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Nanofertilizers: A Novel Approach Towards Sustainable and Precision Agriculture

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The rapidly growing global population, coupled with declining per-capita agricultural land availability, is placing unprecedented pressure on agricultural systems to increase food production. However, growth in agricultural productivity is staggered at on place, while the intensive use of external inputs such as fertilizers, herbicides, pesticides, and irrigation water continues to increase. Fertilizers are one of major input to maintain the productivity but conventional fertilizers are low nutrient use efficiency which resulting substantial nutrient loss like volatilization, leaching, surface runoff and other pathways which leads to increase in cost of crop production with adverse environmental effects also. This imbalance highlights the need for more efficient and sustainable agricultural production systems that can produce more food from limited land and resources while minimizing environmental impacts. So, Nanotechnology can be a possible solution for all kind of problem. Nanotechnology is the application of nanoscience, which involves the study and manipulation of materials and phenomena at the nanoscale, typically within the range of 1–100 nm, to develop novel products, materials, and devices with enhanced properties and functionalities. At this extremely small scale, electrons and holes become confined within a limited space, resulting in **quantum confinement**, whereby their energy levels become discrete rather than continuous. This phenomenon gives rise to unique **quantum effects**, causing significant changes in the optical, electrical, magnetic, catalytic, and other physicochemical properties of materials compared with their bulk counterparts. These distinctive nanoscale properties make nanotechnology a promising approach for developing innovative solutions across various fields, including **agriculture, medicine, environmental science, and energy**.

The adoption of nano fertilizers in agriculture has been increasing owing to their potential to improve nutrient-use efficiency, reduce nutrient losses, and enhance crop productivity. The growing interest in nano fertilizers is also reflected in the expansion of the global market. According to IMARC Group (2025), the global nano fertilizer market was valued at approximately **USD 107.6 million in 2025** and is projected to reach **USD 156.8 million by 2034**, registering a compound annual growth rate (CAGR) of **4.28% during 2026–2034** (IMARC Group, 2025). This increasing market demand highlights the growing interest in nanotechnology-based fertilizer formulations as an emerging approach for improving the efficiency and sustainability of nutrient management in agriculture. Nano fertilizers differ fundamentally from conventional chemical fertilizers in that their nanoscale particle size (typically 1–100 nm) confers a markedly higher surface area-to-volume ratio, allowing them to penetrate plant tissues more efficiently through stomata, cuticular pores, and other natural openings, and to be readily translocated within the plant via the phloem (Upadhyay *et al.*, 2023). This enhanced entry and systemic distribution, coupled with their slow and targeted nutrient-release behaviour, allows nano fertilizers to synchronize nutrient supply more closely with crop physiological demand, thereby minimizing losses that typically occur with bulk fertilizers and resulting in a substantially higher nutrient use efficiency (NUE) compared with conventional fertilizers. Nanofertilizers can be applied to crops through both soil application and foliar spraying. However, foliar application is generally more common, as it enables nutrients to be delivered directly to plant tissues, potentially improving nutrient absorption and utilization while reducing losses associated with soil-applied fertilizers.

Despite the promising potential of nanofertilizers to improve nutrient-use efficiency, reduce nutrient losses, and enhance crop productivity, their effectiveness depends on nanoparticle characteristics, fertilizer formulation, application method, crop species, soil properties, and environmental conditions. Moreover, questions related to their long-term environmental fate, biosafety, cost-effectiveness, field-level performance, and regulatory frameworks remain to be fully addressed (Usman *et al*., 2020). Therefore, a comprehensive understanding of the opportunities and limitations of nanofertilizers is essential for their responsible integration into modern agriculture. In this context, the present article reviews the current status of nanofertilizers, their types, mechanisms of nutrient delivery, and applications in crop production, with particular emphasis on their role in improving nutrient-use efficiency which supporting precision nutrient management, and promoting sustainable agricultural systems. The article also discusses the major challenges, environmental and safety concerns, and future prospects for the wider adoption of nanofertilizers in sustainable and precision agriculture.

Current status of nono-fertilizer

India has witnessed rapid adoption of nanofertilizers, with cumulative sales reaching 1,593.37 lakh bottles of Nano Urea and Nano DAP by March 2026 (Ministry of Chemicals and Fertilizers, PIB, 2026). Field trials indicate that Nano Urea (25-50%) and Nano DAP (Up to 50%) can partially substitute conventional fertilizers, while maintaining comparable crop yields under appropriate management. Government-led ICAR research is further evaluating their long-term effectiveness, nutrient-use efficiency, and performance across diverse agro-ecological conditions. The Namo Drone Didi (NDD) Scheme highlights the integration of nanofertilizers with precision agriculture through drone-based foliar application. With an outlay of ₹1,261 crore (2023–26), the scheme has supported the distribution of 1,094 drones, including 500 under NDD, along with DGCA-authorized training. In parallel, ICAR has procured 297 drones and conducted 36,882 demonstrations covering 38,280 ha and benefiting over 4.26 lakh farmers (Government of India, 2026). These initiatives demonstrate the potential of combining nanofertilizers, drones, and precision agriculture for targeted farm-level input application.

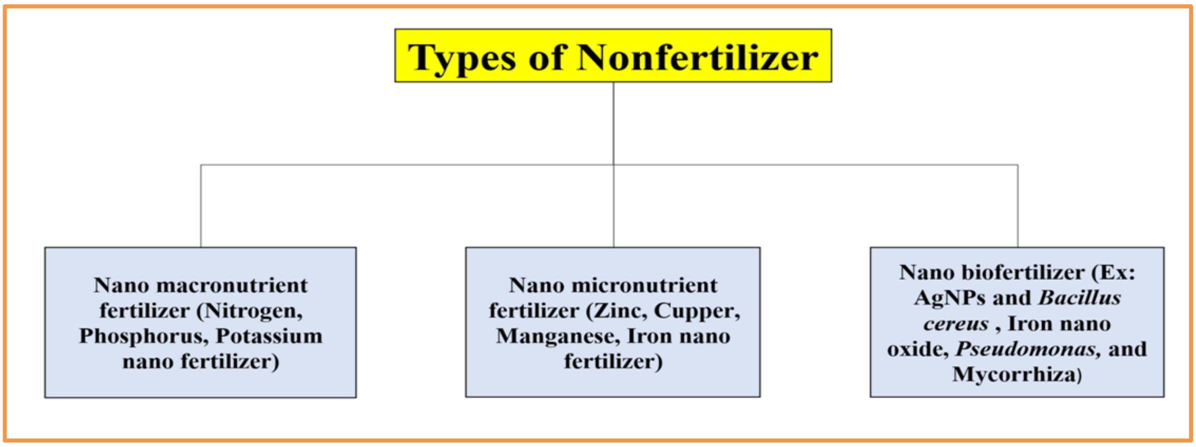
Types of nono-fertilizer

Nanofertilizers can be broadly classified based on the type of nutrient they provide. These fertilizers are formulated using nanoscale materials, generally within the range of 1-100 nm, with the aim of improving nutrient availability, absorption, and utilization by plants.

Nano-macro fertilizer: Macronutrients are required by crops in large quantities, but conventional fertilizers often have low nutrient-use efficiency, leading to considerable nutrient losses. Nanomacronutrient fertilizers offer a promising approach to improve nutrient uptake and reduce these losses.

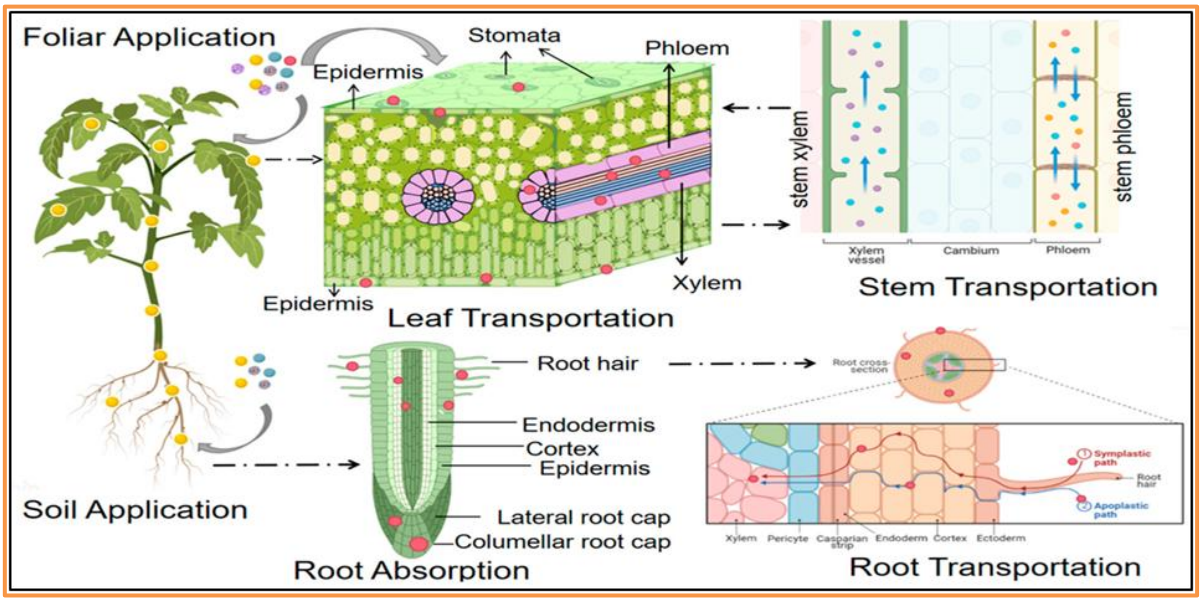
Nano-micro fertilizer: Nano-micronutrient fertilizers supply essential micronutrients such as Zn, Fe, Mn, Cu, and B in nanoscale formulations, potentially improving their availability and uptake by plants. Compared with conventional micronutrient fertilizers, they may enhance nutrient-use efficiency and reduce nutrient losses, making them useful for correcting micronutrient deficiencies more efficiently. Examples include nano-zinc, nano-iron, nano-boron, and nano-manganese fertilizers.

Nano biofertilizer: Nano-biofertilizers combine nanotechnology with beneficial microorganisms or biological materials to improve nutrient availability and plant growth. They can enhance microbial activity, nutrient solubilization, and nutrient-use efficiency while potentially reducing dependence on chemical fertilizers. Examples include nano-formulations containing nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and plant growth-promoting rhizobacteria (PGPR).



Mechanisms of nutrient delivery

Nanoparticles enter the plant system through multiple pathways, mainly via foliar application; through stomata, the epidermis, and cracks on the leaf surface and via soil application, where they are absorbed by root hairs and through the root epidermis and cortex. Once inside the leaf, nanoparticles move through leaf tissue and enter the vascular system, being transported through the xylem and phloem in the stem. At the root level, nanoparticles pass through the epidermis, cortex, and endodermis, following either the symplastic pathway (through living cell contents) or the apoplastic pathway (through cell walls and intercellular spaces), before reaching the xylem for upward transport. Within the plant, movement occurs by diffusion, bulk flow, and phloem loading, allowing nanoparticles to reach different plant parts. The efficiency of this uptake and transport is influenced by several factors; particle size and shape, surface properties (charge), the pH of the application solution, and the presence of other ions or compounds. Together, these pathways explain how nanofertilizers, once applied, are able to reach target tissues and deliver nutrients more precisely than conventional fertilizers. (Wang *et al.*, 2023)



Impact on crop production

Among conventional fertilizer levels, 100% RDNP gave the highest bolls, yield (1453 kg seed cotton ha^{-1}), and nutrient uptake, while 50% RDNP showed the best N and P use efficiency. Among nanofertilizers, nano DAP (4 ml/L at 40, 60, 80 DAS) gave comparable results 46.7 bolls/plant and 1420 kg seed cotton ha^{-1} with similarly high use efficiency, while nano urea foliar spray (2 ml/L) improved soil-available N, P, and K the most (Sajjan *et al.*, 2025). A field experiment on wheat evaluated foliar application of nano-phosphorus (nano-P) alongside varying levels of conventional P fertilizer. The treatment combining 100% N and K + 75% P + 2 foliar sprays of nano-P (at tillering and panicle initiation) gave the best results a 37.1% yield increase over 100% RDF, while saving 25% of the recommended P dose. Highest grain micronutrient content (Zn, Cu, Mn, Fe) was recorded in the no-P-foliar treatment (T3), and nano-P also slightly improved post-harvest soil nutrient status. Overall, nano-P at 75% conventional P proved a viable substitute for DAP, reducing P leaching risk while maintaining or improving yield (Poudel *et al.*, 2023). A two-year field trial (2022–2023) at Nubaria Research Station, Egypt, evaluated nano-Zn, nano-Mn, and nano-Mo (each at 20 and 40 mg/L) against their conventional chelate/salt forms on maize in calcareous soil. The 40 mg/L dose was most effective overall, giving the highest grain weight/plant (239.4 g), 100-grain weight (40.7 g), and yield (15.1 t/ha). Nano-Zn (40 mg/L) also boosted leaf P, K, Fe, Zn, and Cu content, while nano-Mn and nano-Mo raised leaf Mn and N, respectively. Overall, nano-micronutrient fertilizers outperformed conventional forms in growth, yield, and nutrient uptake under calcareous soil conditions (Sary *et al.*, 2025).

Major challenges

Despite their considerable promise, the use of nanoparticles in agriculture is accompanied by several unresolved challenges that limit their large-scale adoption. One of the foremost concerns is dose-dependent toxicity: nanoparticles that stimulate plant growth at low concentrations can become harmful at higher doses. The long-term environmental fate of nanoparticles remains poorly understood; their extremely small size makes them prone to unpredictable behaviour in soil, whether through leaching into groundwater or irreversible fixation within soil matrices, raising concerns that are yet to be fully addressed. Besides all of this; adoption is also slowed by practical and policy issues. Most countries still lack clear safety rules or approval processes for nano-based agricultural products. High production costs make large-scale manufacturing difficult, and many consumers remain wary of "nano" food products, even when they're proven safe. Research is also limited mostly focused on a few nanoparticles like zinc, iron, silver, and titanium dioxide, and tested on only a handful of crops. Overall, wider use of nanoparticle-based fertilizers will need more field studies, clearer regulations, and cheaper production methods.

Future prospectus

Looking ahead, nanofertilizers can be combined with smart farming tools, like sensors and AI, to apply nutrients exactly when and where crops need them. More long-term field studies are needed to fully understand their effects on soil, microbes, and food safety. Clearer, globally consistent safety rules would also help build trust and support wider use. Making production cheaper and using eco-friendly, waste-based methods can help more farmers afford these fertilizers. Research should also expand to cover more nutrients and crops, not just the few studied so far. Most importantly, these technologies need to reach ordinary farmers through training and support programs, not stay limited to labs and large farms.

References

1. IMARC Group. (2026). *India nano fertilizer market size, share, trends and forecast by raw material, method of application, application, and region, 2026–2034* (Report No. SR112026A30342). https://www.imarcgroup.com/india-nano-fertilizer-market
2. Upadhyay, P. K., Dey, A., Singh, V. K., Dwivedi, B. S., Singh, T., Rajanna, G. A., Babu, S., Rathore, S. S., Singh, R. K., Shekhawat, K., Rangot, M., Kumar, P., Yadav, D., Singh, D. P., Dasgupta, D., & Shukla, G. (2023). Conjoint application of nano-urea with conventional fertilizers: An energy efficient and environmentally robust approach for sustainable crop production. *PLOS ONE*, 18(7), e0284009.https://doi.org/10.1371/journal.pone.0284009
3. Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., Rehman, H. U., Ashraf, I., & Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and

future opportunities. *The Science of the total environment*, 721, 137778. https://doi.org/10.1016/j.scitotenv.2020.137778
4. Ministry of Chemicals and Fertilizers, Department of Fertilizers, Government of India (2026, March 20). *Government Highlights Significant Progress in Nano-Fertilizer Adoption and Drone-Led Agricultural Transformation*. Press Information Bureau (PIB), New Delhi. Release ID: 2242958.
5. Wang, X., Xie, H., Wang, P., & Yin, H. (2023). Nanoparticles in Plants: Uptake, Transport and Physiological Activity in Leaf and Root. *Materials*, 16(8), 3097.https://doi.org/10.3390/ma16083097
6. Sajjan, G., Shashikumar, C., Sunil, C. M., Navi, S., & Yogananda, S. B. (2025). Effect of Nano Fertilizers on Yield, Nutrient Uptake, Soil Nutrient Status and Fertilizer Use Efficiency of Bt Cotton. *Journal of Advances in Biology & Biotechnology*, 28(2), 663–672. https://doi.org/10.9734/jabb/2025/v28i22026
7. Poudel, A., Singh, S. K., Jiménez-Ballesta, R., Jatav, S. S., Patra, A., & Pandey, A. (2023). Effect of Nano-Phosphorus Formulation on Growth, Yield and Nutritional Quality of Wheat under Semi-Arid Climate. *Agronomy*, 13(3), 768.https://doi.org/10.3390/agronomy13030768
8. Sary, D.H., Abd El-Aziz, M.E. Synthesis and characterization of nano-micronutrient fertilizer and its effect on nutrient availability and maize (*Zea Mays* L.) productivity in calcareous soils. *Sci Rep* 15, 25838 (2025). https://doi.org/10.1038/s41598-025-11273-7