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## Nanofertilizers: A Technical Perspective on Sustainable Nutrient Delivery Systems

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Modern agriculture relies heavily on chemical fertilizers to meet global food demand; however, inefficient nutrient utilization leads to significant losses through leaching, volatilization, and runoff, causing environmental pollution and soil degradation. Studies indicate that up to 50-70% of applied nitrogen is lost in conventional systems. In this context, nanofertilizers have emerged as a promising alternative, offering precision nutrient management through nanotechnology. These materials deliver macro- and micronutrients in a regulated manner, thereby improving crop productivity and sustainability.

### Classification

Nanofertilizers can be broadly classified based on their composition and function. Nutrient-based nanoparticles contain essential plant nutrients such as nitrogen, phosphorus, potassium, zinc, and iron, with common examples including ZnO nanoparticles and nano-urea. Nano-encapsulated fertilizers involve nutrients enclosed within nanomaterials such as polymers or zeolites, enabling slow and controlled release. Nanocomposite fertilizers combine nanoparticles with bulk fertilizers to enhance stability and nutrient use efficiency. Additionally, bio-nanofertilizers integrate nanoparticles with beneficial microorganisms, thereby improving soil fertility and plant-microbe interactions.

### Synthesis techniques

The synthesis of nanofertilizers is achieved through multiple approaches. Top-down techniques such as mechanical milling and lithography break bulk materials into nanoscale particles, whereas bottom-up approaches, including chemical precipitation and sol-gel methods, construct nanoparticles atom by atom. More recently, green synthesis methods utilizing plant extracts, bacteria, and fungi have gained attention due to their eco-friendly nature and reduced toxicity.

### Mechanism of action

Nanofertilizers function through several advanced mechanisms. One of the primary mechanisms is controlled nutrient release, wherein nanomaterials regulate the availability of nutrients in accordance with plant demand, minimizing losses. Additionally, nanoparticles enhance nutrient uptake and transport by entering plants through roots or stomata and moving via xylem and phloem pathways to target tissues. Their high surface-to-volume ratio improves nutrient adsorption and interaction with plant cells. Furthermore, nanofertilizers influence plant metabolism by enhancing photosynthesis, increasing enzyme activity, and improving antioxidant defense systems.

### Agronomic benefits

From an agronomic perspective, nanofertilizers offer several benefits. They significantly improve nutrient use efficiency, with reported increases of up to 30%, and enhance crop yields by 20-30% across various crops. Moreover, they reduce fertilizer consumption, as application rates can be 30-100 times lower than conventional fertilizers. Nanofertilizers also

enhance plant tolerance to abiotic stresses such as drought, salinity, and heat by regulating gene expression and antioxidant enzyme activity. Importantly, they contribute to environmental protection by reducing nutrient runoff, greenhouse gas emissions, and soil and water contamination.

### **Applications in agriculture**

In agricultural practice, nanofertilizers are applied through multiple methods, including foliar application (e.g., nano urea and nano zinc), soil application for slow nutrient release, seed treatment (nano-priming), and use in hydroponics and precision farming systems. Additionally, they improve postharvest quality and shelf life by enhancing nutrient composition and reducing microbial activity.

### **Market segmentation**

The global nanofertilizer market is experiencing rapid growth, reflecting increasing adoption of sustainable agricultural technologies. The market was estimated at approximately USD 3–4 billion in 2024-2025 and is projected to reach USD 8.7–14 billion by 2033–2035, with a compound annual growth rate (CAGR) of around 12-15%. Nitrogen-based nanofertilizers dominate the market with an approximate 30% share. By application method, soil application accounts for about 54% of usage, while foliar spray is the fastest-growing segment, with a CAGR of around 13%. In terms of crop types, cereals and grains dominate the market with approximately 46% share, while fruits and vegetables exhibit significant growth potential.

### **Key industry players**

Key industry players driving the development and commercialization of nanofertilizers include Indian Farmers Fertiliser Cooperative Limited (IFFCO), EuroChem Group, Yara International, and BASF SE. These companies are investing in crop-specific formulations, smart delivery systems, and scalable production technologies. Technological trends shaping the market include the development of liquid nanofertilizers, which account for approximately 60% of the market, the emergence of stimuli-responsive nanocarriers, the use of bio-based and biodegradable nanomaterials, and the integration of nanofertilizers with AI-driven precision farming systems.

### **Recent advances and research trends**

Recent research advancements in the field of nanofertilizers focus on the development of smart fertilizers with stimuli-responsive release mechanisms, integration with precision agriculture and Internet of Things (IoT) technologies, and the use of green synthesis methods for nanoparticle production. Additionally, nanofertilizers are being explored for improving the nutritional quality of crops, including increased vitamin content and antioxidant levels.

### **Future prospects**

The future of nanofertilizers lies in the development of smart systems capable of real-time nutrient sensing, integration with digital agriculture platforms, and large-scale commercialization through cost reduction. The development of eco-friendly and biodegradable nanocarriers is also expected to play a crucial role. By 2035, nanofertilizers are anticipated to become a core component of precision and climate-smart agriculture systems, potentially replacing a significant portion of conventional fertilizers, improving global food security, and supporting climate-resilient agriculture. However, long-term field studies, environmental risk assessments, and regulatory frameworks are essential to ensure their safe and effective adoption.

### **Conclusion**

Nanofertilizers represent a transformative innovation in modern agriculture by providing efficient nutrient delivery, enhancing crop productivity, and promoting environmental sustainability. Despite their considerable potential, challenges related to safety, cost, and regulatory approval must be addressed to enable their widespread adoption and commercialization.