AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 02, Issue: 10 (October, 2025)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Nano Fertilizers: Applications and Future Prospects

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The major challenge for global food and nutrition security is to feed the increasing global population with nutritious food. Nanotechnology has emerged as a revolutionary science in order to fulfil the food demand of ever-increasing population of the world, which is expected to reach 9.6 billion by 2050, for more food. The use of conventional chemical fertilizers has great contribution in food security, but their overdose and unjust use have caused some serious environmental issues like nutrient imbalance thereby leading to low soil fertility, nitrate leaching causing water pollution and many others related with general ecosystem. Under current scenario, there is a need to develop smart materials which can release nutrients in a slow and steady manner to the targeted sites. Nano-nutrition of crop plants is an emerging field and various nano particles have been successfully utilized as macro and micronutrients to improve soil fertility, nutrient uptake by the crop plants and ultimately their productivity.

Keywords: Nanotechnology, Nonfertilizer, Growth and Yield

Introduction

Technological progress and population growth have historically driven agricultural revolutions, reshaping global food systems and productivity. The first agricultural revolution during the neolithic age (~12,000 BCE) marked the transition from hunting to settled agriculture through domestication of plants and animals. The second agricultural revolution (18th–19th centuries) introduced mechanization, improved agronomic practices and the use of chemical fertilizers, enhancing crop yield and labor efficiency. The third agricultural revolution or green revolution (1930s onward), emphasized high-yielding varieties, irrigation and intensive fertilizer use, significantly increasing food grain production worldwide. However, these revolutions also created major ecological and agronomic challenges. Excessive dependence on chemical fertilizers and limited crop diversity have led to soil degradation, nutrient imbalance, pest resistance and pollution of soil and water bodies. The nutrient use efficiency of conventional fertilizers remains low about 30–40% for nitrogen and 15–20% for phosphorus resulting in substantial nutrient losses and environmental hazards.

With the global population expected to exceed 9.6 billion by 2050, sustainable intensification of agriculture has become crucial. The next agricultural transformation must focus on enhancing productivity while conserving resources through innovative and efficient input management. In this context, nanotechnology offers a promising solution. Nano-fertilizers, formulated at the nanoscale (<100 nm), allow controlled and targeted nutrient release, improving nutrient uptake and minimizing losses. Their high surface area and reactivity enable effective nutrient delivery even at lower dosages compared to conventional fertilizers. Thus, nanotechnology represents a major step toward sustainable, efficient and environmentally safe agriculture, ensuring food security for future generations.

Nano technology

Nanotechnology is the art and science of manipulating matter at nano scale (1×10^{-9} m) to create new and unique materials and products. Nanotechnology is emerging out as the greatest imperative tools in recent agriculture and predictable to become a driving economic force in the near future. Nanotechnology helps to precisely detects and delivers the correct quantity of nutrients and other agrochemicals like herbicides and fungicides that promotes productivity of the crop while ensuring environmental safety.

Approaches of nanoparticle production

Nanoparticles are synthesized based on two approaches – the top-down approach and the bottom-up approach (Tripathy *et al.*, 2023). The top-down approach starts with the bulk form of the material and through various processes, the bulk matter is split into tiny parts till nanoparticles are formed. The bottom-up approach is quite the opposite, where we begin with the tiniest possible particle, the atom and nanoparticles are built by the organized assembly of these atoms.

Based on these two approaches, several methods of synthesis of nanoparticles have been devised. We can broadly classify these methods into three categories – physical methods, chemical methods, and biological methods.

As the name suggests, the Physical methods of nanoparticle synthesis involve the application of physical forces to derive nanoparticles from bulk materials. For example, the High energy ball milling and Melt Mixing methods involve the application of mechanical forces, while other methods use thermal and electrical energy, melting, evaporation and other physical forces to generate nanomaterials. The Biological methods of synthesis offer a unique advantage of being eco-friendly. These methods use the metabolic power of microorganisms, plants, and biomolecules to generate nanoparticles.

The Chemical methods of synthesis of nanoparticles happen in two distinct phases. In the first phase, the bulk metals are reduced to the precursor atoms with the help of some reducing agents. In the second phase, the atoms undergo a process called nucleation, where they are broken down, and then a slow growth process generates nanomaterials.

Applications of nanotechnology in agriculture

Controlled released nano fertilizers improve crop growth, yield and productivity. Nano-based target delivery approach is used for crop improvement. Nano pesticides can be used for efficient crop protection. Uses of nano sensors and computerized controls greatly contribute to precision farming. Nanomaterials can also be used to promote plant stress tolerance and soil enhancement.

Nano fertilizers

Nano fertilizers" are synthesized or modified form of traditional fertilizers with the help of nanotechnology used to improve the fertility of soil for a better yield and increased crop quality are called Nano fertilizers. It is also called "smart fertilizer" as new facilities to enhance nutrient use efficiency and reduce costs of environmental protection (Chinnamuthu and Boopathi, 2009).

Nano-Fertilizers: Types and Mechanisms

They include nanoscale particles of conventional nutrients, nutrient-loaded nanocarriers and nano-composites.

1. **Nano-urea (N):** Liquid urea encapsulated in nanoparticles or stabilized by nanocarriers, such as silica or polymer shells.
2. **Nano-DAP (P):** Phosphorus fertilizer at the nanoscale (e.g. nanophosphate or nano-hydroxyapatite).
3. **Nano-NPK:** Multi-nutrient formulations combining N, P, K in nanoparticulate form. • Nano-micronutrients: Essential elements like ZnO, Fe_3O_4 or Fe_2O_3, CuO nanoparticles (often foliar-applied).

4. **Nanocomposite fertilizers**: Nutrients bound to nano-clays (e.g. zeolite composites), graphene oxide orbiochar-based nanosheets for slow release.
5. Polymer-coated fertilizers where nanofertilizers: nutrients are Controlled-release entrapped within biodegradable polymer nanoparticles or hydrogel networks.

Mechanisms of Nanoparticle Uptake by Plants

In the soil, nanoparticles (NPs) undergo a series of biotic and abiotic transformations that determine their bioavailability, mobility, and potential phytotoxicity (Ali *et al*., 2020). Uptake begins with adsorption onto root surfaces, followed by internalization and translocation to aerial organs. The size, surface charge, and chemical composition of NPs are crucial factors influencing their absorption and movement within plant tissues. Smaller particles (3–5 nm) can penetrate root epidermal cells through cell wall pores, osmotic gradients, or capillary forces, while larger NPs may induce new pores or modify cell wall structures to facilitate entry.

Once internalized, NPs can move apoplastically through extracellular spaces to the vascular cylinder, from where the xylem transports them unidirectionally upward. To cross the Casparian strip, NPs follow the symplastic pathway via endocytosis, carrier-mediated transport, or pore formation at the endodermal cell membrane (Ali *et al*., 2020). Intercellular transport may also occur through plasmodesmata, allowing the exchange of NPs between adjacent cells. Some particles that fail to penetrate accumulate on the Casparian strip or root surfaces, potentially influencing nutrient absorption and rhizosphere interactions.

Following uptake, NPs are redistributed within the plant through the phloem, leading to their accumulation in roots, stems, leaves, fruits, and grains. Foliar-applied NPs enter primarily through stomata or the cuticle, depending on size: particles <5 nm can diffuse through cuticles, whereas those between 10–200 nm enter via stomatal openings and move through apoplastic and symplastic routes. Uptake efficiency depends on NP size, concentration, application method, and environmental conditions, as well as leaf surface features such as trichomes, waxes, and exudates (Ali *et al*., 2020).

Role of Nano Fertilizers on Plant Growth

Foliar application of zinc nano fertilizers has been shown to significantly enhance plant growth and physiological performance. The nano zinc application at 10 mg L^{-1} increased shoot length by 15.1%, root length by 4.2%, and root area by 24.2% compared to untreated controls. Additionally, chlorophyll content and total soluble leaf protein increased by 24.4% and 38.7%, respectively, suggesting enhanced photosynthetic activity and protein synthesis. The improved growth responses are attributed to enhanced auxin production mediated by Zn nanoparticles, which likely penetrate plant cells through stomatal openings or natural nanopores, stimulating metabolic activities and supporting higher crop productivity. The results highlight the efficiency of nano zinc as a micronutrient and its potential role in improving crop growth and yield (Tarafdar *et al*. (2014)).

Application of 50% RDN urea + 50% N nano urea and 60% RDN urea + 40% N nano urea increased plant height of rice, with 60% RDN urea + 40% N nano urea showing the best performance. The number of tillers per m^2 and dry matter production were also highest under 50% RDN urea + 50% N nano urea, due to the small particle size and large surface area of nano urea, which enhanced leaf penetration and nutrient uptake. Additionally, nano urea shortened the days to 50% flowering, promoting earlier panicle initiation and better plant development. These findings indicate that nano urea, especially when combined with reduced doses of conventional urea, improves nutrient use efficiency, growth, and productivity in rice, offering a sustainable approach to fertilization (Kumar *et al*., 2021).

Treatment with 500 ppm $Mg(OH)_2$ NPs resulted in the highest germination percentage (100%) and lowest mean germination time (1.2 days) compared to untreated seeds. Enhanced germination is attributed to nanoparticle adhesion to the seed coat, facilitating water uptake and nutrient penetration. NPs increase water absorption, which mobilizes gibberellic acid to activate amylase, hydrolyzing starch into sugars for energy. They also elevate nitrate reductase activity, improving the seed's capacity to absorb and utilize water and nutrients. These findings demonstrate that $Mg(OH)_2$ nanoparticles can promote early germination and seedling vigor in maize (Shinde *et al*. (2018).

Role of nano fertilizers on yield and economics

A field experiment at Zonal Agricultural Research Station, Bengaluru evaluated the response of sunflower (*Helianthus annuus* L.) to nano boron fertilization during *Kharif* 2016 (Kavitha *et al*., 2017). Treatments included nano boron seed priming, foliar spray, and soil application of borax. The highest seed yield (2788 kg ha^{-1}), stalk yield (5256 kg ha^{-1}) and B:C ratio (2.82) were recorded with nano boron @ 0.2% seed priming, closely followed by foliar application and soil-applied borax. The control produced the lowest yields (1629 and 4429 kg ha^{-1}, respectively). Enhanced performance was attributed to improved germination and seedling establishment, as nano boron particles could penetrate the seed coat, facilitating water and nutrient absorption. These findings highlight the potential of nano boron as an effective fertilization strategy to improve sunflower productivity.

A field study following TNAU fertilizer recommendations evaluated nano-urea foliar spray on rice (Arya *et al*., 2022). 50% RDN basal + 0.5% nano-urea at panicle initiation and booting stages produced the highest grain yield (3413 kg ha^{-1}), while lower nano-urea doses gave reduced yields. The improvement was attributed to enhanced nutrient uptake through stomata, better translocation, increased cell division, and higher photosynthate accumulation, resulting in more productive tillers. These results indicate that nano-urea effectively supplements conventional fertilizers and improves rice growth and productivity.

Foliar application of nano zinc + silicon @ 40 ppm each at 40 days after transplanting of rice recorded the highest grain yield (6034 kg ha^{-1}), straw yield (6693 kg ha^{-1}) and B:C ratio (2.5), followed by nano zinc alone. Yield improvement was attributed to enhanced grains per panicle, better metabolite translocation, reduced transpiration, and alleviation of biotic and abiotic stress. These results highlight the synergistic effect of nano zinc and silicon in improving rice growth and productivity (Lahari *et al*., 2021).

Limitations of nano fertilizers

- Lack of production and availability of nano fertilizers in required quantities.
- High cost of nano fertilizers
- Lack of standardization in the formulation process.
- Environmental impact
- Shows high reactivity

Future Prospects of Nano Fertilizers

Nanotechnology offers a sustainable approach to agriculture through nano fertilizers that provide efficient and controlled nutrient delivery. Unlike conventional fertilizers, they ensure higher nutrient uptake, reduced losses and lower environmental impact. Future efforts will focus on developing biodegradable, non-toxic and eco-friendly nano formulations using green synthesis from biological sources. Integrating nano fertilizers with organic manures and biofertilizers can enhance soil fertility, microbial activity and crop resilience to stresses. Combining them with micro and secondary nutrients can address multiple deficiencies simultaneously. For large-scale use, studies on nanoparticle behaviour, safety and regulatory frameworks are essential. Overall, nano fertilizers promise improved nutrient efficiency, reduced costs and sustainable soil and crop productivity for future food security.

Conclusion

Nanoparticles have a great potential as 'magic bullets' loaded with nutrients and targeting specific plant tissues to release their charge to desired plant part to achieve the desired results. Seed treatment with nano fertilizers significantly influenced the seed germination, seedling growth and vigour index of crops. Application of nano fertilizers at different growth stages resulted in increased yield and yield attributes of many crops. Controlled release of nutrients from nano fertilizers resulted in increased fertilizer use efficiency and these nano fertilizers minimize the cost of production, maximize the profit and also helps in reduction of pollution.

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