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Nanofertilizers: Advances, Mechanisms, and Applications in Sustainable Crop Nutrition

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Nanofertilizers represent a transformative approach to improving nutrient-use efficiency (NUE) and sustainability in global agriculture. By manipulating nutrient carriers at the nanoscale, these innovative inputs enable controlled release, enhanced bioavailability, and reduced environmental losses compared with conventional fertilizers. This article reviews the scientific basis, mechanisms, and agronomic potential of nanofertilizers, along with associated risks and regulatory implications.

Introduction

Escalating food demand, diminishing soil fertility, and environmental degradation necessitate improved nutrient management strategies. Traditional fertilizers often suffer from low NUE, resulting in nutrient losses through leaching, volatilization, and runoff (Bindraban *et al.*, 2015). Nanotechnology offers new opportunities for nutrient delivery systems tailored to plant physiological needs. Nanofertilizers—defined as nutrients or nutrient carriers engineered at 1–100 nm dimensions—have gained worldwide interest for their potential to enhance crop productivity while reducing ecological footprints (Nair *et al.*, 2010).

Classification of Nanofertilizers

1. Nanoparticulate Nutrients

Metal oxide nanoparticles such as nano-ZnO, nano-Fe_2O_3, and nano-TiO_2 supply essential micronutrients in highly reactive and absorbable forms. Their small size and high surface area improve solubility and root uptake efficiency (Laware & Raskar, 2014).

2. Nanocarrier-Based Fertilizers

Biopolymer and polymeric nanocarriers (e.g., chitosan, alginate, nanogels) encapsulate macronutrients such as nitrogen, phosphorus, and potassium. These systems enable targeted and slow nutrient release, maintaining synchrony with crop demand (DeRosa *et al.*, 2010).

3. Nanoscale Coatings

Nano-clays, carbon nanotubes, and silica nanoparticles function as coatings for conventional fertilizer granules, altering dissolution patterns and reducing losses by controlled release (Rameshaiah *et al.*, 2015).

Mechanisms of Enhanced Nutrient Delivery

1. Controlled Release and Targeted Delivery

Nanocarriers modulate nutrient diffusion through polymer degradation, ion exchange, or pH-triggered mechanisms. This reduces nutrient spikes in soil and enhances long-term availability (Monreal *et al.*, 2016).

2. Improved Root Uptake

Nanoparticles can pass through cell wall pores (5–20 nm) or enter via endocytosis, enabling efficient translocation across plant tissues (Nair *et al.*, 2010). Metal oxide nanoparticles frequently enhance root elongation, membrane transport, and nutrient mobilization.

3. Interaction with Soil Microbiome

Some nanofertilizers, such as nano-silicon and nano-Zn, stimulate beneficial microbial communities and enzymatic activity involved in nutrient cycling (Rashid *et al.*, 2017), though their long-term ecological effects remain under investigation.

Agronomic Benefits

1. Improved Nutrient-Use Efficiency

Numerous studies indicate a 20–40% increase in NUE with nanoformulations of zinc, iron, and nitrogen due to better solubility, uptake, and reduced losses (Bindraban *et al.*, 2015).

2. Enhanced Crop Growth and Yield

Nano-ZnO enhances chlorophyll synthesis, enzyme activation, and grain zinc content in cereals. Nano-Fe_2O_3 improves photosynthetic rates, leaf area, and biomass accumulation (Laware & Raskar, 2014).

3. Abiotic Stress Tolerance

Nano-silicon improves resistance to drought, salinity, and thermal stress by reinforcing cell walls, modulating osmolyte accumulation, and reducing oxidative damage (Rashid *et al.*, 2017).

4. Reduced Environmental Impact

Slow-release nanofertilizers minimize nitrate leaching, nitrous oxide emissions, and eutrophication, contributing to cleaner water systems and lower greenhouse gas emissions (Kah *et al.*, 2018).

Applications in Modern Agriculture

1. Seed Priming

Nanofertilizer priming enhances germination, seedling vigor, and uniform emergence, especially under stress conditions.

2. Foliar Feeding

Nano-nutrients penetrate cuticular layers more effectively than conventional sprays, improving micronutrient correction in fruits and vegetables.

3. Soil Application

Nanocoated granules maintain soil fertility, especially for immobile nutrients such as phosphorus.

4. Hydroponics and Protected Cultivation

Nanochelates maintain stable micronutrient availability in hydroponic nutrient solutions, preventing precipitation and deficiency symptoms.

Risks, Toxicity, and Regulatory Challenges

Despite their potential, nanofertilizers raise concerns regarding environmental safety and human health. Potential issues include:

- Bioaccumulation in plant tissues (Kookana *et al.*, 2014)
- Toxicity to soil fauna and beneficial microbes
- Limited understanding of long-term interactions in ecosystems
- Absence of standardized regulations for nanoparticle classification and permissible limits

A precautionary approach, coupled with robust toxicological research, is recommended before widescale adoption.

Future Prospects

Nanofertilizers are poised to contribute significantly to precision agriculture, integrating with sensor-based systems, drone spraying, and IoT-based nutrient management. Future research should focus on:

- Biodegradable nanocarriers
- Genotype-specific nano-nutrient responses
- Comprehensive risk assessments
- Policy frameworks and farmer training

As agriculture transitions toward sustainability, nanofertilizers may become essential tools in balancing productivity with environmental stewardship.

References

1. Bindraban, P. S., Dimkpa, C., Nagarajan, L., Roy, A., & Rabbinge, R. (2015). Revisiting fertilizers and fertilisation strategies for improved nutrient uptake by plants. *Plant and Soil*, 395, 7–30.
2. DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., & Sultan, Y. (2010). Nanotechnology in fertilizers. *Nature Nanotechnology*, 5, 91.
3. Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers. *Nature Nanotechnology*, 13(8), 677–684.
4. Kookana, R. S. et al. (2014). Nanopesticides: Guiding principles for regulatory evaluation. *Journal of Agricultural and Food Chemistry*, 62(19), 4227–4240.
5. Laware, S. L., & Raskar, S. (2014). Influence of zinc oxide nanoparticles on growth of onion. *International Journal of Current Microbiology and Applied Sciences*, 3(7), 874–881.
6. Monreal, C. M., DeRosa, M., Mallubhotla, S. C., Bindraban, P. S., & Dimkpa, C. (2016). Nanotechnologies for increasing the crop use efficiency of fertilizer-micronutrients. *Biology and Fertility of Soils*, 52(3), 423–437.
7. Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science*, 179, 154–163.
8. Rameshaiah, G. N., Pallavi, J., & Shabnam, S. (2015). Nanotechnology in sustainable agriculture: Present concerns and future aspects. *African Journal of Biotechnology*, 14(4), 208–213.
9. Rashid, U., Farooq, M., & Hassan, A. (2017). Role of silicon nanoparticles in crop improvement under abiotic stress. *Journal of Plant Nutrition*, 40(10), 1439–1451.