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Nano-fertilizers and sustainable agriculture: A chemistry based perspective on nutrient delivery and environmental sustainability

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Abstract
The increasing demand for agricultural productivity has intensified the use of conventional fertilizers, while inefficient nutrient utilization can contribute to nutrient losses and environmental degradation. Nano-fertilizers have emerged as a chemistry-driven approach for improving the delivery and utilization of essential plant nutrients. Their distinctive physicochemical properties, including high surface-area-to-volume ratios, tunable surface chemistry, and possibilities for controlled nutrient release, provide opportunities to redesign conventional fertilizer systems. This paper reviews the chemical principles underlying nano-fertilizers, their major classes, nutrient-release mechanisms, application approaches, and potential contributions to sustainable agriculture. Particular attention is given to nano-formulations containing nitrogen, phosphorus, potassium, zinc, iron, and other micronutrients, together with polymeric, mineral, carbon-based, and composite delivery systems. The discussion also considers the interaction of nanomaterials with soil components, roots, microorganisms, and the rhizosphere. Although the literature indicates considerable potential for improving nutrient-use efficiency and reducing nutrient losses, nano-fertilizers should not automatically be regarded as environmentally harmless alternatives. Their behavior depends on particle composition, size, surface properties, concentration, soil chemistry, environmental conditions, and transformation processes. Long-term ecological effects, production costs, standardization, regulatory requirements, and field-scale validation remain important challenges. A chemistry-based understanding of these factors is essential for developing nano-fertilizer systems that are effective, economical, and environmentally responsible.

Keywords: Nano-fertilizers, nanochemistry, nutrient-use efficiency, controlled release, sustainable agriculture, soil chemistry, nanomaterials, environmental sustainability

Introduction

Agriculture depends on the continuous availability of essential mineral nutrients, particularly nitrogen, phosphorus, potassium, sulfur, iron, zinc, manganese, copper, and boron. Conventional fertilizers have played a major role in increasing crop productivity, but their effectiveness is influenced by processes such as leaching, volatilization, fixation, runoff, precipitation, and chemical transformation in soil. Consequently, the quantity of a nutrient applied to soil does not necessarily correspond to the quantity ultimately available for plant uptake (Liu and Lal, 2015) [7]. Nanotechnology offers a different approach to fertilizer design by controlling the physical and chemical characteristics of nutrient-containing materials at very small length scales. Nano-fertilizers may involve nutrients incorporated into nanoparticles, nutrients adsorbed or encapsulated within nanostructured carriers, nano-coated fertilizers, or nanocomposite systems designed to regulate nutrient release. Their importance therefore lies not simply in reducing particle size but in modifying how nutrients interact with water, soil minerals, organic matter, plant surfaces, and biological systems.

The potential of nano-fertilizers has attracted considerable scientific interest because nanostructured materials can provide controlled or targeted nutrient delivery. Reviews have identified several possible advantages, including improved nutrient availability, reduced losses, enhanced plant uptake, and opportunities for more precise fertilizer application (Yadav *et al*., 2023; Kumar *et al*., 2021) [5, 10]. Recent studies have also emphasized that nano-fertilizer development must consider ecological safety and long-term environmental behavior rather than focusing only on crop productivity (Kekeli *et al*., 2025; Khundi *et al*., 2025) [3].

This paper therefore examines nano-fertilizers primarily from a chemistry perspective, with emphasis on material characteristics, nutrient-release mechanisms, soil interactions, sustainability, and research priorities.

Chemical Basis of Nano-Fertilizers

The behavior of a nanomaterial differs from that of its corresponding bulk material because changes in particle size can alter surface area, surface energy, adsorption behavior, solubility, aggregation, and chemical reactivity. These characteristics are particularly relevant to fertilizer systems because nutrient availability is strongly controlled by interactions occurring at solid–liquid and solid–plant interfaces. A nano-fertilizer can be considered a multifunctional chemical delivery system in which the nutrient and carrier are deliberately combined to modify nutrient transport. Depending on its design, the nutrient may be present as part of the nanoparticle itself, attached to its surface, trapped within a carrier, or incorporated into a coating.

Important chemical characteristics include:

1. Particle size and size distribution;
2. Surface charge and surface functional groups;
3. Chemical composition;
4. Solubility and dissolution behavior;
5. Adsorption capacity;
6. Stability in aqueous and soil environments;
7. Aggregation and dispersion behavior; and
8. Interaction with soil minerals and organic matter.

These properties determine whether a nano-fertilizer remains relatively stable, releases its nutrient gradually, dissolves rapidly, or undergoes transformation after application.

Major Classes of Nano-Fertilizers

Nano-fertilizers can be broadly categorized according to their chemical composition and delivery mechanism.

Nano-Macronutrient Fertilizers

Macronutrients such as nitrogen, phosphorus, and potassium are required in relatively large quantities. Nano-enabled formulations seek to improve their availability and reduce losses. Nitrogen-based systems may use nano structured coatings or carriers to regulate the movement of soluble nitrogen compounds. Phosphorus-based systems may employ mineral nano particles capable of supplying phosphorus while modifying its interaction with soil components. Liu and Lal (2014) [6] demonstrated the potential of synthetic apatite nano particles as a phosphorus source for soybean, illustrating how nano scale mineral materials can be investigated as alternatives to conventional phosphorus fertilizer systems.

Nano-Micronutrient Fertilizers

Micronutrients are required in smaller quantities but are essential for plant metabolism. Zinc and iron have received particular attention because deficiencies of these elements are widespread in agricultural systems. Nano-zinc and nano-iron formulations can be designed to alter dissolution, transport, and availability. However, the biological response depends strongly on concentration and chemical form. Therefore, the term "nano" alone cannot be interpreted as evidence of improved fertilizer performance.

Polymeric Nano-Fertilizers

Polymeric materials can function as carriers or coatings for nutrients. Their chemical structure can be modified to regulate water penetration and nutrient diffusion. Such systems are particularly relevant to controlled-release fertilizers because the polymer matrix can act as a barrier between the nutrient and the surrounding environment.

Mineral-Based Nano-Fertilizers

Mineral nanomaterials such as apatite, zeolite, silica-based materials, and related inorganic structures have been investigated as nutrient carriers. Their usefulness is associated with properties such as adsorption capacity, ion exchange, porosity, and chemical stability. Zeolite-based nitrogen nano-fertilizer systems, for example, have been investigated as a means of modifying nitrogen availability and improving fertilizer-use efficiency (Manikandan and Subramanian, 2016) [8].

Nanocomposite and Hybrid Fertilizers

Nanocomposite systems combine two or more materials to obtain specific chemical or physical properties. A nutrient may be combined with a mineral, polymer, carbon-based material, or another nanostructured component. Such systems provide opportunities for simultaneously controlling nutrient loading, release, stability, and interaction with soil. Recent reviews describe nano-hybrid fertilizers as promising precision-fertilizer systems because their formulation can be adjusted according to crop, soil, and environmental requirements (Science of the Total Environment, 2024) [9].

Controlled Nutrient Release

One of the most important concepts in nano-fertilizer chemistry is controlled nutrient release. Conventional soluble fertilizers can produce a relatively rapid increase in nutrient concentration following application. If plant uptake does not occur at the same rate, nutrients may be lost through leaching, runoff, volatilization, or other pathways.

A nanostructured delivery system can potentially regulate release through:

- Diffusion through a carrier;
- Dissolution of the nutrient-containing phase;
- Degradation of a polymeric matrix;
- Ion exchange;
- Desorption from a surface;
- Changes in pH;
- Changes in ionic strength; and
- Interactions with soil organic and mineral components.

The objective is not simply to make nutrient release slower. An effective fertilizer should release nutrients at a rate that is reasonably synchronized with plant demand. Yadav *et al*. (2023) [10] emphasized controlled-release and targeted-delivery systems as important categories of nano-fertilizers. Similarly, recent literature has highlighted the ability of nanostructured materials to influence nutrient availability through surface interactions and controlled delivery (Kekeli *et al*., 2025) [3].

Interaction with Soil Chemistry

After application, a nano-fertilizer enters a chemically complex soil environment. Soil contains clay minerals, organic matter, dissolved ions, microorganisms, water, and numerous reactive surfaces. Consequently, a nanoparticle may not retain its original properties. Important processes include adsorption, desorption, aggregation, dissolution, oxidation–reduction reactions, ion exchange, and complexation. For example, a metal-containing nanoparticle may release ions into soil solution. These ions can subsequently interact with organic ligands, mineral surfaces, or plant roots. Alternatively, the nanoparticle may aggregate with other particles, changing its mobility and availability. Soil pH is particularly important because it can influence surface charge, dissolution, nutrient speciation, and adsorption. Organic matter may also alter nanoparticle mobility by providing binding sites or promoting dispersion. Therefore, laboratory behavior observed in a simplified aqueous system cannot automatically be extrapolated to agricultural soil.

Plant Uptake and Nutrient Transport

Plant roots represent a chemically active interface between soil and plant tissues. Nutrient uptake is influenced by concentration gradients, chemical speciation, root-surface interactions, transport proteins, and physiological processes. Nano-fertilizers may influence nutrient acquisition through several possible pathways. Nanoparticles can interact with the root surface, release soluble nutrient species, or in some cases enter plant tissues depending on their physicochemical properties. Foliar application represents another potential pathway. In this approach, nano-formulations are deposited on leaf surfaces and may interact with the cuticle and stomatal structures before nutrients become available to plant tissues. The biological response is therefore governed by a combination of nanomaterial chemistry and plant physiology. Kumar *et al*. (2021) [5] noted that particle characteristics, application method, and plant response must all be considered when evaluating nano-agricultural inputs.

Potential Contribution to Sustainable Agriculture

The sustainability argument for nano-fertilizers is based primarily on the possibility of obtaining greater nutrient-use efficiency from carefully designed fertilizer inputs.

Potential advantages include:

Improved Nutrient-Use Efficiency

Controlled delivery may reduce the mismatch between nutrient application and plant demand. Better synchronization could decrease nutrient losses and improve the fraction of applied nutrient that contributes to plant nutrition.

Reduced Nutrient Loss

Nutrients that remain available in soil for longer periods may be less vulnerable to immediate leaching or runoff. However, the magnitude of this benefit is dependent on formulation and environmental conditions.

Precision Nutrient Delivery

Nano-carriers may allow nutrients to be delivered through soil, seed, irrigation water, or foliar application. This creates opportunities for more precise nutrient management.

Potential Reduction in Fertilizer Inputs

If equivalent agronomic performance can be obtained using smaller quantities of nutrients, nano-fertilizers could potentially reduce the material requirements associated with fertilizer application.

Compatibility with Sustainable Agriculture

Nano-fertilizers could become one component of integrated nutrient management involving soil testing, organic amendments, crop rotation, microbial inputs, and precision agriculture rather than functioning as a complete replacement for conventional fertilizers. Recent literature supports this broader interpretation, describing nano-fertilizers as promising but emphasizing the need for appropriate dosage, environmental evaluation, and field validation (Kekeli *et al*., 2025; Khundi et al., 2025) [3, 4].

Environmental and Ecological Considerations

The environmental benefits of nano-fertilizers should not be assumed solely from their small size or lower application rate. Nanomaterials may interact with soil microorganisms, plants, soil fauna, surface water, and groundwater.

Potential environmental concerns include:

- Accumulation of persistent nanomaterials;
- Transformation of nanoparticles in soil;
- Release of potentially bioactive ions;
- Effects on beneficial microorganisms;
- Movement into water systems;
- Trophic transfer;
- Changes in soil biochemical processes; and
- Long-term ecological effects.

The environmental response is highly material-specific. A nanoparticle containing an essential micronutrient may behave differently from a chemically persistent carrier material. Similarly, a biodegradable polymeric nanocarrier may have a different environmental profile from a persistent inorganic nanoparticle. Recent risk-assessment literature stresses that environmental evaluation should accompany the development of new nanofertilizer products because effects on soil organisms, water systems, and non-target species remain incompletely understood (ScienceDirect, 2024) [9].

Green Synthesis and Chemistry of Sustainable Nano-Fertilizers

An important direction in nanochemistry is the development of greener synthesis routes. Conventional nanoparticle synthesis may involve high energy requirements, organic solvents, or chemical reducing and stabilizing agents. Biologically mediated synthesis can use plant extracts, microorganisms, agricultural residues, or naturally derived polymers as sources of reducing, stabilizing, or functionalizing molecules. Such approaches may reduce the environmental burden associated with nanoparticle production. However, "green synthesis" should not automatically be equated with complete environmental safety. The final nanomaterial must still be evaluated for composition, stability, transformation, biological activity, and environmental fate. Consequently, sustainable nano-fertilizer chemistry should consider the complete life cycle of the product—from raw materials and synthesis through application, transformation, crop uptake, and eventual environmental disposal.

Major Research Gaps

Despite extensive laboratory research, several questions remain unresolved. First, there is no universally accepted definition that encompasses all products described as nano-fertilizers. Differences in particle size, carrier composition, nutrient loading, and release mechanism complicate comparisons between studies (Yadav *et al*., 2023) [10]. Second, laboratory-scale results do not necessarily predict field performance. Soil heterogeneity, rainfall, temperature, crop variety, microbial communities, and agricultural management can substantially modify nanomaterial behavior. Third, long-term environmental effects require greater attention. A fertilizer that performs well during a single crop cycle may behave differently after repeated applications. Fourth, cost remains important. The synthesis, purification, stabilization, characterization, packaging, and transportation of nanomaterials can increase production costs compared with established fertilizers. Finally, regulatory frameworks need to account for the specific characteristics of nano-enabled agricultural products. Standardized methods for evaluating physicochemical properties, agronomic effectiveness, environmental fate, and safety would improve comparison between products.

Future Perspective

The future of nano-fertilizers is likely to depend less on the simple development of smaller fertilizer particles and more on rational molecular and materials design.

Future research should prioritize:

1. Environmentally degradable or recyclable carrier materials;
2. Nutrient-responsive release systems;
3. Soil-specific fertilizer formulations;

4. Integration with precision agriculture;
5. Field-Scale rather than exclusively laboratory-based evaluation;
6. Standardized environmental-risk assessment;
7. Life-cycle assessment of nano-fertilizer production and use;
8. Cost-effective manufacturing;
9. Long-term soil monitoring; and
10. Transparent regulatory standards.

The most useful nano-fertilizer may therefore be one designed specifically for a particular nutrient, crop, soil, and environmental condition rather than a universal nano-product.

Conclusion

Nano-fertilizers represent an important intersection of chemistry, materials science, soil science, and plant biology. Their principal scientific advantage is the ability to modify nutrient delivery through control of particle properties, surface chemistry, encapsulation, adsorption, dissolution, and release mechanisms. Such characteristics create opportunities for improving nutrient-use efficiency and reducing losses associated with conventional fertilizer systems.

Nevertheless, nano-fertilizers should be regarded as an emerging technology rather than an automatically sustainable replacement for conventional fertilizers. Their effectiveness and environmental compatibility depend on chemical composition, formulation, application method, soil conditions, dose, transformation, and persistence. A sustainable approach must therefore evaluate both agronomic benefits and environmental costs. The literature reviewed in this paper indicates that the future development of nano-fertilizers should focus on precision, controlled release, safer materials, green synthesis, field validation, and life-cycle sustainability. Chemistry provides the foundation for achieving these goals by enabling deliberate control over nutrient–carrier interactions and material behavior. Continued interdisciplinary research will be necessary before nano-fertilizers can be confidently integrated into large-scale sustainable agricultural systems.

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