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Nano-Fertilizers: The Future of Nutrient Delivery Systems

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Global agriculture is under increasing pressure to produce higher yields while reducing environmental degradation and conserving finite natural resources. Conventional fertilizers, although essential for crop production, often exhibit low nutrient use efficiency because of leaching, volatilization, runoff, and soil fixation. These losses not only reduce crop productivity but also contribute to environmental pollution and greenhouse gas emissions. Nano-fertilizers have emerged as a promising next-generation nutrient delivery technology capable of addressing these challenges through controlled and targeted nutrient release. Engineered at the nanometer scale, these fertilizers possess unique physicochemical properties, including a high surface area, enhanced solubility, and improved interaction with plant tissues, enabling greater nutrient uptake and utilization. Recent advances in nanotechnology have facilitated the development of nano-based formulations containing essential macro- and micronutrients, such as nitrogen, phosphorus, potassium, zinc, iron, and copper. Field studies increasingly demonstrate that nano-fertilizers improve crop growth, nutrient use efficiency, stress tolerance, and yield while minimizing fertilizer losses and environmental impacts. Furthermore, the integration of nano-fertilizers with precision agriculture, Internet of Things (IoT)-based nutrient management, and artificial intelligence-driven decision support systems is reshaping sustainable nutrient management. This article discusses recent developments, preparation methodologies, applications, benefits, challenges, and future prospects of nano-fertilizers, emphasizing their transformative potential in building climate-smart, resource-efficient, and sustainable agricultural systems.

Keywords: Nano-fertilizers; Nutrient use efficiency; Precision agriculture; Sustainable agriculture; Controlled nutrient release

Introduction

Agriculture is undergoing a remarkable transformation as scientists search for innovative technologies capable of feeding a growing global population while minimizing environmental damage. Conventional fertilizer application methods suffer from poor nutrient recovery, with crops often utilizing only 30–50% of applied nitrogen and even lower proportions of phosphorus. The remaining nutrients are lost through leaching, runoff, volatilization, and immobilization, contributing to soil degradation, water pollution, eutrophication, and greenhouse gas emissions (Kah et al., 2018).

Nanotechnology has introduced a revolutionary approach to nutrient management through the development of nano-fertilizers. These materials typically range between 1 and 100 nanometers and exhibit unique physicochemical characteristics that enable controlled nutrient release, enhanced mobility, and efficient absorption by plant roots and leaves (Dimkpa & Bindraban, 2018). Unlike conventional fertilizers, nano-fertilizers can

synchronize nutrient release with crop demand, thereby improving nutrient use efficiency while reducing environmental losses.

Recent developments have accelerated the commercialization of nano-fertilizers worldwide. Countries including India, China, Brazil, and the United States have invested heavily in nano-enabled agricultural products. India's introduction of Nano Urea and Nano DAP represents one of the largest initiatives to replace conventional fertilizers with nano-based alternatives. Simultaneously, researchers are developing smart nano-carriers capable of responding to environmental stimuli such as soil moisture, pH, and root exudates, ensuring nutrients are delivered precisely when required (Raliya et al., 2018).

Current trends also emphasize integrating nano-fertilizers with precision agriculture technologies such as drones, satellite imaging, IoT-based sensors, geographic information systems (GIS), and artificial intelligence. Such integration enables site-specific nutrient management, reducing fertilizer waste while maximizing crop productivity. As agriculture moves toward climate-smart and resource-efficient production systems, nano-fertilizers are increasingly recognized as a cornerstone technology capable of supporting sustainable intensification and long-term food security.

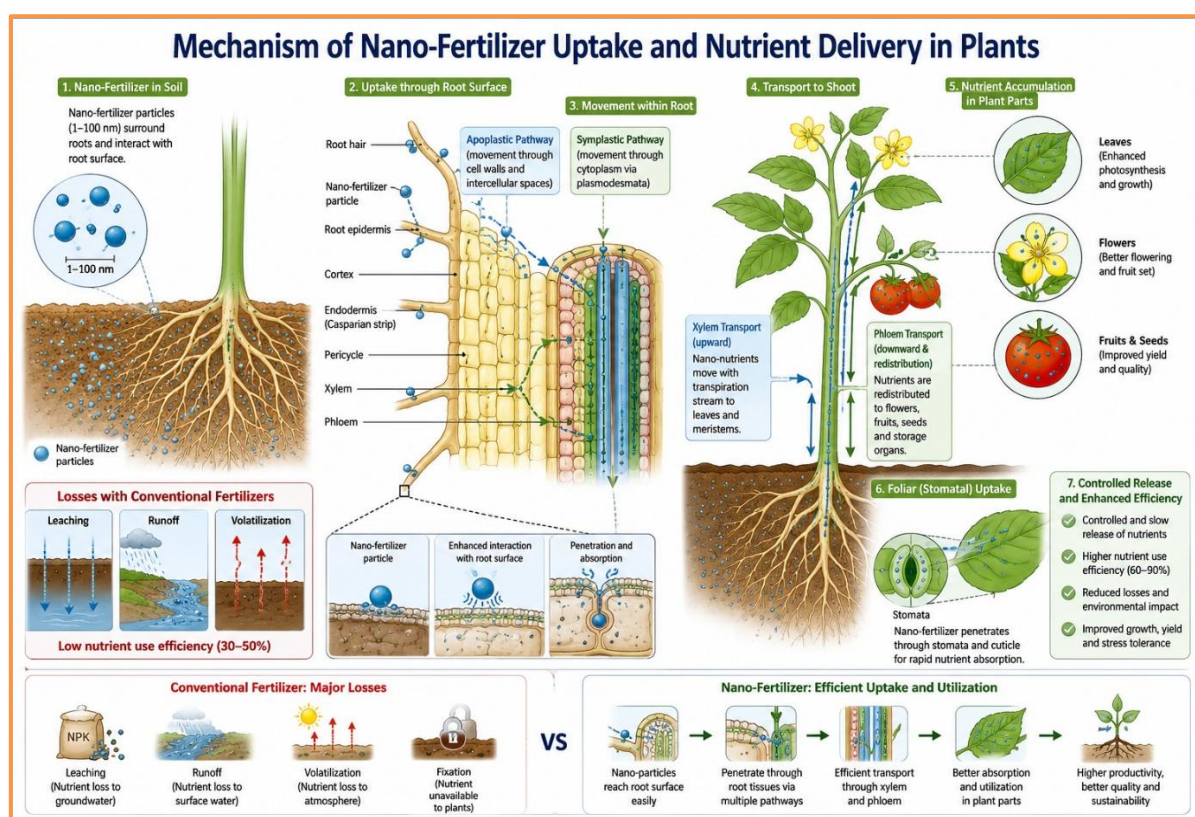


Figure 1. Mechanism of Nano-Fertilizer Uptake and Nutrient Delivery in Plants

Methodology: The Recent Advances

Modern nano-fertilizer production combines advances in nanotechnology, materials science, biotechnology, and precision agriculture to develop highly efficient nutrient delivery systems. Recent methodologies focus on environmentally friendly synthesis techniques that reduce production costs while improving nutrient availability and crop safety.

The first stage involves selecting suitable nutrient sources containing essential macro- or micronutrients such as nitrogen, phosphorus, potassium, zinc, iron, boron, or copper. Depending on the desired formulation, nanoparticles may be synthesized using physical, chemical, or biological methods. Physical approaches include milling, ultrasonication, and laser ablation, whereas chemical synthesis employs precipitation, sol-gel processing, hydrothermal methods, or polymer encapsulation. Increasing attention is now directed toward green synthesis using plant extracts, microorganisms, algae, fungi, or agricultural wastes to minimize hazardous chemical usage (Kumar et al., 2023).

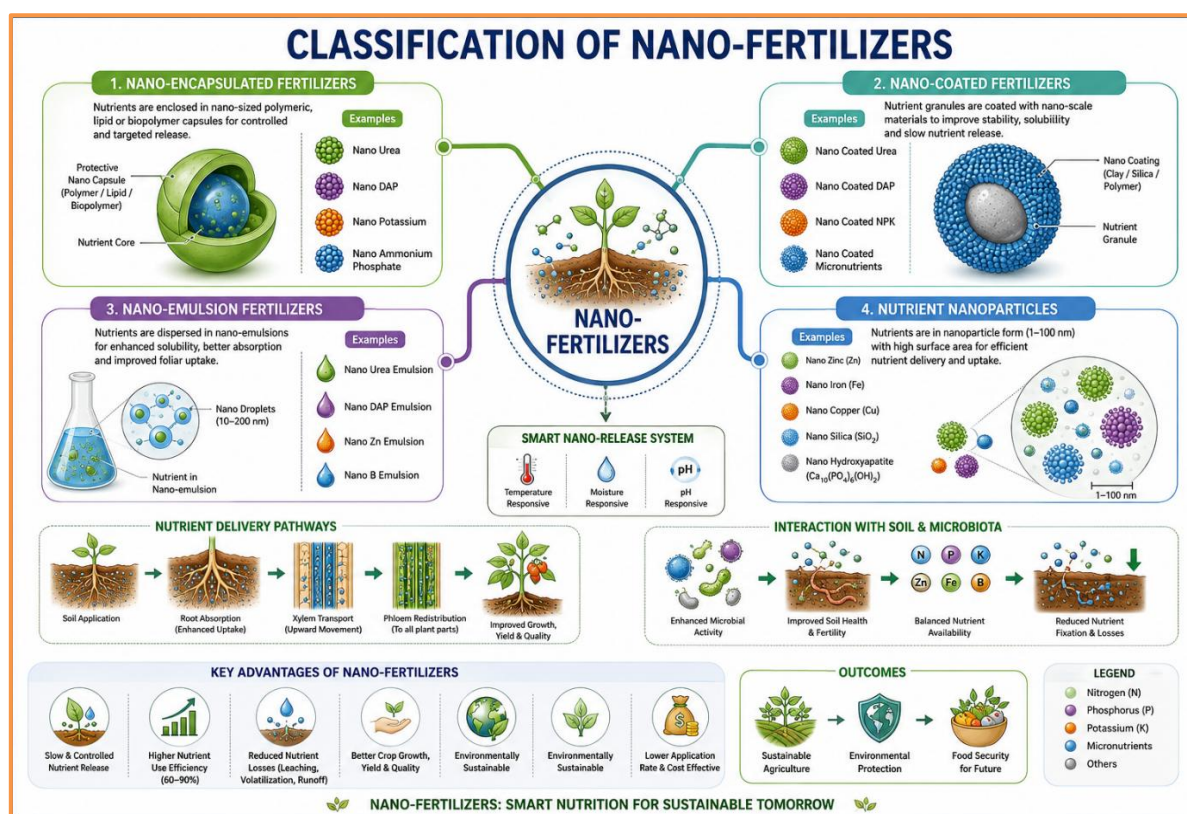


Figure 2. Types and Classification of Nano-Fertilizers

Once synthesized, nanoparticles are thoroughly characterized using advanced analytical techniques. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) determine particle morphology and size, while X-ray Diffraction (XRD) confirms crystalline structure. Fourier Transform Infrared Spectroscopy (FTIR) identifies functional groups responsible for nutrient binding, whereas Dynamic Light Scattering (DLS) evaluates particle stability and distribution. These analyses ensure product quality and consistency before agricultural application.

Controlled-release nano-fertilizers are then prepared by encapsulating nutrients within biodegradable polymers, nanoclays, hydrogels, chitosan, silica nanoparticles, or lipid-based carriers. Such encapsulation protects nutrients from premature losses and enables gradual release according to plant demand. Recent formulations also incorporate responsive nanocarriers capable of releasing nutrients under specific environmental conditions, including changes in soil moisture, pH, temperature, or enzymatic activity.

Application methodologies have also evolved significantly. Nano-fertilizers may be applied through seed priming, soil incorporation, fertigation, hydroponic nutrient solutions, or foliar spraying. Foliar application has become particularly popular because nanoparticles can penetrate leaf cuticles and stomata more efficiently than conventional fertilizers, resulting in rapid nutrient uptake.

Recent research increasingly integrates nano-fertilizer application with digital agriculture. IoT-based nutrient sensors continuously monitor soil nutrient availability, while drones equipped with multispectral cameras identify nutrient deficiencies across agricultural fields. Artificial intelligence algorithms analyze these datasets and generate prescription maps for variable-rate nano-fertilizer application. This precision approach minimizes fertilizer consumption while maximizing nutrient use efficiency and crop performance.

Before commercial deployment, nano-fertilizers undergo greenhouse trials followed by multi-location field experiments to evaluate crop growth, nutrient uptake, yield response, environmental safety, and economic feasibility. Researchers also assess nanoparticle persistence, soil microbial interactions, and food safety to ensure sustainable adoption. These multidisciplinary methodologies have substantially improved the reliability, effectiveness, and commercial potential of nano-fertilizers for modern agriculture.

Results and Discussion

Recent studies consistently demonstrate that nano-fertilizers significantly improve crop productivity, nutrient use efficiency, and environmental sustainability compared with conventional fertilizers.

Table 1. Comparison between Conventional Fertilizers and Nano-Fertilizers

Parameter	Conventional Fertilizers	Nano-Fertilizers
Particle size	Millimeter scale	1–100 nm
Nutrient release	Rapid	Controlled and slow
Nutrient use efficiency	Low (30–50%)	High (60–90%)
Nutrient losses	High	Minimal
Leaching	High	Low
Volatilization	High	Low
Frequency of application	More frequent	Less frequent
Application dose	Higher	Lower
Environmental pollution	Significant	Reduced
Crop productivity	Moderate	Higher
Cost efficiency	Lower over time	Higher long-term benefit
Compatibility with precision farming	Limited	Excellent

One of the most important advantages is enhanced nutrient use efficiency. The nanoscale dimensions increase the surface area available for nutrient exchange, allowing nutrients to be absorbed more efficiently by plant roots and leaves. Controlled nutrient release minimizes losses through leaching, volatilization, and runoff, enabling crops to utilize a larger proportion of applied nutrients (Dimkpa & Bindraban, 2018).

Numerous field experiments have reported substantial yield improvements following nano-fertilizer application. Nano zinc formulations have increased grain yield in cereals by improving chlorophyll synthesis and enzyme activation. Nano iron enhances photosynthesis and chlorophyll production, while nano phosphorus improves root development and energy metabolism. Nano nitrogen formulations have demonstrated improved nitrogen recovery, enabling reduced fertilizer application without compromising crop yield (Raliya et al., 2018). Another significant finding is improved tolerance to abiotic stress. Nano-fertilizers enhance antioxidant enzyme activity, strengthen cellular defense systems, and improve water-use efficiency, enabling crops to better withstand drought, salinity, heat stress, and nutrient-deficient conditions. Such resilience is increasingly valuable under changing climatic conditions.

Environmental benefits are equally noteworthy. Conventional fertilizers frequently contaminate groundwater through nitrate leaching and contribute to eutrophication of rivers and lakes. Nano-fertilizers reduce these losses through targeted nutrient delivery and slow-release mechanisms, decreasing nutrient pollution and lowering greenhouse gas emissions associated with fertilizer production and application (Kah et al., 2018).

Recent investigations have also demonstrated positive effects on soil health. Controlled nutrient availability supports beneficial microbial communities while minimizing salt accumulation and nutrient imbalances. Green-synthesized nanoparticles further reduce ecological risks by replacing hazardous chemical stabilizers with biodegradable materials. Economic analyses indicate that although nano-fertilizers generally have higher manufacturing costs, lower application rates and improved nutrient recovery often compensate for these expenses. Farmers may reduce fertilizer use while maintaining or increasing crop yields, resulting in improved profitability over time.

Table 2. Commercially available nano-fertilizers and their principal agricultural applications.

Nano-Fertilizer	Nutrient	Method of Application	Major Benefits
Nano Urea	Nitrogen	Foliar spray	Higher NUE, reduced nitrogen loss
Nano DAP	Nitrogen + Phosphorus	Foliar spray	Better root growth
Nano Zinc	Zinc	Foliar/Soil	Corrects Zn deficiency
Nano Iron	Iron	Foliar	Improved chlorophyll synthesis
Nano Boron	Boron	Foliar	Better flowering and fruit set
Nano Copper	Copper	Foliar	Improved enzyme activity and disease resistance

Nevertheless, several challenges remain before widespread commercialization can be achieved. Standardized production protocols, regulatory frameworks, toxicity assessments, and long-term environmental monitoring are still evolving. Questions regarding nanoparticle accumulation in soils, food chains, and aquatic ecosystems require comprehensive investigation before universal adoption can be recommended (Parisi et al., 2015).

Current research increasingly focuses on multifunctional nano-fertilizers capable of simultaneously delivering nutrients, growth stimulants, beneficial microorganisms, and plant protection compounds. Integration with precision agriculture technologies further enhances application accuracy. Artificial intelligence can predict nutrient deficiencies, while drones and autonomous sprayers enable site-specific nano-fertilizer application, minimizing waste and labor requirements.

Case Study: Nano Urea Adoption in India

India has emerged as a global leader in the commercialization of nano-fertilizers through the large-scale introduction of Nano Urea (Liquid) developed by the Indian Farmers Fertiliser Cooperative (IFFCO). The technology was designed to improve nitrogen use efficiency while reducing dependence on conventional urea. Nano Urea contains nitrogen particles within the nanoscale range, enabling rapid absorption through leaf stomata and efficient translocation within plants.

Field demonstrations conducted across multiple agro-climatic regions have shown that replacing one bag of conventional urea with a 500 mL bottle of Nano Urea, when used as a foliar spray alongside recommended nutrient management practices, can maintain crop productivity while reducing nitrogen application. Farmers have reported improvements in nutrient use efficiency, lower fertilizer transportation costs, reduced nitrogen losses through leaching and volatilization, and better environmental sustainability. The technology has been evaluated in crops such as rice, wheat, maize, sugarcane, and several horticultural crops, demonstrating encouraging agronomic and economic performance. The Indian experience highlights the potential of nano-fertilizers to support climate-smart agriculture, enhance fertilizer efficiency, and contribute to national goals of sustainable agricultural intensification.

Overall, available evidence strongly suggests that nano-fertilizers represent one of the most promising innovations in sustainable nutrient management. Continued interdisciplinary research involving agronomists, nanotechnologists, environmental scientists, economists, and policymakers will be essential for translating laboratory successes into safe, affordable, and widely accessible agricultural technologies.

Future Perspectives

The future of nano-fertilizers lies in developing intelligent nutrient delivery systems capable of responding dynamically to plant nutritional requirements and environmental conditions. Researchers are currently designing stimulus-responsive nanoparticles that release nutrients

only under specific moisture, temperature, pH, or root exudate conditions, thereby maximizing nutrient use efficiency.

Integration with Agriculture 5.0 technologies will further revolutionize nutrient management. Artificial intelligence, machine learning, digital twins, Internet of Things sensors, satellite remote sensing, and unmanned aerial vehicles will enable real-time monitoring of crop nutrient status and automated variable-rate nano-fertilizer application. Such technologies will support highly precise, resource-efficient farming systems.

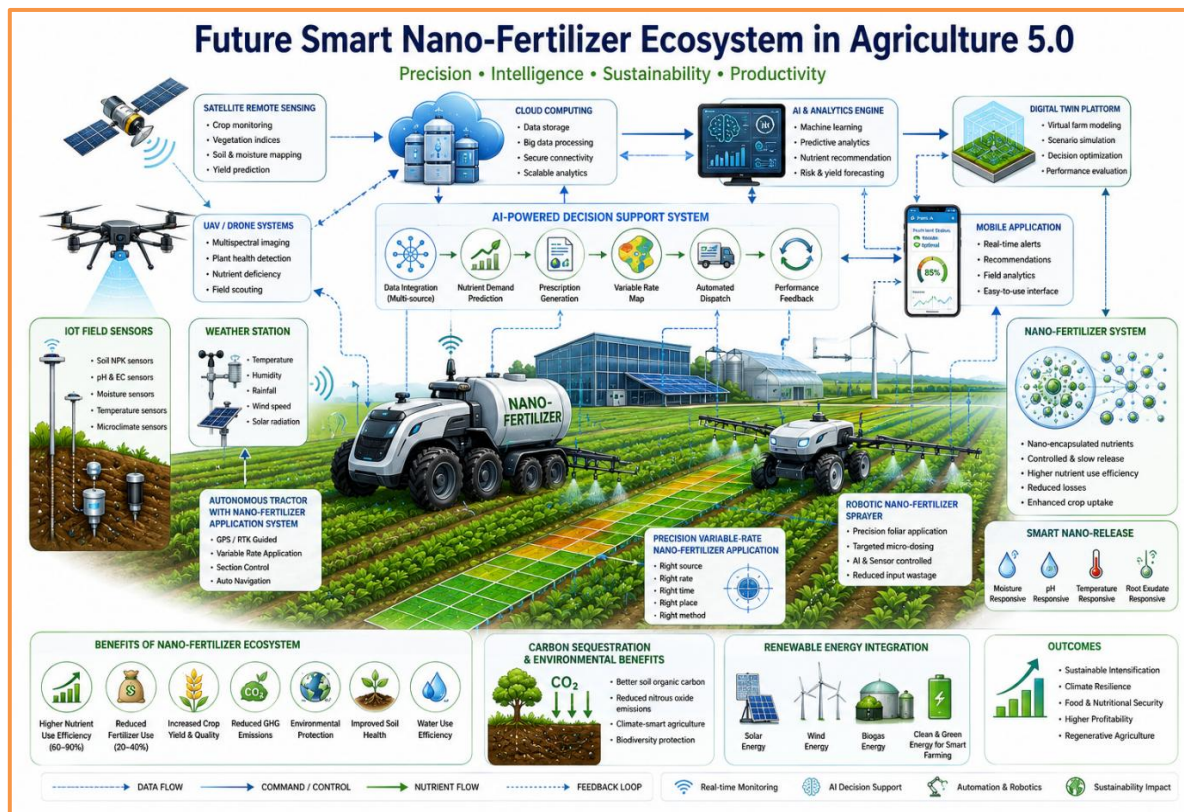


Figure 3. Future Smart Nano-Fertilizer Ecosystem (Agriculture 5.0)

Future investigations should also prioritize biodegradable and bio-based nanomaterials to minimize ecological risks while improving farmer acceptance. Comprehensive life-cycle assessments, standardized toxicity protocols, and harmonized international regulations will be necessary to ensure safe commercialization. Furthermore, reducing production costs through green synthesis using agricultural wastes, microorganisms, and plant extracts can enhance affordability for smallholder farmers. As research advances, nano-fertilizers are expected to become an integral component of climate-smart agriculture, contributing to sustainable food production, improved environmental quality, and enhanced global food security.

Conclusion

Nano-fertilizers represent one of the most significant technological advancements in modern nutrient management. Their unique nanoscale properties facilitate controlled nutrient release, enhanced plant uptake, and improved nutrient use efficiency while minimizing environmental losses associated with conventional fertilizer application. As global agriculture faces increasing challenges related to climate change, declining soil fertility, water scarcity, and environmental degradation, nano-fertilizers offer an innovative pathway toward sustainable crop production.

Recent research demonstrates that nano-fertilizers improve crop growth, nutrient uptake, photosynthetic efficiency, stress tolerance, and yield across diverse agricultural systems. Their compatibility with precision agriculture technologies, including IoT sensors, artificial intelligence, drones, and satellite monitoring, further strengthens their potential for site-specific nutrient management. These integrated systems enable farmers to optimize fertilizer application while reducing production costs and environmental impacts.

Despite these encouraging developments, several challenges require attention before widespread adoption can occur. Long-term environmental safety, nanoparticle persistence, food safety assessments, regulatory harmonization, and farmer awareness remain important research priorities. Continued investment in green synthesis methods and biodegradable nanomaterials will further improve sustainability and public acceptance.

Future agricultural systems will increasingly rely on smart nutrient management technologies capable of balancing productivity with environmental stewardship. Nano-fertilizers are well positioned to become a key component of this transformation by supporting climate resilience, resource conservation, and sustainable intensification. Through interdisciplinary collaboration among researchers, industry, policymakers, and farming communities, nano-fertilizers can contribute substantially to achieving global food security while protecting natural ecosystems for future generations.

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