Opinion Article

Nanotechnology in Agriculture: Enhancing Seed Quality, Yield and Contribution to Sustainable Development Goals (SDGs)

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ABSTRACT

Applications of nanotechnology have the potential to transform agricultural production by enabling improved conservation and management of plant and animal production inputs. The primary input that determines a crop's productivity is seed. Currently, a team of researchers is focusing on carbon nanotubes and metal oxide nanoparticles to enhance rainfed crop germination. Numerous ecosystems are linked to agricultural practices, and nanomaterials may have a direct influence on them. The industrial manufacture of these technological systems and their field use present a number of challenges, such as scale-up, seed priming conditions, and harmful effects on plants and other creatures. Nonetheless, it is evident that the use of nanoparticle systems can change crop management by lowering the amounts of pesticides used and the dangers of contamination, leading to safer farming methods for farmers, consumers, and the environment. In this case study analysis, the potential processes by which nano-priming triggers breaking seed dormancy, promotes seed germination, and affects the generation of primary and secondary metabolites are described in depth. Furthermore, taking into account their current status and potential future developments, the application of nano-based fertilizers and insecticides as efficient materials in nano-priming and plant growth development was also covered. Nanotechnology is emerging as a transformative technology in agriculture, especially in enhancing seed quality and increasing crop yield. By leveraging nanomaterials such as carbon nanotubes, metal oxide nanoparticles, and other forms, nanotechnology can revolutionize the way crops are grown, providing solutions for challenges like poor seed germination, resource inefficiency, and environmental degradation. This technological advancement directly aligns with the achievement of several United Nations Sustainable Development Goals (SDGs), contributing to a more sustainable and productive agricultural system.

Keywords: Nanotechnology, seed, quality, dormancy, yield and SDGs.

INTRODUCTION

Nano means 10^{-9} meter. The size of the particle used in nanotechnological applications will be from one to 100nm with one or multiple dimensions. Nanotechnology, defined by the manipulation of materials at the nanometer scale (1-100 nm), holds great promise for improving agricultural production, particularly in enhancing seed quality and crop yield. Prior to seed treatment, the priming conditions must be assessed, taking into account the size and concentration of the nanoparticles as well as the length of exposure, as these elements may result in adverse effects like decreased plant development and inhibition of germination. Nonetheless, there are a number of benefits to using nanoparticles for seed treatment. When seeds are treated, less nanomaterial exposure occurs than when foliar and soil treatments are used. The low amounts of nanoparticles used for seed treatments, which companies can manage to prevent a high release of these elements into the environment, is another advantage. Although there will likely be very little or no nanoparticle residue in plants, research is still required to clarify the ways in which various nanoparticles, such as metallics, metallic biogenics, and polymerics, affect plant development. By leveraging nanomaterials such as carbon nanotubes, metal oxide nanoparticles, and other forms, nanotechnology can revolutionize the way crops are grown, providing solutions for challenges like poor seed germination, resource inefficiency, and environmental degradation. This technological advancement directly aligns with the achievement of several United Nations Sustainable Development Goals (SDGs), contributing to a more sustainable and productive agricultural system.

Nanotechnology's Role in Seed Treatment and Crop Management

One of the key applications of nanotechnology in agriculture is **seed priming** or **seed treatment**, where nanoparticles are used to enhance seed germination, growth, and resistance to environmental stresses. Here’s how nanotechnology helps in this area:

1. ***Improved Seed Coatings***

   - **Nanomaterials for Seed Protection**: Seed coatings have long been used to protect seeds from environmental stress, pathogens, and pests. The incorporation of nanoparticles (such as silica, titanium dioxide, or zinc oxide) into these coatings enhances seed durability and protection. These nanoparticles can provide controlled release of fertilizers and pesticides, reducing environmental impact while improving seedling vigor. Eevera *et al.,*2023 reported that eco-friendly seed treatment strategies are possible by nano material seed treatments.

2. ***Enhanced Germination Rates****:* Nanotechnology-based coatings can help in improving water retention in the seed, which is crucial for better germination. Some nanoparticles have also been shown to improve seedling emergence by facilitating better root development. Using nanoparticles or nanomaterials for seed treatment is one example of a technology that can boost seedling growth and yield, which can lead to successful farming and high productivity (Shelar *et al.,* 2023). Mahakham *et al*.,(2017), reported that rice seeds primed with photosynthesised nanoparticles shows enhanced seed germination. The enhanced seedling growth in onion was observed in green synthesised nanoparticles treated seeds by Acharya *et.,al*. 2019. Anandaraj et al., 2018 reported that among ZnO, Ag, CuO and TiO2Nanoparticles, application of nanoparticles ZnO @ 1000mg kg-1 seed improved germination and related physiological parameters in onion cv.CO (On) 5 seeds.

   - **Targeted Nutrient Delivery**: Nanoparticles can act as carriers for micronutrients and growth regulators. For instance, nano-sized fertilizers or hormones can be loaded into the seed coating and released gradually, ensuring the seedling gets the necessary nutrients at the right time, optimizing growth. Santana *et al.,* 2020, explained the possibilities of targeted delivery of nanomaterials in plants. (Fig.1)

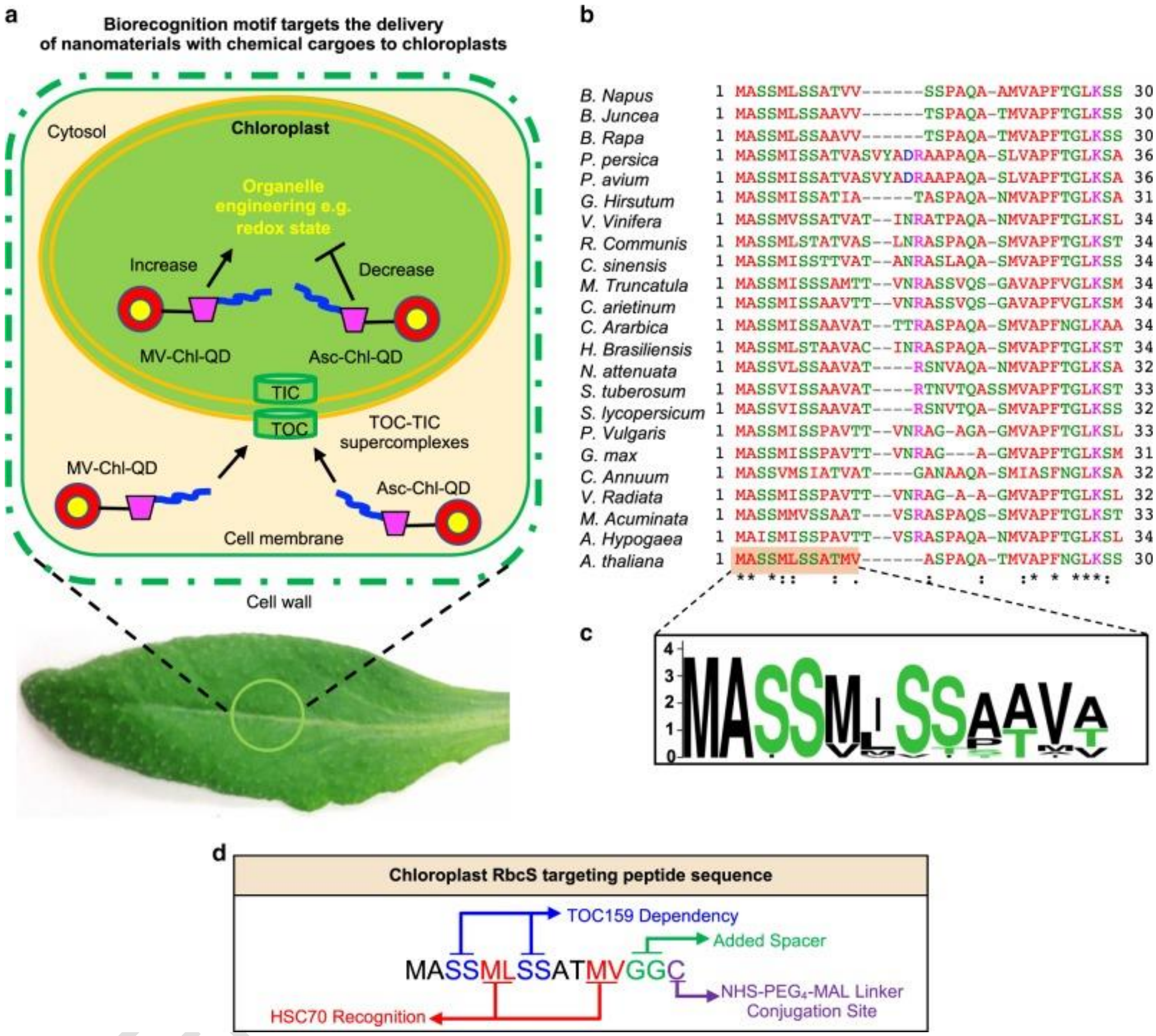

Fig. 1. Targeted delivery of nanomaterials with chemical cargoes in plants enabled by

a biorecognition motif.

(a Quantum dots coated with a chloroplast guiding peptide (in blue) and a β-cyclodextrin (β-CD) molecular basket (in magenta) enable loading of methyl viologen (MV-Chl-QD) or ascorbic acid (Asc-Chl-QD) and targeted modification of the redox status of chloroplasts in planta. The Rubisco small subunit (RbcS) targeting peptide is designed to bind to the translocon supercomplex on the chloroplast outer membrane (TOC). b Multiple sequence alignment analysis (Clustal Omega) of RbcS 1 A chloroplast transit peptide sequences in common dicot crops and Arabidopsis thaliana plants. Asterisk indicates the identical amino acids among all the aligned sequences. Colon and dot indicate conserved substitutions in which an amino acid is replaced by another one with similar properties. Empty space represents a non-conserved substitution. Dash lines are introduced for optimal alignment and maximum similarity between all compared sequences. c Frequency logo plot of RbcS 1 A targeting peptide consensus sequence across selected dicot species. A score of 4 on y-axis means 100% conserved. d Rational design of chloroplast guiding peptide based on

RbcS peptide biorecognition motif for nanoparticle targeting and translocation across chloroplast membranes. The chloroplast targeting peptide includes recognition sites for chloroplast import machinery by TOC, a cysteine residue at the C-terminus for conjugation with NHS-PEG4-MAL linker, and two glycine (G) amino acids as spacers and for increasing the peptide solubility.) ***Source***: Santana *et al.,* 2020

3. Nanomaterials for Enhanced Soil Interaction

- **Nano-Fertilizers and Nano-Pesticides**: One of the major advantages of nanotechnology in agriculture is the development of nano-sized fertilizers and pesticides. These nano-formulations allow for more efficient absorption and utilization by plants, reducing wastage and increasing nutrient uptake. For instance, nano-based fertilizers may improve the bioavailability of nutrients like nitrogen, phosphorus, and potassium, leading to healthier plants and higher yields. Tang *et al.,* 2024, suggested that nano pesticides and fertilizers will be one of the the apt solutions for global food security and sustainability. Thievasanthi *et al.,* 2024 reported that Chitosan has the antimicrobial property and by using various synthesis technics chitosan nanoparticles can be synthesised and can be used for coating NPK fertilizers for its slow release. Ajitha *et al.,* 2024 reported that chlorophyll content of leaves can be increased by $NiFe2O_4$ nanoparticles.
- **Soil Remediation and Health**: Nanoparticles can be used to improve soil structure and fertility. By reducing soil compaction or enhancing microbial activity, nanotechnology can improve soil health, which in turn boosts seed quality and crop yield. *Dhanapal et al.,* 2024 reported that heavy metal contaminated soil can reclaimed by nanoparticles (Fig 2)

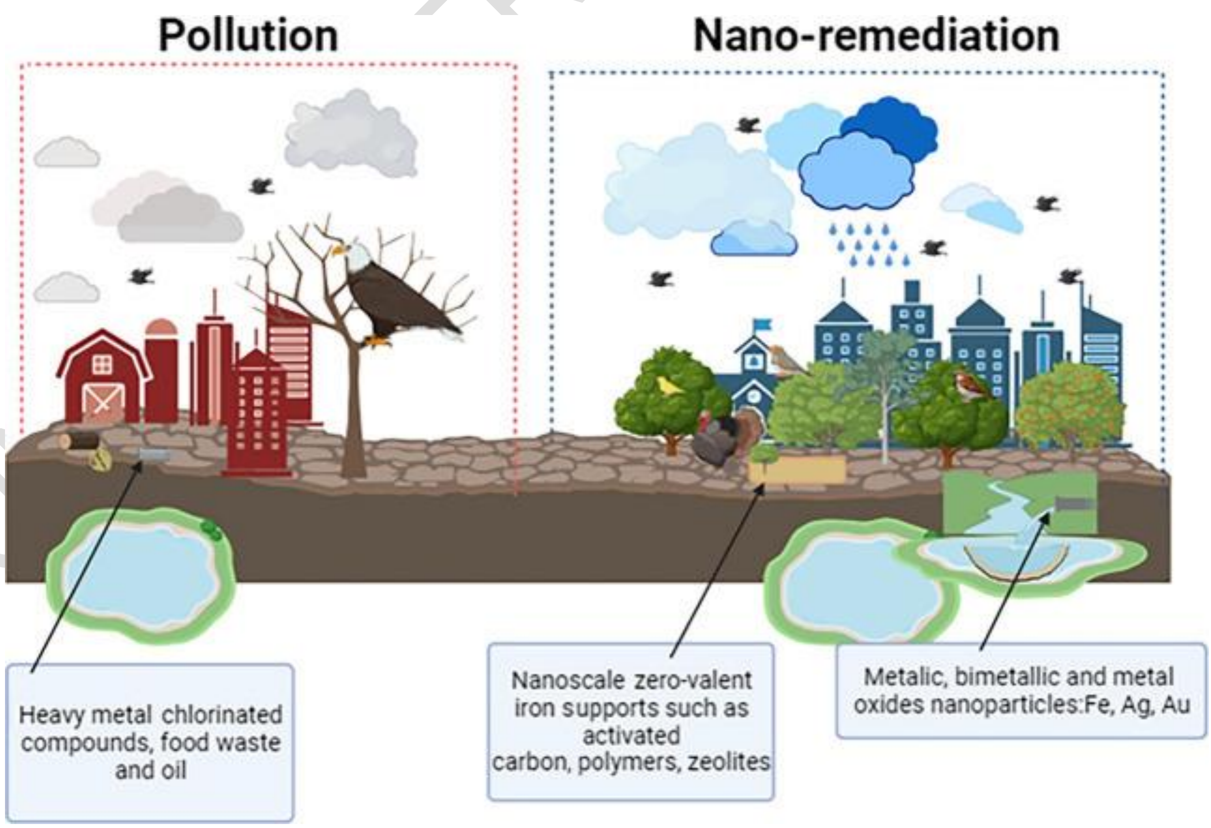

Fig 2. Environmental pollution remediation using nanotechnological approaches. ***Source:*** *Dhanapal et al.,* 2024

4. ***Nano-Priming for Breaking Seed Dormancy***

   - **Stimulating Seed Metabolism**: Nanoparticles, such as metallic and polymeric nanoparticles, can stimulate the seed's metabolic processes, promoting faster and more effective germination. Nano-priming accelerates the seed's natural biological clock, helping it sprout under less-than-ideal conditions.

5. ***Stimulating Seed Germination and Growth***

- **Quantum Dots and Nanoparticles in Plant Growth and Yield**: Quantum dots and other nanoparticles are being explored for their ability to stimulate seed germination and promote root growth. Studies suggest that nanoparticles like gold and silver can enhance metabolic activity in plants, improving photosynthesis and overall plant growth. This is particularly important in seeds that face environmental stress such as drought or low soil fertility. Saidur Rahman *et al.,* 2023, observed that 2.5 mM AgNPs treated seeds performed good in seed germination and yield (Fig.3) .

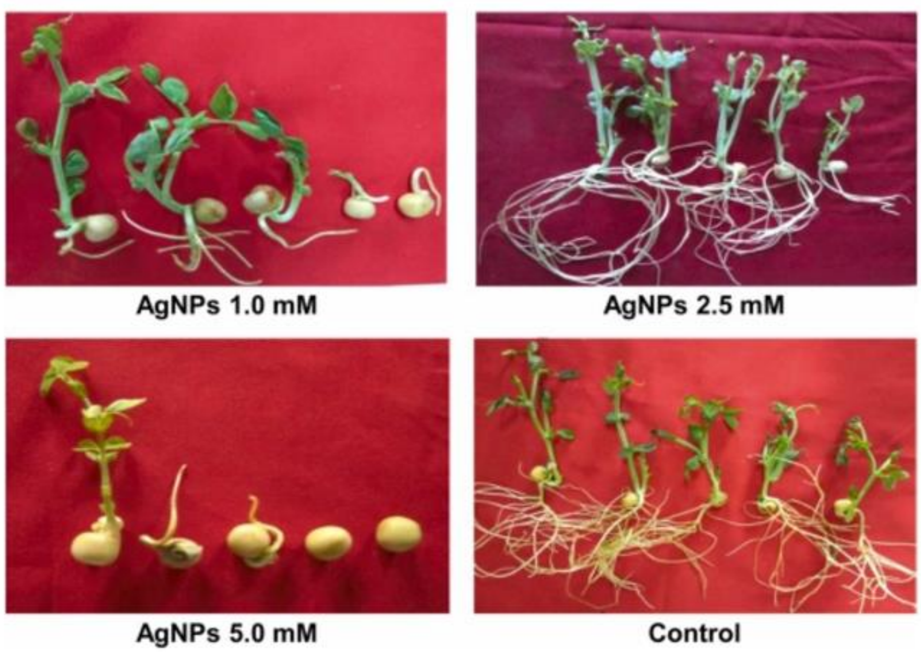

Fig:3 Effect of silver nanoparticles on pea plant germination. **Source:** Saidur Rahman *et al.,* 2023

Enhanced Stress Tolerance: Nanotechnology can help seeds develop enhanced tolerance to biotic and abiotic stress. For example, nanoparticles have been used to protect seeds from extreme temperatures, salinity, and drought, all of which are major limiting factors for crop yield. By improving seed stress tolerance, nanotechnology indirectly contributes to higher yields. Nahaa *et al.,*2024 reported that quantum dots technology has the positive impact against adverse condition like drought stress by regulating antioxidant system and facilitating nutrient uptake. Kumari *et al.,* 2024 described the mechanism of nanoparticle role in alleviating plant stress (Fig 4). There was balance activities between ROS and ADE was observed in nanoparticle treated plants. Al-Khayri *et a*l 2023 clearly elucidated the mechanism of nanoparticles in various stress tolerance mechanism in plants (Fig.5)

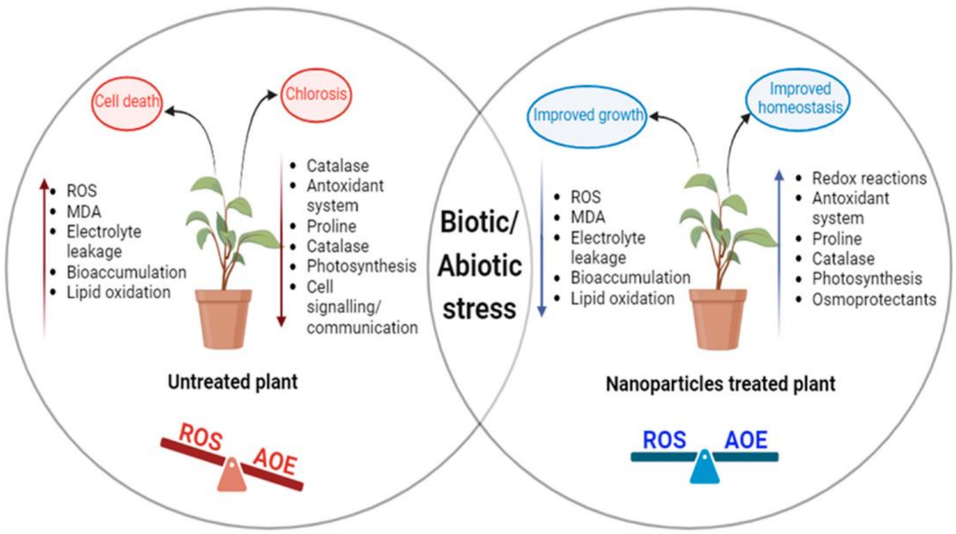

Fig 4. Image describing improved growth of plant upon treatment with nanoparticles in oxidative stress leading to ROS–AOE homeostasis (ROS- Reactive oxygen species; AOE- Antioxidant enzymes). **Source:** Kumari *et al.,* 2024

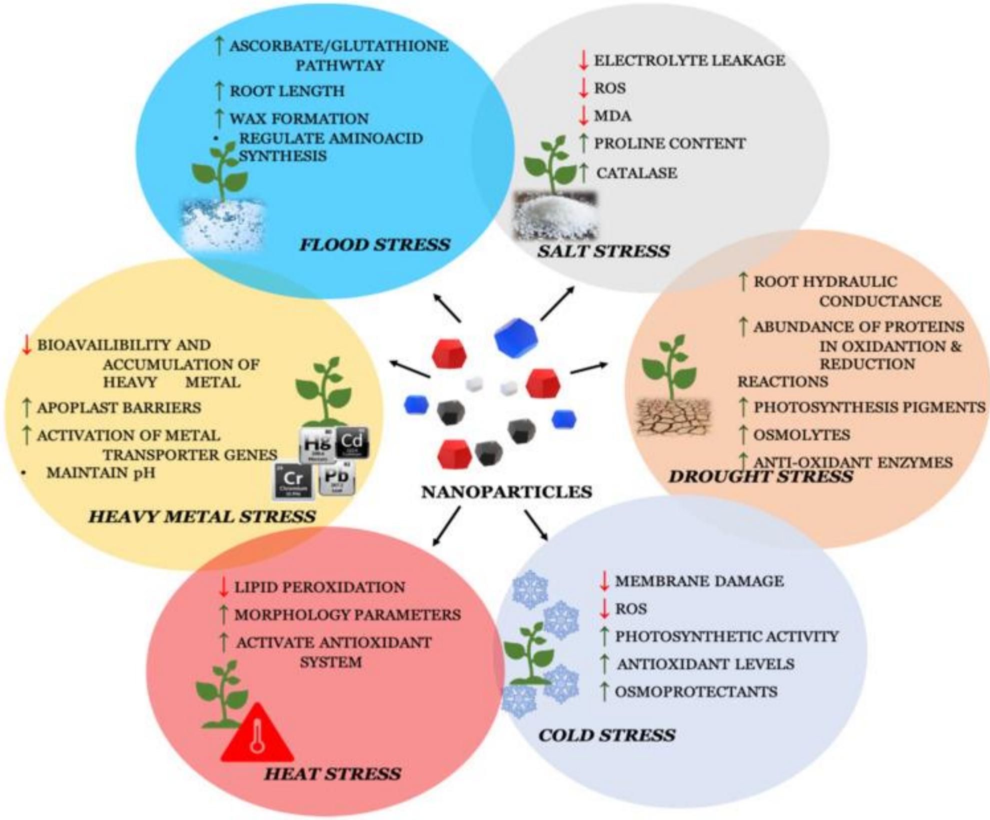

Fig 5. Nanoparticles involved in combating abiotic stress. **Source:** Al-Khayri *et a*l 2023

6. ***Improved Seed Storage**: Nanotechnology can also improve seed storage methods. The application of nanoscale materials can prevent seed deterioration and loss of viability by creating an environment that minimizes moisture, temperature fluctuation, and microbial growth. Dangi *et al.,* 2019, observed that FeNP 500 ppm treated soybean seeds maintained above 70 per cent germination percentage and meeting the minimum germination requirement prescribed as per Indian Minimum Seed Certification Standards up to eight months. Zheng *et al,* 2005 observed that the physiological effects on seeds are related to the TiO_2 nanometre-size particles, but the mechanism by which nano-TiO_2 improves the growth of spinach seeds still needs further study.

Nanotechnology's Impact on Ecosystem and Environmental Sustainability

While nanotechnology offers numerous benefits for improving seed quality and crop yields, it also has implications for ecosystems and environmental sustainability:

- **Reduced Environmental Footprint**: Since nanoparticles can be applied directly to seeds rather than broadcast over entire fields, they reduce the environmental impact of farming. This reduces the need for large-scale pesticide and fertilizer applications, mitigating their harmful effects on soil, water, and biodiversity.

- **Low Residue in Plants**: The amount of nanoparticles applied directly to seeds is generally much smaller than that used in foliar or soil treatments. This reduces the risk of harmful nanoparticle residues accumulating in plants or entering the food chain, which is crucial for maintaining environmental and human health.
- **Challenges in Nanoparticle Toxicity**: Although the use of nanomaterials can have a positive impact, there are concerns about their potential toxicity. The size, concentration, and exposure duration of nanoparticles can lead to unintended consequences, such as hindered plant development or negative effects on soil organisms. Ongoing research is needed to better understand the long-term effects of different types of nanoparticles (metallic, biogenic, polymeric) on plant health, soil quality, and ecosystems.

Contribution to Sustainable Development Goals (SDGs)

Nanotechnology in agriculture is not only about improving productivity but also about fostering **sustainable agricultural practices** that contribute to the achievement of various **Sustainable Development Goals (SDGs)**. The following are key SDGs that are directly impacted by nanotechnology in agriculture:

1. ***SDG 2: Zero Hunger***

   Nanotechnology plays a crucial role in increasing crop yields and improving food security by enhancing seed germination and growth. Nanoparticles can provide crops with the resilience needed to thrive in adverse environmental conditions, such as drought, poor soil quality, and salinity. By improving crop yields with fewer inputs, nanotechnology helps ensure a stable and sustainable food supply for the growing global population.

2. ***SDG 3: Good Health and Well-being***

   The reduction in pesticide use through nanotechnology-based treatments leads to fewer chemicals entering the food chain, improving the safety and nutritional quality of crops. Furthermore, the development of cleaner agricultural practices enhances the overall health and well-being of farming communities and consumers.

3. ***SDG 6: Clean Water and Sanitation***

   Nanotechnology can enhance water management in agriculture by improving water retention in seeds and soils, reducing the need for irrigation. Additionally, the use of nanomaterials in water purification systems can improve access to clean water for agricultural and domestic purposes, especially in water-scarce regions.
4. ***SDG 12: Responsible Consumption and Production***

   Nanotechnology promotes more efficient use of resources, such as water, fertilizers, and pesticides. By improving the precision and efficiency of agricultural inputs, nanotechnology helps reduce waste, optimize resource use, and minimize environmental impact, contributing to more sustainable agricultural practices.
5. ***SDG 13: Climate Action***

   The ability of nanotechnology to improve crop resilience to environmental stressors, such as drought and temperature fluctuations, helps farmers adapt to the impacts of climate change. Additionally, the reduction in pesticide and fertilizer use reduces greenhouse gas emissions and environmental pollution, further supporting climate action.

6. ***SDG 15: Life on Land***

Nanotechnology contributes to the sustainable management of terrestrial ecosystems by reducing the need for harmful chemicals, improving soil health, and promoting biodiversity. By reducing the negative impacts of traditional agricultural practices, nanotechnology can help conserve ecosystems and support biodiversity.

Challenges and Future Directions

While the potential of nanotechnology in agriculture is immense, several challenges remain:

- ***Scale-Up Issues***: The transition from laboratory-based research to large-scale agricultural applications is a significant hurdle. Scaling up the production of nanoparticle-based solutions for field use involves technical, economic, and regulatory challenges that need to be addressed.
- ***Regulatory Frameworks***: The use of nanotechnology in agriculture must be accompanied by stringent regulatory frameworks to ensure the safe application of nanomaterials. This includes monitoring nanoparticle concentrations, environmental impact assessments, and assessing the long-term effects on ecosystems.
- ***Knowledge Gaps***: Research into the effects of various nanoparticles on plant development, soil health, and ecosystem dynamics is still in its early stages. More comprehensive studies are needed to understand the potential risks and benefits of nanotechnology in agricultural systems fully.
- ***Safety Concerns:*** The long-term effects of nanoparticles on human health, ecosystems, and biodiversity are still not fully understood. Extensive research is needed to ensure the safety of nanotechnology-based products before they can be widely adopted in agriculture.
- ***Cost and Accessibility***: The production of nanomaterials and their application in agriculture can be expensive, making it less accessible to smallholder farmers in developing regions. Efforts must be made to reduce costs and make these technologies affordable.
- ***Regulatory Frameworks***: There is a lack of standardized regulations and protocols for the use of nanotechnology in agriculture. Governments and international bodies must work together to establish guidelines that ensure safe and effective use.

Conclusion

Nanotechnology has the potential to transform agriculture by improving seed quality, increasing crop yields, and promoting more sustainable farming practices. Through innovations such as nano-priming for seed treatment, nano-based fertilizers and pesticides, and enhanced water management, nanotechnology addresses key agricultural challenges and directly contributes to several United Nations Sustainable Development Goals (SDGs). However, careful consideration of the environmental, health, and safety implications of nanomaterials is crucial. Ongoing research, coupled with the development of appropriate regulatory frameworks, safety standards, and access to technology will be necessary to ensure that nanotechnology delivers its full potential without unintended consequences for human health, ecosystems, and biodiversity. Continued research and innovation, coupled with international collaboration, will be key to realizing the full potential of nanotechnology in achieving the SDGs.

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