Journal of Agriculture and Ecology Research International

Volume 25, Issue 6, Page 278-295, 2024; Article no.JAERI.128741
ISSN: 2394-1073

Nano-seed Coating Technologies for Enhancing Vegetable Seed Performance and Stress Tolerance

Sultan Singh [a], Stuti Pathak [a*], Yogita [a], Jasdev Singh [b], Mohit Kamboj [a] and Vikram Singh [a]

[a] *Department of Agriculture, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala-133207, Haryana, India.*
[b] *School of Agriculture, NIILM University, Kaithal-136027, Haryana, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jaeri/2024/v25i6658

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/128741

Received: 24/10/2024
Accepted: 27/12/2024
Published: 29/12/2024

Review Article

ABSTRACT

Nano-seed coating technologies have emerged as a revolutionary tool in modern agriculture, offering promising solutions to enhance vegetable seed performance and stress tolerance. These coatings integrate nanomaterials with bioactive compounds, enabling precise delivery of nutrients, growth regulators, and protective agents directly to the seed. The nanoscale size ensures improved adhesion, controlled release, and enhanced interaction with the seed surface, fostering uniform germination and seedling vigour. The application of nano-coatings not only improves the physiological quality of seeds but also enhances their resilience to abiotic stresses such as drought, salinity, and temperature extremes. Encapsulation of essential nutrients and biostimulants within nanocarriers boosts seed metabolic activities, while antimicrobial and antifungal agents in

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**Corresponding author: E-mail: stutipathak94@gmail.com;*

Cite as: *Singh, Sultan, Stuti Pathak, Yogita, Jasdev Singh, Mohit Kamboj, and Vikram Singh. 2024. "Nano-Seed Coating Technologies for Enhancing Vegetable Seed Performance and Stress Tolerance". Journal of Agriculture and Ecology Research International 25 (6):278-95. https://doi.org/10.9734/jaeri/2024/v25i6658.*

the coating provide protection against seed-borne pathogens. Additionally, the technology supports sustainable agricultural practices by reducing the need for excessive agrochemical use. Recent advancements have demonstrated significant improvements in germination rates, root development, and overall plant growth in various vegetable crops, making nano-seed coatings a pivotal innovation for food security in stress-prone environments. Future research should focus on optimizing formulations, evaluating environmental safety, and scaling up production for widespread adoption, bridging the gap between nanotechnology and resilient agricultural systems.

Keywords: Nano-seed coating; vegetable seed performance; stress tolerance; germination enhancement; sustainable agriculture and abiotic stress resilience.

1. INTRODUCTION

Seed coating is a widely used agricultural practice that involves applying a layer of materials around seeds to improve their performance during germination and early plant development (Bhushan, 2017). The purpose of seed coating is to protect seeds from environmental stress, diseases, and pests, while also enhancing germination rates and seedling vigour (Kumar et al., 2017). Traditional seed coating methods have relied on a variety of materials, including fertilizers, fungicides, insecticides, and binders (Gogos et al., 2012).

Historically, seed coatings were designed to improve the mechanical handling of seeds, ensure uniformity in sowing, and prevent direct seed-to-seed contact during planting. Coatings also often include nutrients to support seed germination and early growth (Singh et al., 2023a). For example, fungicides and insecticides are often used in seed treatments to protect the seed from pathogens and pests in the soil (Perez-deluque and Rubiales, 2009). Pelleting and prilling (a method in which a seed is covered with a layer of a material like clay or polymer) are some of the more common traditional coating techniques (Li and Zhang, 2020). These methods enhance seedling establishment by regulating water uptake and reducing the risk of seedling diseases (Lopez-Perz et al., 2015).

While these coatings serve their purpose, they are often limited by factors such as slow nutrient release, environmental concerns related to pesticide runoff, and the need for precise control over seed coating thickness. Additionally, the materials used in traditional coatings can sometimes be non-biodegradable, which may pose a long-term environmental risk (Nair et al., 2010).

2. NANOMATERIALS AND THEIR USE IN SEED COATING

Nanomaterials refer to materials that have at least one dimension in the nanometer range (1-100 nm). This size range gives them unique physical, chemical, and biological properties that are distinct from their bulk counterparts. The high surface-area-to-volume ratio, increased reactivity, and novel optical and magnetic properties of nanomaterials have led to their application in a wide variety of fields, including agriculture. Nanomaterials used in seed coating include metal nanoparticles (such as zinc oxide, titanium dioxide, and silver), carbon-based nanoparticles (like graphene and carbon nanotubes), polymeric nanoparticles, and nanocomposites. These materials can be designed to interact with the seed surface in beneficial ways that improve seed performance.

- **Metal Nanoparticles**: These nanoparticles are often incorporated into coatings due to their antimicrobial properties, which help protect seeds from fungal and bacterial infections. For example, silver nanoparticles have been shown to have effective antimicrobial properties, reducing the risk of seedling diseases caused by pathogens like *Fusarium* and *Rhizoctonia*.
- **Polymeric Nanoparticles**: These are often used for controlled release of nutrients and pesticides. The use of biodegradable polymers such as chitosan and poly(lactic acid) allows for a slow and sustained release of essential nutrients, such as nitrogen and phosphorus, over the early stages of plant growth.
- **Carbon-based Nanomaterials**: Graphene and carbon nanotubes (CNTs) have been incorporated into seed coatings due to their unique electrical conductivity and strength, which can promote seedling

growth by facilitating ion transfer, water uptake, and nutrient absorption.

Nanotechnology can also enable the creation of seed coatings with tailored properties that improve seedling establishment, protect against biotic and abiotic stresses, and even accelerate seed germination.

3. IMPORTANCE OF ENHANCING SEED PERFORMANCE AND STRESS TOLE-RANCE IN VEGETABLES

Vegetable crops are a critical source of nutrients for human populations, providing vitamins, minerals, and dietary fibre. However, vegetable production is often affected by environmental stresses such as drought, heat, salinity, and diseases, which can reduce seed germination rates and seedling establishment (Rodriguez-Fernandez et al., 2023). In recent years, there has been increasing interest in improving seed performance and stress tolerance, particularly in the context of climate change, which is expected to exacerbate these environmental challenges (khan et al., 2019).

- **Enhancing Seed Germination and Early Growth:** Seed germination is a critical phase in plant development, as it determines the success of the subsequent plant growth (Mahapatra et al., 2021). Traditional agricultural practices rely heavily on optimal weather conditions and soil moisture, which are not always guaranteed. Seed coating with nanomaterials can promote better seed hydration, increase the surface area for nutrient uptake, and reduce the likelihood of seedling diseases. Nanomaterials such as carbon nanotubes and polymeric nanoparticles help facilitate rapid water absorption and can protect seeds during the early stages of germination (Sarkar et al., 2021).
- **Improving Stress Tolerance:** In areas affected by drought or high salinity, crop yields are often reduced due to poor seedling establishment and stunted growth. By enhancing seedling vigour, nano seed coatings help plants overcome early-stage stressors (Sharma and Gupta, 2022). Nanomaterials have been shown to improve the osmotic adjustment, antioxidant activity, and protective enzyme synthesis in plants under stress (Baker et al*.,* 2020). For example, coatings that release calcium ions can help plants maintain cellular structure during water deficit conditions, while nanoparticles that contain zinc or copper can improve the plant’s tolerance to high salinity (Chakraborty et al*.,* 2020).
- **Pest and Disease Resistance:** Another key benefit of using nano-coatings is the protection against soil-borne pests and pathogens. Nanoparticles such as silver and copper oxide have been demonstrated to possess strong antimicrobial properties. By incorporating these particles into the seed coating, it is possible to reduce the risk of seedling diseases caused by fungi, bacteria, and viruses. This is particularly important in vegetables that are highly susceptible to pathogens like *Pythium* and *Phytophthora*, which can significantly reduce crop yields (Yadav and Singh, 2021).
- **Long-term Benefits for Sustainability:** The potential for nano-seed coatings to contribute to sustainable agriculture is significant. With the increasing demand for food production due to population growth, agricultural sustainability is becoming a critical concern (Khot et al., 2012). Nano-coatings can reduce the need for external inputs like fertilizers and pesticides, decreasing the overall environmental impact. They can also improve crop yield in suboptimal growing conditions, reducing the need for irrigation and minimizing water waste.

By enhancing seed performance and stress tolerance, nano-seed coatings have the potential to increase crop yields, improve the sustainability of vegetable farming, and contribute to food security in the face of global challenges such as climate change and population growth (Usman and Mehta, 2020).

4. NANOPARTICLES IN SEED COAT-INGS: TYPES AND APPLICA-TIONS

Nanoparticles are defined as particles with at least one dimension in the size range of 1-100 nanometers (nm). Their unique properties, such as a high surface area-to-volume ratio, high reactivity, and ability to interact with biological systems, make them ideal candidates for use in seed coatings. The most common types of nanoparticles used in seed coatings include metallic nanoparticles, carbon-based nanoparticles, and polymeric nanoparticles. Each of these has distinct advantages depending on the goals of seed enhancement, such as improving germination, enhancing stress tolerance, or promoting disease resistance (Gouda and Mohanta, 2020).

a) Metallic Nanoparticles

Metallic nanoparticles, such as silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO_2), copper oxide (CuO), and iron oxide (Fe_2O_3), are among the most widely studied nanomaterials for seed coatings. These particles possess unique antimicrobial, antioxidant, and UV-blocking properties, which are crucial for enhancing seed performance in adverse environmental conditions.

- **Silver Nanoparticles (AgNPs):** Silver nanoparticles are particularly known for their antimicrobial properties, making them effective against a wide range of seed-borne pathogens. When incorporated into seed coatings, AgNPs help protect seeds from fungal, bacterial, and viral infections, promoting better germination and seedling growth. Silver's ability to disrupt the cell membranes of pathogens makes it an ideal material for enhancing disease resistance in plants.
- **Zinc Oxide Nanoparticles (ZnO):** Zinc is an essential micronutrient for plants, and its nanoparticles offer dual benefits. ZnO nanoparticles have been shown to stimulate seed germination and seedling vigour, especially under stress conditions like drought and salinity (Chakraborty et al., 2018). ZnO can also act as a protective agent against fungal pathogens due to its antifungal properties.
- **Titanium Dioxide (TiO2):** TiO2 nanoparticles are primarily known for their role in enhancing seed germination and growth. These particles also have photocatalytic properties, which can be harnessed to help protect seeds from UV radiation, particularly in high-altitude regions or areas with high solar radiation. TiO2 nanoparticles may also enhance nutrient uptake by the plants, thereby improving overall seedling health and development.

b) Carbon-based Nanoparticles

Carbon-based nanoparticles, including **graphene**, **carbon nanotubes (CNTs)**, and **fullerenes**, have garnered significant attention in nanotechnology due to their remarkable mechanical, electrical, and chemical properties. These materials are particularly beneficial in seed coatings due to their ability to facilitate water retention, enhance nutrient uptake, and improve stress tolerance.

- **Graphene:** Graphene, a single layer of carbon atoms arranged in a two-dimensional lattice, has excellent conductivity and mechanical strength. Graphene oxide (GO) has been studied as a seed coating material for its ability to enhance water retention, regulate ion exchange, and improve nutrient uptake in seeds. Its excellent biocompatibility and high surface area make it effective for improving seedling growth under stress conditions such as drought or salinity.
- **Carbon Nanotubes (CNTs):** CNTs are cylindrical nanostructures made of carbon atoms. These nanomaterials are ideal for seed coatings due to their strength, conductivity, and ability to interact with biological systems. CNTs have been shown to promote seed germination, seedling growth, and resistance to abiotic stresses by improving water and nutrient absorption, as well as facilitating gas exchange at the seed surface (Vishwakarma et al., 2020).

c) Polymeric Nanoparticles

Polymeric nanoparticles are synthesized using biodegradable polymers, making them environmentally friendly and safe for agricultural use. These nanoparticles are often designed for controlled release of nutrients, pesticides, and growth regulators, providing sustained benefits to seeds and seedlings (Ahmad and Mark, 2009).

- **Polylactic Acid (PLA) and Poly (lactic-co-glycolic acid) (PLGA):** These biodegradable polymers are commonly used in agricultural applications due to their controlled release properties. When used as a seed coating, PLA and PLGA nanoparticles can slowly release fertilizers or other beneficial compounds, thereby reducing the need for frequent chemical applications (Prasad et al., 2017).
- **Chitosan-based Nanoparticles:** Chitosan, a biopolymer derived from chitin (a major component of crustacean shells), has been used in seed coating technologies due to its antimicrobial properties and ability to enhance seed germination (Muthuramalingam and

Raghupathi, 2017). Chitosan nanoparticles can protect seeds from pathogens, enhance seedling growth, and improve stress tolerance by modulating plant physiological processes such as antioxidant activity (Hernández et al., 2019).

5. NANO-CLAYS, NANOCOMPOSITES, AND BIO-BASED NANOPARTICLES IN SEED COATINGS

Nanoclays, nanocomposites, and bio-based nanoparticles have emerged as important alternatives or supplements to traditional nanoparticles in seed coating technologies (Ghouri et al., 2021). These materials can offer additional functionalities such as enhanced nutrient delivery, controlled release, and reduced environmental impact (Ahmed et al., 2023).

a) **Nano-clays**
Nano-clays are naturally occurring clay minerals that are exfoliated into nanosheets with unique structural properties. These materials have been incorporated into seed coatings due to their high surface area, mechanical strength, and ability to enhance water retention and nutrient release.

- **Montmorillonite:** This is a type of clay that is frequently used in agricultural applications due to its high cation-exchange capacity (CEC), which can facilitate the slow release of nutrients and improve soil structure. When applied as a seed coating, montmorillonite nanoparticles can enhance seedling growth by promoting water retention and nutrient uptake. Additionally, nano-clays can encapsulate fertilizers or biocontrol agents, providing a controlled release mechanism for these compounds.

b) **Nanocomposites**
Nanocomposites are materials that combine nanoparticles (such as metal, carbon, or polymeric) with a matrix material to enhance specific properties like mechanical strength, flexibility, and barrier resistance. These composite materials are used in seed coatings to improve the overall functionality of the coating and ensure better seed protection (Abd-Elsalam and Hashim, 2019).

- **Polymer-based Nanocomposites:** Incorporating nanoparticles into a polymer matrix can enhance the properties of the coating material. For example, polymer-clay nanocomposites can be used to improve seedling growth by facilitating the controlled release of nutrients while also providing protection against pathogens. The clay nanoparticles increase the structural integrity of the polymer coating, enhancing its durability in the soil and preventing rapid degradation.

c) **Bio-based Nanoparticles**
Bio-based nanoparticles are derived from renewable resources such as plant extracts, microorganisms, or agricultural waste. These materials are biodegradable, non-toxic, and environmentally friendly, making them a promising option for sustainable agriculture (Rathore et al., 2022).

- **Bio-derived Polymeric Nanoparticles:** Polysaccharides such as cellulose and starch can be used to create biodegradable nanomaterials for seed coatings (Ramin and Zare, 2018). These bio-based nanoparticles are typically non-toxic, eco-friendly, and capable of delivering nutrients and growth regulators in a controlled manner. Additionally, bio-derived nanoparticles can encapsulate plant growth promoters or biocontrol agents, improving disease resistance and promoting growth under stress (González et al., 2019).

6. NANOSTRUCTURED POLYMERS AND THEIR ROLE IN SEED COATINGS

Nanostructured polymers are polymers that have been engineered at the nanoscale to enhance their physical, chemical, and mechanical properties (Ma et al., 2010). These materials are designed to provide more effective and controlled seed coating, offering better protection and improved performance.

6.1 Polymeric Nanostructures for Seed Coating

Nanostructured polymers can be used to encapsulate nutrients, fertilizers, and pesticides for slow-release applications. Polymeric nanocapsules and nanocapsules-based polymers are designed to deliver controlled amounts of these compounds over time, reducing the need for frequent reapplication. This feature helps in minimizing environmental pollution while enhancing seedling growth (Baruah and Dutta, 2009).

- **Nanostructured Polymeric Films:** Polymeric films made from materials like polyvinyl alcohol (PVA) or polylactic acid (PLA) can be combined with nanoparticles for a strong, protective coating around seeds. These films offer excellent moisture retention properties, protect seeds from physical damage, and control the release of encapsulated nutrients and agrochemicals (Hidalgo et al., 2017).

6.2 Benefits of Nanostructured Polymers in Seed Coatings

Nanostructured coatings significantly enhance seed performance by providing a robust barrier against pests, pathogens, and extreme environmental conditions, thereby ensuring improved seed protection. These coatings incorporate polymers such as chitosan, PLA, and PVA, which enable the controlled release of nutrients, offering consistent support to seeds during their early growth stages. Additionally, the use of nanostructured polymers enhances seedling vigor by improving water absorption and nutrient uptake from the surrounding soil, fostering healthier and more resilient plant development.

6.3 Nano-Coatings Interaction with the Seed Surface to Promote Germination

Seed germination is a crucial phase in plant development. The process involves the absorption of water, activation of metabolic pathways, and initiation of cell division and growth. Nano-coatings play an essential role in optimizing these processes by improving the interactions between the seed and its surrounding environment, promoting better germination rates and seedling establishment.

1. **Nano-coating Interaction with the Seed Surface:**
   Nano-coatings are typically composed of nanomaterials such as metals, carbon-based nanoparticles, polymers, and bio-based materials, which form a thin, uniform layer around the seed. This coating interacts with the seed surface in several ways:

a. **Increased Surface Area for Water Absorption:** Nano-coatings significantly increase the surface area of seeds. This is particularly important for water absorption during the initial stages of germination. Nanoparticles like carbon nanotubes (CNTs) or graphene oxide (GO) increase the seed's hydrophilicity, enhancing water uptake (Chakraborty et al., 2020). The more hydrophilic the coating, the more effectively the seed can absorb water from the environment, which accelerates the germination process.

b. **Improved Oxygen Exchange and Gas Permeability:** The nano-coatings can also improve the gas exchange between the seed and the surrounding environment. For example, **graphene oxide** has a porous structure that allows for better oxygen diffusion, which is critical for the metabolic processes required during seed germination (Sharma et al., 2019).

c. **Encapsulation of Growth Regulators and Nutrients:** Nanomaterials used in coatings can encapsulate growth regulators (like gibberellins) or nutrients (e.g., nitrogen, phosphorus, potassium) in a controlled-release manner. These compounds gradually release their contents, providing essential growth factors that facilitate better seed germination and early growth stages (Prasad et al., 2017). This ensures that the seed receives a steady supply of nutrients, even if soil conditions fluctuate.

6.4 Promotion of Germination

Nano-coatings facilitate germination by promoting efficient water uptake, providing physical protection against mechanical damage, and even modulating the seed's biochemical environment (Singh et al., 2023b). Additionally, zinc oxide (ZnO) nanoparticles, for example, have been found to enhance seed germination by stimulating enzymatic activities that are essential for early seedling development (Zhao et al., 2015). This combination of enhanced water retention and nutrient provision enables the seed to transition into a healthy, strong seedling.

6.5 Role of Nanomaterials in Water Retention, Nutrient Uptake, and Disease Resistance

Nanomaterials used in seed coatings not only help in the initial stages of seed germination but also enhance the seed's ability to survive under varying environmental conditions by improving water retention, nutrient uptake, and disease resistance (Ditta, 2012).

- **Water Retention:** One of the key challenges in agriculture, particularly in arid regions, is water scarcity. Nano-coatings can significantly improve the seed's ability to retain water, thus improving the seed's resilience to drought and optimizing germination and early growth. For instance, nanomaterials like hydrogels and graphene oxide are known to enhance water retention. These nanomaterials absorb large amounts of water and release it slowly, ensuring a continuous supply of moisture to the seed during its critical early growth phase.
- **Graphene oxide (GO)**: It has been demonstrated to significantly improve water retention in seeds by creating a hydrophilic surface that attracts water molecules and retains moisture within the seed coating. By controlling the release of water into the seed, the coating reduces the risk of water stress, especially during the germination and early stages of seedling growth.
- **Nutrient Uptake:**
  Nanomaterials in seed coatings can enhance nutrient uptake by improving the seed's interaction with the soil, enabling better absorption of nutrients such as nitrogen, phosphorus, and potassium. Nanoparticles like zinc oxide (ZnO) and silicon nanoparticles are known to improve nutrient uptake by stimulating root growth and enhancing the efficiency of nutrient absorption from the soil. For example, ZnO nanoparticles have been shown to activate enzymes involved in nitrogen and phosphorus metabolism, promoting better nutrient utilization during germination (Chakraborty et al*.,* 2018). Similarly, silicon nanoparticles have been reported to improve phosphorus uptake by stimulating root activity and facilitating better nutrient mobilization in the soil (Ma et al*.,* 2020).
- **Disease Resistance:**
  Seed-borne diseases are a major challenge in agriculture, particularly fungal and bacterial infections. Nanoparticles, such as silver (AgNPs), copper oxide (CuO), and titanium dioxide (TiO_2), have strong antimicrobial properties that help prevent seed and seedling infections caused by pathogens such as *Fusarium*, *Pythium*, and *Rhizoctonia*. When incorporated into seed coatings, these nanoparticles form a protective barrier that inhibits the growth of microorganisms on the seed surface, thereby reducing the incidence of seed-borne diseases.
- **Silver nanoparticles (AgNPs)**: Silver particles disrupt microbial cell membranes, preventing fungal and bacterial infections and promoting healthier seedling development. Additionally, TiO_2 nanoparticles possess antifungal properties and can protect seeds from soil-borne pathogens, contributing to better seedling survival rates.

6.6 Impact of Nano-Coatings on Seed Hydration and Early Root Development

Hydration is one of the first and most critical processes that influence seed germination. Nano-coatings can help manage seed hydration by improving the seed's ability to absorb and retain water while also protecting the seed from external stressors. In addition, nano-coatings can significantly influence early root development, which is crucial for establishing healthy seedlings (Bouwmeester et al., 2009).

6.6.1 Seed hydration

Hydration is the process by which seeds absorb water, triggering metabolic processes that lead to germination. Nano-coatings improve hydration by enhancing the seed's water uptake efficiency. Hydrophilic nanomaterials such as graphene oxide and chitosan-based nanoparticles attract water molecules, facilitating seed hydration and improving seedling growth under conditions where water availability is limited.

- **Graphene oxide (GO)** has shown significant potential in improving the water retention of seed coatings. GO can absorb water into its structure and then release it slowly, providing a constant supply of moisture to the seed during the germination process (Chakraborty et al*.,* 2020). This slow-release mechanism reduces the risk of dehydration, particularly in dry soils or during the early stages of seedling growth.
- **Chitosan-based nanoparticles**, which are biodegradable and nontoxic, have also been used to enhance water retention in seed coatings. Chitosan has hydrophilic properties, allowing it to bind with water molecules and retain moisture in the

coating, which can help seeds germinate more quickly and uniformly.

6.6.2 Early root development

The initial stages of root growth are critical for seedling establishment. Nano-coatings can influence early root development by enhancing the seed's interaction with the surrounding soil and improving nutrient and water uptake. Nanoparticles such as **silicon nanoparticles** and **zinc oxide (ZnO)** have been found to promote root growth and increase root length, which is essential for seedling establishment.

- **Silicon nanoparticles (SiNPs)** are known to improve root elongation and increase root surface area, which enhances the seedling's ability to absorb nutrients and water from the soil. SiNPs also promote cell division and elongation in the root system, ensuring that the seedling establishes a strong foundation for further growth.
- **Zinc oxide (ZnO)** nanoparticles also stimulate early root development by promoting cell division and increasing root biomass. ZnO nanoparticles can activate various enzymes involved in the synthesis of proteins and nucleic acids, which are essential for root development (Chakraborty et al*.,* 2018).

6.7 Effects of Nano-Coatings on Germination Rates and Seedling Vigour

6.7.1 Improvement in germination rates

The germination of seeds is a complex physiological process influenced by a variety of internal and external factors. Water availability, oxygen supply, temperature, and the presence of growth inhibitors or pathogens all play key roles in determining the success of seed germination. Nano-coatings can positively impact each of these factors, thereby improving germination rates.

1. **Water Uptake and Hydration:** One of the most significant impacts of nano-coatings on seed germination is their ability to enhance water uptake and seed hydration. Hydrophilic nanomaterials such as **graphene oxide (GO)**, **zinc oxide (ZnO)**, and **chitosan nanoparticles** attract water molecules, allowing seeds to hydrate more efficiently (Sharma et al*.,* 2015). Water absorption is essential for the activation of metabolic processes in seeds, and faster hydration can lead to quicker and more uniform germination, especially in soils with low moisture content. Graphene oxide (GO) coatings, for example, create a hydrophilic interface that helps seeds retain moisture longer, reducing the risk of dehydration during the early stages of germination. This results in improved germination rates under both normal and drought conditions.
2. **Controlled Release of Nutrients and Growth Regulators:** Nano-coatings can also serve as carriers for essential nutrients, growth regulators, or biocontrol agents, which are gradually released during seed imbibition and early growth stages. By providing a continuous supply of nutrients like nitrogen, phosphorus, and potassium, or growth hormones such as gibberellins, nano-coatings create an optimal environment for seedling emergence (Prasad et al*.,* 2017). This controlled release ensures that seeds have the necessary resources for germination without the risk of nutrient imbalances, which can delay or hinder growth.

   Zinc oxide (ZnO) nanoparticles have been shown to stimulate the production of enzymes involved in seed metabolism, which can enhance the breakdown of stored starches and proteins, thereby speeding up germination (Chakraborty et al*.,* 2018). The release of nutrients such as zinc can also promote seedling vigour and improve early root growth.

6.7.2 Seedling vigour and growth

In addition to improving germination rates, nano-coatings also contribute to seedling vigour. Seedling vigour refers to the rapid establishment and development of healthy seedlings that can efficiently absorb nutrients and water. Nano-coatings provide several benefits to seedling growth:

- **Enhanced Root Development:** Early root development is critical for seedling establishment. Nano-coatings can stimulate root growth by enhancing water uptake and promoting the activity of plant hormones such as auxins. **Silicon nanoparticles (SiNPs)**, for example, have been shown to increase root length and surface area, which improves nutrient absorption and water retention (Zhao et al., 2016). The enhanced root system also helps seedlings establish more effectively in the soil.

- **Stress Tolerance:** Nano-coatings can increase the resilience of seedlings to abiotic stresses such as drought, heat, and salinity. The controlled release of nutrients and growth hormones supports seedling development during stressful conditions. **Silver nanoparticles (AgNPs)**, for example, possess antimicrobial properties, which protect seedlings from diseases, allowing them to grow more vigourously under adverse conditions.

7. NANO-SEED COATINGS FOR SEEDLING ESTABLISHMENT UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

7.1 Seedling Establishment Under Water Stress (Drought Conditions):

Water scarcity is one of the most critical challenges faced by agriculture, especially in arid and semi-arid regions. Nano-seed coatings can improve seedling establishment under drought conditions by enhancing water retention and reducing water loss from the seed surface.

- **Hydrophilic Nanomaterials for Water Retention: Graphene oxide (GO)** and **chitosan-based nanomaterials** can increase the water retention capacity of the seed, allowing it to stay hydrated longer during the germination process. These nanomaterials absorb and retain water, creating a moisture reservoir around the seed that can be gradually released as the seed requires it. This mechanism is especially beneficial in water-limited environments, where seeds need to be able to tolerate periods of low water availability.
- **Improved Root Development:** Seedlings facing water stress often struggle with inadequate root development. By promoting root elongation and enhancing root surface area, nano-coatings like **silicon nanoparticles** help seedlings access deeper soil layers, where water may be more available. This leads to improved drought tolerance.

7.2 Seedling Establishment Under Salinity Stress

Soil salinity is another environmental stressor that impedes seedling establishment. High salt concentrations can damage plant cells, inhibit water uptake, and restrict nutrient absorption. Nano-coatings can help mitigate the effects of salinity stress by improving seedling tolerance to saline conditions.

- **Enhanced Osmotic Regulation: Polymeric nanoparticles** such as **chitosan** can enhance the osmotic regulation of seeds, which helps seedlings maintain cellular hydration under saline conditions. By improving the seed's ability to regulate water and solute balance, these coatings help seedlings adapt to high salinity (Hernández et al., 2019).
- **Antioxidant Activity:** Nanoparticles like **zinc oxide (ZnO)** and **silicon (Si)** have been shown to increase antioxidant enzyme activity in plants, which helps mitigate the oxidative stress caused by high salinity. These nanoparticles stimulate the production of reactive oxygen species (ROS) scavengers, which protect seedling cells from salt-induced damage (Chakraborty et al., 2018).

7.3 Seedling Establishment Under Temperature Extremes (Heat or Cold Stress)

Temperature extremes, both heat and cold, can hinder seed germination and seedling growth. Nano-coatings help maintain seedling vigour under these conditions by stabilizing physiological processes.

- **UV Protection and Temperature Tolerance: Titanium dioxide (TiO_2)** nanoparticles have been shown to provide UV protection for seeds, preventing damage caused by ultraviolet light. Additionally, TiO2 nanoparticles can absorb excess heat, protecting seeds and seedlings from thermal stress. By regulating temperature fluctuations around the seed, nano-coatings help seedlings establish more effectively in regions with extreme temperatures.
- **Improved Seedling Tolerance to Heat and Cold Stress:** The controlled release of nutrients, growth regulators, and antioxidants by nano-coatings can also

enhance seedling resilience to heat and cold stress. Nanomaterials such as **silver nanoparticles (AgNPs)** have been shown to mitigate temperature-induced oxidative stress, supporting seedling growth even under suboptimal thermal conditions.

7.4 Vegetable Seeds that are benefitted from Enhanced Germination through Nano-Coatings

Certain vegetable seeds have shown particularly promising results when coated with nanomaterials, leading to enhanced germination and seedling vigour (Kumar et al., 2023). Some examples of these vegetables include:

a) Tomato (*Solanum lycopersicum*):

- **Nano-coatings** containing ZnO and AgNPs have been shown to improve tomato seed germination rates and reduce seed-borne diseases such as fungal infections. These coatings protect the seeds from pathogens while enhancing early root and shoot development (Lee et al., 2020).

b) Lettuce (*Lactuca sativa*):

Lettuce seeds benefit from graphene oxide (GO) coatings that enhance water uptake and improve germination under low-water conditions (Alvi et al., 2021). Additionally, these coatings improve seedling growth by supplying nutrients like nitrogen and phosphorus, which are crucial for early development.

c) Cucumber (*Cucumis sativus*):

- Chitosan nanoparticles have been successfully used to coat cucumber seeds, improving germination rates and seedling growth under various environmental conditions, including heat stress (Johnson et al., 2022). Chitosan also provides antimicrobial benefits, reducing the risk of fungal infections in cucumber seedlings (Prasad et al., 2017).

d) Carrot (*Daucus carota*):

- **Silicon nanoparticles** have been used to coat carrot seeds, enhancing germination under saline conditions. The nanoparticles promote better root development, allowing carrot seedlings to better tolerate soil salinity.

8. NANOCOATING TECHNIQUES AND APPLICATION METHODS

Nanotechnology has revolutionized multiple industries, including healthcare, electronics, automotive, and energy. One of its critical applications is nanocoating, a process where nanoscale materials are applied to surfaces to enhance properties such as durability, water repellence, UV resistance, and anti-corrosion (Li and Gao, 2019). This article explores nanocoating techniques and application methods, focusing on their principles, advantages, and practical uses (Chen et al., 2014).

Nanocoatings are thin films applied at the nanoscale level, typically ranging between 1 and 100 nanometers. These coatings are designed to modify the surface properties of materials without altering their bulk properties significantly (Greer and Street, 2011). Their application leverages the unique characteristics of nanoparticles, such as a high surface area-to-volume ratio and distinct chemical reactivity.

8.1 Key Nanocoating Techniques

Chemical Vapor Deposition (CVD) is a versatile process where gaseous precursors chemically react on a substrate to form solid coatings, commonly used in semiconductor manufacturing and for creating wear-resistant layers on cutting tools. It produces uniform coatings that adhere well to the substrate and is applied in anti-corrosion layers, optical coatings, and wear-resistant films. Physical Vapor Deposition (PVD) involves vaporizing materials in a vacuum and depositing them as thin films on substrates, creating dense and durable coatings for hard tools, decorative finishes, and optical layers. Sol-Gel Coating is an environmentally friendly, cost-effective liquid-phase process used to create nanocoatings like anti-reflective coatings, thermal insulation, and hydrophobic surfaces. Electrochemical Deposition uses electrochemical reactions for precise thickness control, making it suitable for corrosion-resistant coatings and biomedical devices. Spray Coating, a low-cost and scalable method, is used for self-cleaning surfaces, hydrophobic coatings, and anti-graffiti layers. Spin Coating, often used in microfabrication, produces highly uniform coatings for optical films, electronic components, and biosensors. Dip Coating is a simple, cost-effective method used for anti-corrosion layers and water-repellent surfaces. Layer-by-Layer (LbL) Assembly offers excellent control over thickness and composition, useful in biomedical devices and sensors. Atomic Layer Deposition (ALD) allows atomic-level thickness control for semiconductor devices and protective barriers, while Plasma Spraying, using a plasma jet, creates strong, durable coatings for thermal barriers, wear-resistant layers, and medical implants (Kumar and Das, 2022disease).

8.2 Application Methods of Nanocoatings

Nanocoatings are applied using various techniques tailored to specific needs and scales. Manual application methods, such as brushes, rollers, or sponges, are cost-effective for small-scale projects. Automated systems, including robotic arms and specialized machines, are widely used in industrial settings to ensure consistent and efficient application (Basnet et al., 2022; Meena et al., 2021). Advanced methods like vacuum deposition chambers, including CVD, PVD, and ALD, rely on controlled environments to achieve precise coatings. Electrostatic spraying enhances efficiency by attracting nanoparticles to the substrate, while thermal spraying uses molten material for deposition. Post-application processes like UV or heat curing improve adhesion and durability, and roll-to-roll processing is ideal for continuous application on flexible substrates like films and textiles (Kumar et al., 2019).

Nanocoatings have diverse applications across industries. In the automotive sector, they enhance vehicle aesthetics, provide scratch resistance, and improve fuel efficiency by reducing drag. Electronics benefit from protective coatings that shield components from moisture, dust, and corrosion, extending their lifespan. In healthcare, antimicrobial nanocoatings are used in surgical instruments, implants, and hospital surfaces to prevent infections. The construction industry utilizes nanocoatings for self-cleaning properties, UV protection, and thermal insulation, while aerospace components achieve better fuel efficiency and durability with lightweight coatings. Energy applications include solar panels and wind turbines, where nanocoatings enhance efficiency and longevity.

8.3 Regulatory Aspects and Safety Concerns in Nanotechnology for Agriculture

Nanotechnology has emerged as a transformative field with promising applications in agriculture, including pest control, nutrient delivery, and seed enhancement. However, its adoption in the agricultural sector is not without challenges, especially concerning regulation, safety, and public perception. This document explores the regulatory challenges, safety assessments, and risk management practices related to nanotechnology in agriculture, with a specific focus on nano-seed coatings (Bhagat et al., 2022).

8.4 Regulatory Challenges for Nanotechnology in Agriculture

Nanotechnology in agriculture poses unique regulatory challenges due to the novelty and complexity of nanoscale materials (Gupta et al., 2020). Regulatory frameworks must address several concerns:

Lack of Standardized Definitions: Globally, there is no universal definition of nanomaterials, which complicates regulatory processes (Amenta et al., 2015). For instance, the European Union (EU) defines nanomaterials based on size, but the criteria may vary in other regions, leading to inconsistencies in regulation (EFSA, 2018). Evaluation of Novel Properties: Nanomaterials exhibit distinct physical and chemical properties compared to their bulk counterparts. These properties may influence their environmental behavior and interaction with biological systems, requiring unique risk assessment protocols (Kah et al., 2018). Cross-Jurisdictional Challenges: Nanotechnology often falls under multiple regulatory jurisdictions, including environmental, health, and food safety authorities. Coordination among these bodies is essential to ensure comprehensive oversight. Evolving Guidelines: Regulatory agencies, such as the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA), are continually updating guidelines to address nanotechnology's risks. However, the rapid pace of innovation often outstrips the regulatory updates.

8.5 Safety Assessments for Nanomaterials in Food Production

Nanomaterials are increasingly incorporated into agricultural inputs, such as fertilizers, pesticides, and seed coatings, to improve efficiency and sustainability. Safety assessments are critical to ensuring their safe use in food production systems. Toxicity Testing: Assessing the toxicity of nanomaterials involves evaluating their size, shape, surface area, and reactivity. Studies suggest that these properties influence nanomaterials' bioavailability and toxicity in plants, animals, and humans (Buzea et al., 2007; Sahoo et al., 2007). The persistence, degradation, and bioaccumulation of nanomaterials in soil and water systems are critical factors in safety assessments. Research highlights potential risks, such as the unintended accumulation of nanoparticles in edible plant parts (Servin et al., 2015). Agencies mandate comprehensive data on nanomaterials' safety. For example, EFSA requires detailed characterization, exposure assessment, and toxicological data for food-related applications (EFSA, 2018). Traditional toxicity assays may not fully capture nanomaterials' effects, necessitating the development of nanospecific testing protocols.

8.6 Risk Assessments and Public Perception of Nano-Seed Coatings

Nano-seed coatings have emerged as a promising application of nanotechnology in agriculture, offering enhanced germination, pest resistance, and stress tolerance. However, their adoption raises questions about risks and public acceptance. Comprehensive risk assessments for nano-seed coatings involve evaluating potential exposure pathways, including soil leaching, plant uptake, and trophic transfer in ecosystems. Concerns include the potential for nanomaterials to alter soil microbiomes, affect non-target organisms, and disrupt ecological balance.

Public Perception: Public concerns about nanotechnology often stem from a lack of understanding and perceived risks. Transparent communication about the benefits and risks of nano-seed coatings is essential to gain public trust (Falkner, 2010). Ethical debates around nanotechnology focus on environmental justice, equitable access, and the potential monopolization of technologies by large corporations (Bawa & Anilakumar, 2013).

9. FUTURE PROSPECTS AND INNOVATIONS IN NANO SEED COATING

9.1 Advances in Nano-Material Design for Specific Stress Tolerances

The agricultural sector faces growing challenges due to climate change, including increased heat waves, drought conditions, and unseasonal frost. Nano seed coating represents a transformative approach to mitigating these issues by enhancing seed resilience through tailored nano-materials. Recent advancements in nano-material science focus on creating particles that can address specific environmental stresses (Kah and Hofmann, 2014).

- **Heat Tolerance:** Thermo-responsive nanoparticles are being developed to modulate water retention and enhance seed metabolism under high temperatures. For example, hydrogels incorporated with nanoparticles can regulate seed microenvironments to prevent desiccation.
- **Cold Tolerance:** Encapsulation with antifreeze proteins and nanoparticles helps seeds endure suboptimal germination temperatures. Studies have demonstrated the ability of silica-based coatings to provide insulation during cold spells.
- **Drought Tolerance:** Engineered nanoparticles, such as those functionalized with superabsorbent polymers, significantly improve water uptake (Mukherjee and Senapati, 2016). Nanoclay composites are also promising, as they enhance soil-seed water dynamics and provide sustained hydration.

  These advancements signify a leap towards custom-designed seed coatings that align with regional agro-climatic requirements, supporting sustainable agricultural practices in challenging environments (IUPAC, 2020).

9.2 Potential of Precision Agriculture and Smart Coatings for Site-Specific Seed Enhancement

Precision agriculture integrates cutting-edge technologies, including nano seed coatings, to optimize crop productivity with minimal resource input. Smart coatings embedded with nanosensors are revolutionizing site-specific seed enhancement, ensuring precise delivery of nutrients and other growth-promoting agents (Sant and Carpenter, 2021).

- **Controlled Release Mechanisms:** Smart nano-coatings are engineered to release active compounds, such as fertilizers or pesticides, in response to environmental cues like soil pH or moisture levels. For instance, zinc oxide nanoparticles improve micronutrient availability to seeds, enhancing growth under nutrient-deficient conditions (Mehta and Gupta, 2021).
- **Data Integration:** Coatings integrated with nanosensors enable real-time monitoring

of soil and seed conditions. This data can guide farmers in making timely interventions, optimizing resource use, and improving yields (Chhipa and Joshi, 2016).

- **Environmental Sustainability:** Smart coatings reduce chemical runoff, preserving soil health and preventing groundwater contamination. Such innovations align with global goals of sustainable agricultural intensification (Alam et al., 2022).

  By bridging nanotechnology and precision agriculture, these innovations empower farmers with tools for adaptive and efficient farming in diverse landscapes.

10. ROLE OF GENETIC ENGINEERING IN CONJUNCTION WITH NANO-COATINGS FOR OPTIMIZED PERFORMANCE

Genetic engineering and nano-coatings are synergistic technologies that have the potential to redefine seed performance. While genetic engineering enhances the inherent qualities of seeds, such as pest resistance or drought tolerance, nano-coatings provide an external layer of protection and functionality. Genetically modified seeds with these traits can be further strengthened by nano-coatings for added robustness (Ahamed et al., 2010). Nano-carriers are also being explored for the targeted delivery of gene-editing tools, like CRISPR-Cas systems, directly into seeds. This precise method reduces off-target effects and accelerates trait development. Additionally, nano-coatings are being studied for their role in improving hybrid seed production by incorporating growth regulators or pollen inhibitors. This dual approach ensures more efficient resource utilization and offers solutions to global challenges, including food security and climate change resilience (FAO, 2022).

10.1 Challenges and Limitations of Nano Seed Coatings

The application of nanotechnology in agriculture has seen remarkable advances, with nano seed coatings being one of the promising innovations. These coatings aim to enhance seed performance by delivering nutrients, agrochemicals, or other functional agents directly to seeds (Jangir et al., 2021). However, like any technology, nano seed coatings face significant challenges and limitations that need to be addressed before large-scale adoption (Das and Sen, 2023). Below, we discuss the primary challenges, including the potential toxicity and ecological impacts of nanomaterials, high production costs, scalability issues, and concerns about long-term effects on soil health and plant microbiomes.

10.2 Potential Toxicity and Ecological Impacts of Nanomaterials

One of the foremost concerns surrounding nano seed coatings is the potential toxicity of the nanomaterials used. Engineered nanoparticles, while beneficial for seed enhancement, can inadvertently leach into the soil and water systems. Studies suggest that some nanoparticles may be toxic to soil-dwelling organisms, aquatic life, and plants themselves. For example, metal-based nanoparticles like silver and zinc oxide have shown antimicrobial properties that can disrupt beneficial soil microbial communities essential for nutrient cycling and plant growth. Moreover, nanoparticles can accumulate in ecosystems, leading to unforeseen ecological consequences. The lack of comprehensive toxicological data makes it challenging to predict how these materials interact with various environmental matrices, such as soil organic matter and water bodies. For instance, carbon-based nanomaterials, though considered less toxic than their metal counterparts, can still alter soil structure and water infiltration patterns when used excessively.

10.3 High Production Costs and Scalability Issues

Another limitation of nano seed coatings is their high production cost. Manufacturing nanoparticles with precise specifications requires sophisticated equipment, extensive energy input, and high-quality raw materials, which collectively inflate costs. Techniques like chemical vapor deposition (CVD) or laser ablation, commonly employed in nanoparticle synthesis, are resource-intensive and may not be viable for large-scale agricultural applications. Scalability is another significant hurdle. While laboratory-scale production and application of nano seed coatings have shown promising results, transitioning these processes to field-scale operations presents logistical and economic challenges. Farmers, particularly in developing countries, may find these technologies inaccessible due to their expense. Additionally, ensuring uniform coating on a large number of seeds while maintaining functional properties of nanoparticles is a technical challenge yet to be fully resolved.

10.4 Long-Term Effects on Soil Health and Plant Microbiomes

The long-term impact of nano seed coatings on soil health and plant-associated microbiomes is poorly understood. Many nanoparticles remain persistent in soils for extended periods, potentially altering the chemical and physical properties of the soil. This persistence can influence the diversity and function of soil microbiota, which play a crucial role in nutrient availability, organic matter decomposition, and overall soil fertility. Nano seed coatings could potentially create imbalances in plant-microbe interactions. For example, nanoparticles that inhibit pathogenic microbes might also affect symbiotic relationships, such as those between legumes and nitrogen-fixing bacteria (Rhizobia). Furthermore, the effects of nano seed coatings on microbial resistance are a growing concern. Prolonged exposure to sub-lethal concentrations of nanoparticles could lead to the evolution of resistant strains, akin to antibiotic resistance observed in pathogenic bacteria.

11. MARKET POTENTIAL AND ECONOMIC IMPLICATIONS OF NANO-ENHANCED SEEDS

11.1 The Growing Market for Nano-Enhanced Seeds and Their Commercial Viability

The global agricultural industry is undergoing a transformative phase, driven by advancements in nanotechnology. Nano-enhanced seeds are emerging as a promising innovation that combines nanomaterials with traditional seed technologies to improve germination rates, nutrient efficiency, pest resistance, and stress tolerance. The market for nano-enhanced seeds is poised for significant growth, fueled by the increasing demand for sustainable agricultural practices and the need to address challenges like food security and climate change (Bartal and Finkelstein, 2017). According to market reports, the global nanotechnology in agriculture market is expected to grow at a compound annual growth rate (CAGR) of approximately 12% between 2021 and 2030, with seeds being a major segment of this growth. The integration of nanotechnology into seed coatings or delivery systems enhances seed performance, making it attractive to both large-scale agribusinesses and smallholder farmers. Additionally, the adoption of nano-enhanced seeds aligns with government initiatives worldwide to promote sustainable agriculture. These seeds are gaining traction in regions with unfavorable growing conditions, as they offer improved resilience to abiotic stresses like drought and salinity. Their commercial viability is further strengthened by ongoing research and development investments from both private companies and public institutions.

11.2 Economic Advantages for Farmers

Nano-enhanced seeds offer significant economic benefits to farmers, making them a viable option in modern agriculture. These seeds are engineered to optimize nutrient uptake, leading to better plant growth and higher yields. For example, seeds coated with nano-fertilizers deliver essential nutrients more efficiently than conventional fertilizers (Dimkpa and Bindraban, 2018; Srivastava and Singh, 2022). Additionally, the precise delivery of nutrients and pesticides through nano-enhanced systems reduces the quantity of inputs required, allowing farmers to save on fertilizers and pesticides, thus lowering overall production costs. Nano-enhanced seeds are also designed to withstand environmental stresses such as drought, heat, and salinity, minimizing crop losses and ensuring a more stable income. Furthermore, seeds treated with nanomaterials often exhibit extended storage stability, reducing financial losses from seed spoilage. A case study in India demonstrated that smallholder farmers using nano-enhanced seeds for rice cultivation experienced a 20-30% increase in yield and a 15% reduction in fertilizer usage. These outcomes emphasize the economic viability of this technology, especially for resource-constrained farming communities.

11.3 Consumer Acceptance and Market Demand for Nano-Enhanced Vegetable Products

The consumer market is increasingly focused on sustainability and health. Nano-enhanced seeds contribute to the production of high-quality vegetables with improved nutritional content, reduced pesticide residues, and extended shelf life, aligning with consumer preferences for safe and sustainable food products (Mittal et al., 2023). However, the acceptance of nano-enhanced vegetable products hinges on transparent communication and stringent regulatory frameworks. Studies indicate that consumers are willing to pay a premium for vegetables grown using advanced agricultural technologies if these products are demonstrated to be safe and environmentally friendly (Wang et al., 2016). The market demand is also driven by urbanization and the growing middle-class population, particularly in developing countries. With increased awareness of food security and sustainable practices, nano-enhanced products are likely to find a substantial consumer base in regions such as Asia-Pacific and Latin America.

12. CONCLUSION

Nano-enhanced seeds represent a significant leap forward in agricultural technology, offering a blend of economic, environmental, and societal benefits. Their market potential is vast, driven by the dual imperatives of sustainability and productivity. By addressing current challenges and leveraging the advantages of this technology, stakeholders can unlock the full potential of nano-enhanced seeds, contributing to global food security and economic prosperity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/128741