Nanoparticles in Modern Agriculture: From Synthesis to Field Applications

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ABSTRACT

Nanoparticles (NPs) are extremely tiny molecules with features that typically differ from those of larger substances. There are four types of NPs, each with its own set of physical and chemical features. NPs are increasingly being employed in agriculture to improve productivity and resource efficacy. NPs are commonly used as nano fertilizers, seed primers, and nano-based sensors to improve food quality and for water purification. In modern agriculture, nanoparticles have become a game-changer, providing solutions to long-standing agricultural challenges.

INTRODUCTION

The NPs are incredibly tiny particles with a size range between 1-100 nm. Because of their very small size and a very large surface-to-volume ratio, they can possess some very distinct physical and chemical characteristics. The properties of NPs are frequently different from those of bulk materials, which results in increased strength, reactivity, and other desired attributes. When a particle size reaches the nanoscale, or less than the de Broglie wavelength, the periodic boundary limitations of the crystalline particle are eliminated.

NPs' historical context: Around 600 and 300 BC, carbon-made nanotubes were discovered in ceramic materials from India. In approximately 900 AD, cementite nanowires were found to be present in Damascus steel. The gold nanoparticles are believed to have been used in the Roman era, as well as in

Ayurvedic medicines like "Swarna-Bhasma" to promote greater health benefits. In 1991, Carbon nanotubes were discovered, and in 1993, Japanese scientist Sumio Iijima reported a single-wall carbon nanotube with 1 nm diameter using electron microscopy (Altammar, 2023).

Categorization of NPs: According to their dimensions, the NPs are classified into the following categories:

i. Zero-dimensional: carbon quantum dots, graphene quantum dots, and fullerenes
ii. Single-dimensional: nanotubes, nanofibers, nanorods, and nanowires
iii. Two-dimensional: nanofilms and nanolayers
iv. Three-dimensional: nano-cubes and nano-cages

Approaches for the synthesis

1. **Top-down:** To produce nanostructured materials, the bulk materials are broken down to nano scale using top-down techniques. Some major techniques involved are laser ablation, mechanical milling, lithography, electrospinning, and sputtering.

2. **Bottom-up approaches:** By using these techniques, small atoms and molecules are combined to create the nanostructured particles. Chemical and biological methods are among them. Some bottom-up techniques are hydrothermal, microwave synthesis, and template methods (Altammar, 2023).

Characteristics of NPs

1. **Physical properties:** The NPs possess an extremely small size, a large surface area to volume ratio, exhibit unique optical behaviors, high mechanical strength, hardness, and magnetic properties like super paramagnetism.

2. **Chemical properties:** NPs are highly reactive due to their large surface area and high surface energy. They serve as catalysts in various reactions. Also, surface functionalization of NPs can easily be achieved by attaching various functional groups like hydroxy, carboxyl, amine, and thiols to their surface cavities.

Uptake and transport of NPs by plants

There are several pathways by which the NPs can infiltrate the plant system. The NPs can enter the plant system through the roots, and the plants can use the symplastic (cytoplasmic) or apoplastic (cell wall and extracellular spaces) parts of the root to be absorbed in plants. Smaller NPs may use the root endodermis and can enter vascular tissues. Foliar exposure of sufficiently tiny and suitably charged NPs to plants permits them to enter the leaves through the stomatal and sub-stomatal cavities. The transportation of NPs in the plant system occurs mostly via xylem and phloem tissues. The xylem tissues helps in acropetal transport (root to shoot), whereas the phloem tissues assist the bidirectional transport. This combined system helps the NPs to access the leaves, roots, fruit, and storage tissues of plants.

Applications in agriculture: NPs are increasingly used in agriculture to enhance productivity and resource efficacy. Some of the major applications of these materials in the field of agriculture.

1. **Nano-based fertilizers:** A form of fertilizer known as "nano-fertilizer" makes use of nanotechnology to enhance the efficiency and delivery of nutrients to plants. They are further used as nano-encapsulated fertilizers such as nano urea and nano DAP. Mineral-based fertilizers, such as zinc, iron, copper, and other essential micronutrients. Nano-composite fertilizers made by combining two or more

types of NPs, Eg, Nano-NPK composite, and Bio-based nano-fertilizers containing organic or biological nanomaterials, such as those derived from chitosan, humic acid, or natural polymers (Semenova *et al*., 2024).

2. **Nano-particles in seed sciences:** NPs in seed sciences focus on how nano-scale materials can improve seed quality, germination, vigor, and early seedling establishment. In seed priming, common NPs such as carbon-based NPs, ZnO, and SiO_2 are employed to improve biological and physiological activities. In coating and encapsulation, chitosan, silver, and polymer-based NPs can be utilized to direct supply of nutrients, insecticides, and growth regulators to the seed while boosting their resistance to pests and disease, and ensuring consistent germination.

3. **Food safety**: Pathogens in food items can be identified and removed by using NPs. The NPs may lower the risk of foodborne infections and enhance the sensitivity of biosensors for the detection of bacteria like *Listeria*, *Salmonella*, and *E.coli*. The NPs may also be included in food packaging to actively stop the growth of fungi and pathogens, which can cause serious health issues.

4. **Nano-based sensor:**Plant health, soil conditions, water quality, and environmental elements, including temperature, humidity, and air quality, may all be monitored with NPs based sensors in agricultural settings. NPs based sensors can increase production, sustainability, and efficiency by facilitating real-time data collection and more precise control over agrarian processes. NPs can also be used to monitor variations in soil *p*H, detect plant diseases and nutrient levels, as well as the detection of various contaminants, pesticides, and microorganisms in soil (Vishvakarma *et al*., 2025).

5. **Water purification and pollution control:** Because of their special physicochemical characteristics, the NPs are emerging as a potent instrument for environmental protection. The use of NPs in water purification includes disinfection, catalytic degradation, and adsorption, which makes it possible to effectively remove pathogens, organic contaminants, and heavy metals. It also looks at how NPs may be used to reduce air and soil pollution, emphasizing how they can break down airborne poisons and immobilize pollutants. Nanoparticle-enabled disinfection has the potential to become a key component of next-generation water treatment technologies with additional research and risk management (Anwar *et al*., 2025).

CONCLUSION:

In present-day agriculture, the persistent problems related to agricultural yield, environmental sustainability, and resource management have been creatively solved by use of NPs. Because of their excellent physicochemical properties, they are suitable for various applications in agriculture, ranging from nano fertilizers to nano seed growth promoters. They possess special characteristics that enable them to be applied in food safety materials, nano-based sensors, water purification, and pollution control. Moreover, research is underway to manufacture metal NPs with exact size and shape control.

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