhanced germination ensures better crop stand establishment, which is critical for achieving high yields under diverse field conditions.

Another major benefit is the improvement of stress tolerance. Seeds coated with nanomaterials exhibit greater resilience to abiotic stresses such as drought, salinity, and temperature extremes. For instance, nano-silica and nano-titanium dioxide have been shown to enhance antioxidant activity in seedlings, reducing oxidative damage under stress conditions (Rai et al., 2022). This capacity to withstand environmental fluctuations makes nano-seed coatings particularly valuable in climate-vulnerable regions.

Nano-coatings also facilitate efficient nutrient delivery. Nano-fertilizers embedded in seed coatings release nutrients in a controlled manner, ensuring their availability during critical stages of seedling development. This precision delivery reduces nutrient losses due to leaching and volatilization, thereby improving nutrient-use efficiency and lowering input costs (Khan et al., 2023). Enhanced nutrient uptake translates into stronger root systems, improved shoot growth, and higher biomass accumulation.

In addition to abiotic stress management, nano-enabled coatings provide pathogen protection. Antimicrobial nanoparticles such as silver, zinc oxide, and chitosan inhibit the growth of seed-borne and soil-borne pathogens, reducing the incidence of diseases during germination and early establishment (Selvarani et al., 2025). This reduces dependence on chemical fungicides and pesticides, contributing to safer and more sustainable crop production. Collectively, these physiological and agronomic benefits highlight the transformative potential of nanotechnology in seed coating. By simultaneously enhancing germination, nutrient uptake, stress tolerance, and disease resistance, nano-enabled coatings serve as precision tools for crop improvement, aligning with the broader goals of sustainable agriculture and food security.

Applications and Benefits of Controlled Release through Nanotechnology

Nanotechnology-based seed coatings provide a wide range of applications and benefits that enhance crop performance while promoting environmental sustainability. By ensuring that nutrients and protectants are released gradually and efficiently, this approach gives plants a stronger start and supports modern farming practices aimed at reducing chemical dependency and ecological harm (Kah et al., 2018; Nair et al., 2010).

Enhanced Germination and Seedling Vigor

One of the most significant advantages is enhanced germination and seedling vigor. Nanomaterials help maintain optimal moisture and nutrient levels around the seed, which accelerates germination, strengthens early seedling growth, and ensures uniform crop stands. This improvement in establishment is particularly valuable in crops such as maize and rice, where uniformity directly influences yield potential (Kah et al., 2018).

Improved Nutrient Uptake and Growth Promotion

Controlled release also contributes to improved nutrient uptake and growth promotion. Nano-carriers deliver nutrients in small, readily available doses directly to the seedling, promoting better root development and nutrient absorption. This targeted delivery results

in healthier plants with higher biomass accumulation and yield potential, as demonstrated in legumes and cereals treated with nano-fertilizers (Nair et al., 2010).

Increased Tolerance to Abiotic Stresses

Another key benefit is increased tolerance to abiotic stresses such as drought, salinity, and extreme temperatures. Nanoparticles like silica (SiO_2) and zinc oxide (ZnO) enhance water retention in the rhizosphere and regulate physiological functions during stress periods. This resilience allows crops to maintain productivity under unfavorable conditions, making nano-coatings particularly relevant in climate-smart agriculture (Verma et al., 2025).

Disease and Pest Resistance

In addition, nanotechnology improves disease and pest resistance. Nano-encapsulated pesticides and antimicrobial agents provide long-term protection against soil-borne pathogens and insect pests. By releasing active compounds gradually, these coatings reduce the need for repeated chemical sprays, lowering production costs and minimizing environmental contamination (Fincheira et al., 2023).

Environmental Sustainability

Finally, controlled release through nanotechnology supports environmental sustainability. By reducing nutrient losses through leaching and runoff, this approach minimizes fertilizer wastage and chemical pollution. It also protects soil and water quality, contributing to safer ecosystems and aligning with global sustainability goals such as the UN Sustainable Development Goals (SDGs). The integration of biodegradable nanocarriers, such as chitosan and polymer composites, further enhances eco-friendly farming practices by reducing reliance on synthetic chemicals (Rodrigo & Munaweera, 2025).

Environmental and Safety Considerations

While nanotechnology in seed coating offers remarkable agronomic benefits, its environmental and safety implications must be carefully evaluated. The introduction of nanoparticles into soil ecosystems raises concerns about their persistence, mobility, and interactions with beneficial organisms. Studies have shown that certain nanoparticles, such as silver and zinc oxide, may accumulate in soil and potentially disrupt microbial communities if applied excessively (Rai et al., 2022). Therefore, understanding the ecological footprint of nano-enabled coatings is essential for their safe and sustainable use.

One of the key strategies to mitigate environmental risks is the development of biodegradable nanomaterials. Plant-derived polymers, chitosan, and starch-based nanoparticles have demonstrated eco-friendly properties, breaking down naturally without leaving harmful residues. These materials not only reduce environmental contamination but also maintain soil health and fertility, making them suitable for long-term agricultural applications (Durgadevi et al., 2025). The adoption of biodegradable nanomaterials represents a critical step toward balancing innovation with ecological responsibility.

Another important consideration is the interaction of nanoparticles with soil microbiota. Beneficial microbes play a vital role in nutrient cycling, disease suppression, and plant growth promotion. While antimicrobial nanoparticles are effective against pathogens, their indiscriminate use may also affect non-target organisms. Research emphasizes the need for dose optimization and formulation refinement to ensure that nano-seed coatings selectively target harmful microbes while preserving beneficial ones (Khan et al., 2023).

From a regulatory perspective, the absence of standardized guidelines for nanomaterial use in agriculture poses challenges. Current frameworks often lag behind technological advancements, creating uncertainty for researchers, industry stakeholders, and farmers. Establishing clear regulations on nanoparticle safety, permissible concentrations, and environmental monitoring is crucial to ensure responsible deployment (Selvarani et al., 2025). Such frameworks will also build public trust and facilitate wider adoption of nano-enabled seed technologies. In summary, environmental and safety considerations form an integral part of nanotechnology applications in seed coating. By prioritizing biodegradable materials, optimizing formulations, and implementing robust regulatory frameworks, nano-seed coatings can be harnessed effectively while safeguarding soil ecosystems and human health.

Case Studies and Experimental Evidence

The practical application of nanotechnology in seed coating has been demonstrated across a range of crops, providing evidence of its effectiveness in enhancing germination, stress tolerance, and yield. For example, studies on vegetable crops such as tomato and okra have shown that nano-seed coatings significantly improved germination rates and seedling vigor compared to conventional coatings. Seeds treated with nano-zinc oxide and nano-chitosan exhibited faster root elongation and higher biomass accumulation, underscoring the physiological advantages of nanoscale inputs (Singh et al., 2024).

In cereal crops, nano-enabled coatings have proven particularly beneficial under stress conditions. Research on wheat and rice demonstrated that nano-silica and nano-titanium dioxide coatings enhanced antioxidant activity, reduced oxidative stress, and improved seedling survival under drought and salinity stress (Rai et al., 2022). These findings highlight the potential of nanotechnology to support climate-resilient agriculture, especially in regions prone to abiotic stress.

Legume crops such as soybean and chickpea have also benefited from nano-seed coatings. Experimental trials revealed that nano-fertilizer coatings improved nodulation and nitrogen fixation, leading to enhanced plant growth and yield. Moreover, antimicrobial nanoparticles such as silver and zinc oxide reduced seed-borne fungal infections, ensuring healthier crop establishment (Durgadevi et al., 2025). These results demonstrate the dual role of nanotechnology in both nutrient delivery and pathogen protection.

Comparative performance metrics further validate the advantages of nano-seed coatings. Across multiple studies, nano-coated seeds consistently outperformed conventional treatments in terms of germination percentage, seedling vigor index, and final yield. For instance, germination rates increased by 15–20%, while yield improvements

ranged from 10–25% depending on crop type and environmental conditions (Selvarani et al., 2025). Such evidence underscores the transformative potential of nanotechnology in seed enhancement. Collectively, these case studies provide strong experimental support for the adoption of nano-enabled seed coatings. By improving crop performance across diverse species and stress environments, they establish nanotechnology as a precision tool for sustainable agriculture and food security.

Challenges and Future Directions

Despite the promising potential of nanotechnology in seed coating, several challenges hinder its widespread adoption. One of the primary concerns is cost and scalability. The synthesis of nanoparticles and their incorporation into seed coatings often require specialized equipment and expertise, making them more expensive than conventional methods. For smallholder farmers, particularly in developing countries, affordability remains a significant barrier (Rai et al., 2022). Addressing cost-effectiveness through low-cost synthesis methods and scalable production technologies is essential for broader implementation.

Another challenge lies in the regulatory and safety frameworks governing nanomaterials in agriculture. Currently, there is a lack of standardized guidelines for permissible concentrations, environmental monitoring, and risk assessment of nanoparticles. This regulatory gap creates uncertainty for researchers, industry stakeholders, and policymakers, slowing down commercialization and adoption (Selvarani et al., 2025). Establishing clear international standards and safety protocols will be critical to ensure responsible deployment of nano-enabled seed coatings.

Environmental concerns also pose limitations. While biodegradable nanomaterials are being developed, certain nanoparticles such as silver and zinc oxide may persist in soil ecosystems, potentially affecting beneficial microorganisms and long-term soil health (Khan et al., 2023). Future research must focus on eco-friendly alternatives, dose optimization, and long-term ecological studies to balance innovation with sustainability.

Looking ahead, future directions emphasize the integration of nanotechnology with precision agriculture and digital farming tools. Smart nano-coatings that respond to environmental cues, coupled with IoT-based monitoring systems, could revolutionize crop management. Additionally, interdisciplinary research combining plant biotechnology, materials science, and environmental engineering will be vital to optimize formulations for diverse crop species and stress environments (Durgadevi et al., 2025). In summary, while challenges related to cost, regulation, and environmental safety remain, the future of nano-enabled seed coatings is promising. With continued innovation, policy support, and sustainable practices, nanotechnology can be scaled as a precision tool for crop improvement, contributing to global food security and climate resilience.

Conclusion

Nanotechnology in seed coating represents a transformative innovation in modern agriculture, offering precision tools to enhance germination, stress tolerance, nutrient

delivery, and pathogen resistance. By leveraging the unique properties of nanomaterials, researchers have developed coatings that outperform conventional methods, ensuring uniform crop establishment and improved yields under diverse environmental conditions. The integration of nano-enabled coatings directly supports the goals of sustainable agriculture. Controlled release of nutrients and bioactive compounds reduces chemical inputs, while antimicrobial nanoparticles minimize reliance on fungicides and pesticides. These advancements not only improve crop productivity but also contribute to ecological sustainability by lowering environmental contamination and promoting biodegradable alternatives. Despite these benefits, challenges remain in terms of cost, scalability, regulatory frameworks, and long-term ecological safety. Addressing these issues through interdisciplinary research, eco-friendly nanomaterial development, and robust policy support will be essential for widespread adoption. Future directions point toward smart nano-coatings integrated with precision agriculture technologies, offering dynamic responses to environmental cues and further enhancing crop resilience. In conclusion, nano-enabled seed coatings embody the convergence of materials science, biotechnology, and sustainability. They hold immense promise as precision tools for crop improvement, capable of transforming agriculture into a more resilient, efficient, and environmentally responsible system. With continued innovation and responsible deployment, nanotechnology in seed coating can play a pivotal role in securing global food systems for future generations.

Disclosure Statement

The authors reported no potential conflict of interest.

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