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Role of Nanotechnology in Enhancing Seed Quality and Longevity

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The seeds are the basis of agricultural productivity, and their quality and storage period are also important to the establishment and yield of crops, as well as to food security. The deterioration of seeds during storage and the effect of unfavorable growing conditions on seed germination continue to be two of the most important challenges in seed technology. A transformative solution is emerging through nanotechnology—an interdisciplinary field that operates at the nanoscale. Nanomaterials such as nanoencapsulated particles, nanocapsules, and nanocoatings are currently being evaluated for their potential to improve seed germination, increase resistance to stress, protect against pathogens that are transmitted through seeds, and increase seed viability. The current review article summarizes the most recent developments in the application of nanotechnology to improve the quality and life of seeds. It describes the mechanisms through which nanomaterials may alter physiological and biochemical functions in seeds and discusses applications and delivery methods, as well as safety and regulatory concerns associated with these technologies. The review presents the possibility that nanotechnology will profoundly change the field of seed science. However, the necessity of comprehensive risk analysis and sustainable incorporation of nanotechnology into agricultural systems remains.

Introduction

Seeds are a vital biological resource. They store genetic potential and ensure plant species continue. In agriculture, high-quality seeds that germinate well and last a long time are crucial for consistent crop growth and maximum yield. However, seed quality can decline due to environmental stress, pests, and poor storage conditions. This decline significantly impacts agricultural productivity and seed systems around the world. Seed science has mainly focused on traditional methods like treating seeds with fungicides, priming them with nutrients, and creating controlled storage conditions. While these approaches have led to better results, they often do not solve complex issues. These include rapid deterioration under non-living stress, insufficient protection against new pests, and nutrient imbalances that affect early seedling growth. Nanotechnology, which involves engineering materials at sizes between 1 and 100 nanometers, provides unique properties that can be used to improve seed performance. At this tiny scale, materials have a larger surface area, higher reactivity, and different interactions with biological systems. These features make nanomaterials promising tools for enhancing seeds. They can improve nutrient delivery, offer protection against living and non-living stressors, and create systems that control how seed treatments work. This article looks at the role of nanotechnology in improving seed quality and longevity. It explores how nanomaterials interact with seeds, current applications in seed enhancement, the effects on seeds' physiology and biochemistry, and potential challenges and safety issues.

Nanotechnology Fundamentals Relevant to Seed Science

Nanotechnology involves the design and application of nanomaterials—structures with dimensions on the scale of atoms and molecules. Because of their small size and large surface area-to-volume ratio, nanomaterials such as metal nanoparticles (e.g., silver, zinc oxide), carbon-based nanomaterials (e.g., carbon nanotubes), and polymeric nanoparticles display properties distinct from their bulk counterparts.

Key mechanisms by which nanomaterials influence biological systems include:

- **Enhanced surface interactions:** Nanoscale materials interact more effectively with cellular membranes and biological molecules.
- **Controlled release:** Nanoencapsulation can regulate the release of nutrients, bioactive compounds, and protective agents.
- **Catalytic activity:** Some nanoparticles can catalyze biochemical reactions or act as reactive oxygen species (ROS) modulators.
- **Barrier and protective functions:** Nanocoatings can provide physical protection against pathogens and environmental stress.

These characteristics form the basis for applying nanotechnology to seed enhancement.

Nanotechnology in Enhancement of Seed Quality

1. Nanopriming and Seed Germination

Nanopriming involves treating seeds with nanomaterials to enhance their germination and early growth as seedlings by combining the best of both conventional seed priming methods and the distinctive characteristics of nanomaterials. The following mechanisms may be involved in how nanopriming improves seed quality: • Improved water absorption via increased wettability of the seed coat. • Increased metabolic activation during the germination process; and, • Modulating an antioxidant defence mechanism that reduces oxidative stress experienced by seeds. For example, zinc oxide nanoparticles (ZnO NPs) and silicon dioxide nanoparticles (SiO2 NPs) have been shown to increase germination rates and metabolic activity by facilitating the transportation of water and enhancing seed enzymatic activity. Nanoparticles also modulate the activity of plant hormones that regulate seed germination.

2. Nanomaterials in Consideration of Stress

Seeds may be subjected to environmental stresses (drought, salinity, and temperature fluctuations) which negatively impact germination and establishment as seedlings. Nanomaterials may mitigate the effects of climates on plant growth and establishment by modulating stress signal systems and providing protection against adverse environmental conditions. Examples of possible nanomaterial applications include: • Cerium oxide nanoparticles (CeO2 NPs) are able to scavenge reactive oxygen species (ROS) in order to prevent oxidative damage to seeds due to environmental stress. • Carbon-based nanomaterials (e.g. carbon nanotubes (CNT's)) may enhance the transportation of water and nutrients to the seed, increasing seedling vigour under a variety of environmental stresses. These interactions between nanoparticles and stress allow seeds to develop into healthy seedlings and survive adverse weather conditions during their germination and establishment stages.

3.Nanocoatings for Protection Against Pathogens

Nanotechnology reduces chemical inputs by providing specific nanotechnology for each seed type. - Provides lower pesticide concentrations than typical fungicide treatments. - Prevents pathogen entry into seeds through a barrier created around the seed and the soil environment. - Provides a means to protect seeds during transit when environmental conditions may not be optimal.

4.Nanotechnology for Seed Storage and Longevity

Seed longevity—defined as the period over which seeds remain viable—is influenced by moisture content, temperature, and biochemical stability. Nanotechnology contributes to improved seed storage by:

- **Nanohydrophobic coatings:** reducing moisture ingress and protecting seeds from humidity-induced deterioration.

- **Antioxidant nanocarriers:** delivering antioxidants that stabilize seed cellular structures.

By slowing down aging processes and reducing oxidative damage, nanotechnology can extend the viability and shelf life of seeds.

Physiological and Biochemical Impacts of Nanomaterials on Seeds

Nanomaterials can impact plant seeds on many biological levels: Nanoparticles penetrate through seed coats to reach their embryos, leading to a modification of metabolic pathways within the seeds. Nanoparticles possessing antioxidant capabilities have an influence over the levels of reactive oxygen species during seed germination and seed storage. Nanomaterials also impact the functionality of enzymes that are related to seed metabolism, such as amylases and proteases, thereby promoting faster germination of seeds. The nature of the nanoparticles, the concentration used and, of course, the type(s) of seeds can determine how these effects can occur. On the whole, the use of low levels of nanoparticles can lead to beneficial effects. Conversely, if nanoparticles are applied inappropriately (over concentration, etc.), then those same nanoparticles can exert detrimental effects on seed germination and seed growth (phytotoxicity, damage to DNA, metabolic disturbance). Therefore, it is important to develop optimal formulations and applications for these types of products.

Challenges and Safety Considerations

1. Environmental and Human Health Risks- Nanoparticles that may end up in aquifer systems (via land application or irrigation), and eventually into our food supply may have unintended consequences on the ecology of non-target species. The environmental impact of the use of nanoparticles on soil microbiota (the beneficial bacteria and fungi that exist in the soil) and the long-term effects on beneficial insects and humans is not fully understood.

2. Standardization and Regulatory Concerns- There are no standardized protocols for synthesizing, characterizing and applying nanoparticle technologies in agriculture today. As a result, standards of practice (and regulatory frameworks) for safe applications, as well as labeling, of nano-enabled agricultural seed products are still evolving and vary across many countries today.

3. Cost of Commercial Production and Scalability- The cost associated with commercial production of nanomaterials in a consistent quality will still be a barrier for many. To enable the agricultural sector to use nanotechnology-based seed treatments at the scale needed, cost-effective synthesis and delivery systems need to be developed.

4. Perception by the Public- Consumers and farmers may not be willing to adopt nanotechnology in agriculture due to perceived risks and a lack of understanding. Therefore, effective communication about the benefits of using nanotechnology, in conjunction with safety data, will be critical for acceptance by consumers and farmers alike.

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