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REVIEW

Nanofertilizers: Applications, Challenges, and Their Role in Sustainable Agriculture

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ABSTRACT

Nano-fertilizers are a new technology that has attracted more attention in plant nutrition since they can be designed to improve the efficiency of nutrient delivery, control nutrient release and reduce different types of nutrient loss in soil and surrounding environment. Such fertilizers include materials containing nutrients in nano-form, nano-carriers that can transport and release nutrients in a controlled manner or hybrid formulations containing mineral, organic and biological components. This review covers the concept of nano-fertilizers, their classifications, preparation methods and mechanisms of action. Discussion is also on their potential impact on plant growth, crop productivity and nutrient-use efficiency. The relation of these technologies to sustainable agriculture is also discussed, including possible risks such as phytotoxicity, environmental accumulation, effects on micro-organisms and economic viability. The current literature indicates some nano-formulations may improve the availability or utilization efficiency of selected nutrients under specific conditions. However, the response is dependent on type of material, dosage, crop, soil and mode of application. One of the major challenges that hinder the generalization of findings is the lack of long-term field trials and the absence of standardized protocols for characterization and evaluation. The review concludes that nano-fertilizers are a promising technology which can contribute to the advancement of plant nutrition systems if rigorously evaluated based on scientific evidence, economic feasibility and environmental safety and integrated into comprehensive nutrient management strategies rather than being seen as a universal substitute for conventional fertilizers.

Keywords: *Nano-fertilizers; Sustainable Agriculture; Nutrient Use Efficiency; Controlled Release; Plant Nutrition; Environmental Risks*

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INTRODUCTION

Modern agriculture is confronted with increasing challenges such as growing food demand, degradation of some soil properties, water scarcity and increasing concerns of environmental pollution due to the imbalanced use of chemical substances. Mineral fertilizers are an integral part of agricultural production. They provide plants with important elements for nutrition, formation of plant tissues and increase in the yield and quality of crops. However, plants do not use all the nutrients supplied by fertilizers to their full extent; some are lost by leaching, volatilization or fixation in the soil or by being converted into forms less available to plant roots. The efficiency of fertilizer use is influenced by numerous factors, such as the type of fertilizer, application rate and timing, soil characteristics including pH levels and organic matter content and the specifics of the irrigation system. Over-fertilization leads to higher production costs and greater water and soil pollution. Under-fertilization can result in stunted growth, decreased productivity and depletion of the soil nutrient reserves over time (Mehta *et*

al., 2024). In this context, nanotechnology has emerged as a modern research field which can provide new approaches to deliver nutrients to plants. Some nanomaterials have a high surface area, surface and chemical properties that can be modified, factors that influence the solubility and release of nutrients and their interaction with soil components or with plant surfaces. Moreover, “nano-fertilizers” include a variety of products with different compositions and modes of action (Easwaran *et al*., 2024; Maaz *et al*., 2025). While some studies have been promising, Nano-fertilizer is not a magic word that guaranties a product is more effective and less risky than traditional fertilizers. To prove such advantages, comparisons must be made considering the real amount of the nutrient, the particularities of the material used and the agricultural conditions in which the product was tested. Therefore, the significance of this review is to critically review nano-fertilizers and their potential role in sustainable agriculture, emphasizing their mechanisms of action, agricultural applications, potential benefits, and the scientific, environmental, and economic challenges to be addressed for their up-scaling.

2. CONCEPT AND CLASSIFICATION OF NANO-FERTILIZERS

2.1. Concept of Nano-fertilizers

Nano-fertilizers are products and technologies based on nanomaterials for plant nutrition, which seek to improve the delivery, availability or controlled release of nutrients. A nanomaterial can be a source of a nutrient or a carrier which contains and releases a nutrient gradually. It can be a component of a hybrid composition where different materials are combined to achieve certain properties. It is important to differentiate between fertilizers that contain actual nanoparticles and conventional fertilizers that are coated or modified with nanomaterials or formulations that use nanocarriers to deliver nutrients. This distinction has implications for the assessment of efficacy, safety and environmental risks (Ayenew *et al*., 2025; Mehta *et al*., 2024).

2.2. Fertilizers based on nano-elements or nanocompounds

This category includes materials with nutrients or compounds related to nutrients in the form of nanoparticles or microstructures with nanoscale properties. These include certain compounds of iron, zinc and manganese which are examined as sources of micro-nutrients vital for plant metabolic processes and for the synthesis of enzymes and pigments. The effectiveness of these materials depends on their chemical composition, solubility, particle size, surface properties and the nature of the soil. Hence, it is not possible to assume that an element in its nanoscale form is necessarily more bioavailable to a plant than the same element in a conventional form. Moreover, some of the reported effects might be due to dissolution of the material and subsequent release of ions rather than uptake of intact nanoparticles into plant tissues (Thangavelu *et al*., 2024; Wang *et al*., 2025).

2.3. Slow-Release Nano-Fertilizers

This category refers to the coating or embedding of fertilizers in a coating or carrier material that controls the rate of nutrient release. The goal is to slow down the rapid release of nutrients after application and better match the availability of nutrients in the soil with the needs of the plant at different stages of its growth. These coatings can be of polymeric, mineral or organic materials depending on the desired characteristics of the product. The release process is influenced by the thickness, composition, and degradation rate of the coating, and by environmental factors including temperature, moisture, soil pH, and microbial activity. However, labeling a fertilizer as "slow-release" is not, in itself, sufficient to confirm its efficacy; the nutrient release rate must be measured over time and compared against that of conventional fertilizers under similar conditions (Adams, 2013; Lawrencia *et al*., 2021; Haydar *et al*., 2024).

2.4. Hybrid Nano-fertilizers

Hybrid nano-fertilizers consist of two or more materials; they may combine a nutrient source with a carrier substance or a coating that helps modulate nutrient release, stability, or interaction with the surrounding environment. Such formulations allow for the design of products tailored to the specific needs of certain crops or the particular characteristics of a given soil. However, an increased number of components can add complexity to manufacturing, characterization, and environmental assessment. Therefore, each formulation should be studied independently, and findings from one specific hybrid fertilizer should not be generalized to all hybrid fertilizers (Easwaran *et al*., 2024).

2.5. Nano-biofertilizers

This comprises strategies that pair nanomaterials with beneficial microorganisms or their derivatives, or employ advanced carrier materials to assist in the addition of these microorganisms to the root zone. Such approaches may also include nitrogen-fixing bacteria or phosphate-solubilizing organisms or some fungi associated with root (Thirumurugan *et al*., 2025). One central hypothesis is that an appropriate carrier may improve the stability or survival of the formulation and the efficiency of delivery to the plant. However, this needs to be empirically validated as some nanomaterials may inhibit the microorganisms intended to be used and the response of microorganisms may vary depending on the type, concentration, and properties of the nanomaterial (Mgadi *et al*., 2024; Arora *et al*., 2024). Therefore, it is necessary to evaluate the viability and effectiveness of the microorganisms after preparation, storage and application. Also, the possible effects on the indigenous soil microbial community need to be studied to avoid compromising beneficial organisms and their ecologic roles (Pedrino and Lacava, 2025).

3. PREPARATION METHODS AND PROPERTIES OF NANO-FERTILIZERS

3.1. Preparation Methods

The materials used in nano-fertilizers can be prepared by chemical, physical or biological methods depending upon the type of material and desired properties. Methods based on chemistry include precipitation, hydrolysis and chemical synthesis, and use agents that promote the formation and stabilization of particles. Physical methods may be based on milling, fragmentation, or other operations for reducing particle size or preparing materials with desired surface properties (Saurabh *et al*., 2024; Ayenew *et al*., 2025). Biosynthesis uses plant extracts, microorganisms or bio-based substances to assist in the formation or stabilization of particles. This method has the advantage of minimizing the consumption of specific chemical reagents, but it does not guaranty the safety, homogeneity or industrial scalability of the final product; some difficulties may arise in the control of the synthesis parameters and in the standardization of the properties of the obtained particles (Osman *et al*., 2024). The chosen process must be evaluated based on the purity of the product, particle size distribution, manufacturing cost, energy consumption, potential for mass production with consistent properties and reproducibility of results between different batches (Nagime and Chandak, 2024; Ayenew *et al*., 2025).

3.2. Physical and Chemical Properties

The physical and chemical properties of nano-fertilizers affect the behavior of nano-fertilizers in the soil and the response of the plants to them.

The most important of these properties are:

- Particle size and distribution: These affect surface area and interaction with the surrounding environment.
- Shape: Particle behavior may vary depending on whether they are spherical, rod-shaped, or platy.
- Chemical composition: This determines the nature of the element or compound and its solubility or solubility.

- Surface charge: This may affect interaction with clay, organic matter, and biofilms.
- Agglomeration: This may lead to changes in the actual particle size in solutions and soil.
- Dissolution and release rate: This determines the rate at which the nutrient becomes available.
- Stability during storage: This affects the product's shelf life and homogeneity before use.

A single microscopic image is insufficient to demonstrate all the product's properties, and the measured volume in water may differ from the actual volume after adding the material to the soil solution or irrigation water (Sadiq *et al*., 2025).

3.3. The Importance of Characterization Prior to Agricultural Application

The characterization of any nano-fertilizer should include clear information regarding its chemical composition, particle size and distribution, nutrient content, release rate, and stability. Furthermore, the actual quantity of the nutrient applied to the soil or plant must be determined; comparing equal masses of two different products can be misleading if their nutrient concentrations differ. Reviews on nano-fertilizers highlight that variations in preparation methods, characterization techniques, and experimental design are factors that hinder the comparability and generalizability of published results (Mehta *et al*., 2024; Thangavelu *et al*., 2024).

4. MECHANISMS OF ACTION OF NANO-FERTILIZERS

4.1. Nutrient Release

Nutrients may be released from nano-fertilizers through gradual dissolution, diffusion from a carrier material, or the chemical or biological degradation of a coating. The rate of release depends on the properties of the material, as well as factors such as pH, moisture, temperature, salinity, and soil composition. In the case of coated fertilizers, the controlled-release mechanism is intended to reduce nutrient loss and better synchronize nutrient availability with plant requirements. However, verifying this benefit requires conducting time-dependent release tests and comparing the results against conventional sources of the same nutrient (Haydar *et al*., 2024).

4.2. Root Uptake

Once released from the fertilizer and dissolved in the soil solution, nutrients can reach the plant, move toward the roots, and be absorbed via the plant’s specific transport systems. This process is influenced by root characteristics and physiological activity, nutrient concentration, soil pH, and the interactions between the nutrient and soil components. However, high nutrient uptake efficiency is not necessarily an indication that intact nanoparticles have been taken up by the plant tissues. Instead, the uptake may be due to ions released by the material. So it is important to distinguish between the study of nutrient uptake and that of the translocation of the nanoparticles themselves in the plant.

4.3. Foliar Absorption

Foliar sprays are applied to the leaf surface to deliver specific nutrients, and can be especially useful when a given nutrient is not readily available in the soil. However, the efficiency of foliar application is affected by a number of factors such as leaf surface characteristics, thickness of the waxy cuticle, droplet size, humidity, temperature and formulation of the spray solution. Local burning or toxicity can occur if high concentrations or unsuitable substances are used and care must be taken to avoid this. The assertions on the ability of nanoparticles with standard properties to enter leaves and move to different plant parts need strong empirical backing, since their behavior depends on the material, plant species, and application conditions (Duan *et al*., 2025; Haydar *et al*., 2025).

4.4. Physiological Effects

Some of the substances used in nano-fertilizers may affect root growth, chlorophyll synthesis, enzymatic activity and nutrient content in the plant. Also, changes can be observed in the indicators of oxidative stress or the plant response to environmental conditions. However, these effects should be interpreted with care as they may be due to the provision of the nutrient itself, the inherent properties of the nanomaterial or changes in the soil rather than necessarily due to a single specific mechanism. Therefore, experiments should be designed with appropriate comparative treatments to distinguish the effects of the conventional nutrient, the carrier material and the nano-formulation itself (Thangavelu *et al*., 2024; ALrashidi *et al*., 2025).

5. THE IMPACT OF NANO-FERTILIZERS ON PLANT GROWTH AND CROP PRODUCTIVITY

5.1. Germination and Root Growth

Germination and root length are the indicators in the preliminary assessment of the efficacy of nanomaterials and their potential effects on plants. Some formulations, at the right concentrations, can help to provide essential elements that plants need in the early stages of growth. By contrast, some substances at high concentrations may inhibit germination, reduce root elongation or induce undesirable physiological changes. Hence, an increase in root length or germination in a single experiment should not be taken as sufficient evidence for a substance to be suitable for field application (Zamora-Ledezma *et al*., 2025).

5.2. Vegetative Growth and Photosynthesis

The effect of nano-fertilizers on vegetative growth can be determined by measuring plant height, leaf area, biomass, chlorophyll content, and various physiological parameters. These indicators may improve in some cases where the applied material corrects a nutrient deficiency or improves nutrient availability. However, increased vegetative growth does not necessarily equate to a higher final yield: productivity is also affected by the distribution of dry matter between the vegetative and economically valuable parts of the plant, and by environmental conditions, plant variety and agricultural management practices. Experiments should measure crop yield and quality rather than just early-stage growth indicators (Mahdy and Fathi, 2025; Kekeli *et al*., 2025).

5.3. Nutrient Use Efficiency

Nutrient use efficiency (NUE) is an important index for assessing the performance of nano-fertilizers and modern fertilization technologies. It indicates the efficiency with which a plant can take up added nutrients and use them for growth and yield. This efficiency can be measured by different indicators, above all the recovery efficiency of the added nutrient, the agronomic efficiency and the productivity per unit of fertilizer applied. However, these indicators differ in the way they are computed and what they imply, and hence the indicator used should be clearly specified when comparing results between studies. Ideally, comparisons should be made with similar doses of a specific nutrient to determine if a nano-fertilizer can increase the use efficiency of that specific nutrient, assessing the nutrient content in the plant and estimating the final yield. It is also advisable to try to establish a nutrient budget where possible to approximate the quantities added, taken up and removed from the agricultural system. Although nano-fertilizers may be beneficial in some situations, increases in crop yield or improvements in a specific efficiency measure do not necessarily translate into a reduction in environmental losses, and determining environmental impact requires independent measurements and strong field data (Maaz *et al*., 2025; Lyons *et al*., 2025).

5.4 .Cereal Crops

The use of nano-fertilizers is explored in cereal crops such as wheat, maize and rice among the most important crops. This is due to their potential to improve the availability of essential macronutrients (especially nitrogen and phosphorus) and micronutrients necessary for plant growth and production. Some nanoformulations can assist in improving nutrient use efficiency and productivity with a potential of reducing nutrient loss. However, these effects are dependent on the type and concentration of the nano-fertilizer, plant variety, soil characteristics, and timing of application, irrigation system and environmental conditions. Therefore, such technologies should be evaluated through field trials that compare them against recommended conventional fertilization programs ensuring equivalent nutrient dosage while measuring grain yield and its components, nutrient use efficiency, and the nutrient content of the grain. Furthermore, the limited availability of field-based evidence warrants caution when generalizing findings or adopting nano-fertilizers as a complete replacement for conventional fertilizers (Ranjan *et al*., 2025; Maaz *et al*., 2025).

5.5. Vegetable Crops

Vegetable crops offer opportunities to study the use of nano-fertilizers for improving plant mineral nutrition, particularly in agricultural systems that require precise control over fertilizer application rates and timing. The significance of these applications lies in their ability to correct nutrient deficiencies and to improve the nutritional value of crops, e.g. in terms of increased levels of iron, zinc, or selenium in the edible parts of the plant. This depends on the type of nanomaterial, its properties, and the conditions under which it is applied. However, the success of these applications cannot be gaged only in terms of gains in growth or increase in yield. It is important to consider the qualitative characteristics of the fruit, leaves or roots depending on which part is eaten and to check that the concentrations of nutrients remain within safe limits for human consumption. Furthermore, selecting an appropriate nano-fertilizer requires careful consideration of crop requirements, soil characteristics, and the specific cultivation system. Also important is the assessment of the risk of undesirable accumulation of elements or nanomaterials in the edible parts of the plants before any large-scale adoption (Ayenew *et al*., 2025; Minello *et al*., 2025).

5.6. Fruit Trees and Perennial Crops

Nano-fertilizers may be relevant for the nutrition of fruit trees and perennial crops, particularly in orchards where the soil chemistry does not provide sufficient micronutrients. Studies in fruit trees including pomegranates have shown the possibility of using nano-nutrients to improve the nutritional status of trees and to improve some characteristics of the fruit such as yield and quality (Salimi *et al*., 2025). The degree of response, however, depends on the type of fertilizer, the rate, method of application and environmental conditions (Table 1). These applications require experiments over more than one growing season to investigate the effects of treatments on tree growth and productivity, and the long-term sustainability of the response. Besides monitoring the nutrient content of the fruit, changes in soil properties, and the root zone must be looked at. These components should not build up to undesirable levels. Therefore, nano-fertilizers efficacy should not be assessed by vegetative growth indicators in a single growing season but also by cumulative yield, fruit quality and safety, and overall potential impacts on the agricultural system (Zahedi *et al*., 2020; Maaz *et al*., 2025).

Table (1) Summary of the Effects of Nano-fertilizers on Crop Productivity

Crop	Type of Nanofertilizer or Element	Major Effects on Productivity	Reported Increase	Reference
Wheat	Various nano-compositions, including multi-element nano-fertilizers	Improvement in grain yield and biological yield in the studies covered by the review	Grain yield increased by approximately 20–55%	Ranjan *et al*. (2025)
Maize	Various nano-compositions	Improved plant growth, grain yield, and nutrient use efficiency	Grain yield increased by approximately 22–50%	Ranjan *et al*. (2025)
Rice	Various nano-compositions	Improvement in grain yield in some studies	Grain yield increased by approximately 30–40%	Ranjan *et al*. (2025)
Potato	Various nano-fertilizers	Improved crop productivity in the studies covered by the review	Yield increased by approximately 20–35%	Goyal *et al*. (2025)
Maize	Nano-zinc and nano-silicon	Improved cob length, grain yield, and nutrient use efficiency, particularly under saline conditions	A field study reported grain yield increases of 66% and 106% for nano-zinc and nano-silicon treatments, respectively, compared with the control under saline conditions	Shoukat *et al*. (2024)

6. THE ROLE OF NANO-FERTILIZERS IN SUSTAINABLE AGRICULTURE

6.1. The Production Dimension

The productive potential of nano-fertilizers can be associated with the enhancement of the availability of some plant nutrients or controlled release in accordance with the plants' requirements during different growth stages. This can have a positive effect on nutrient-use efficiency, plant growth and overall productivity under certain agricultural conditions. However, their productive viability can be evaluated only after field trials with consistent results in diverse locations and seasons, and comparison with conventional fertilization programs with equivalent amounts of nutrients. In addition, it is important to distinguish improvements that are a consequence of the specific nano-scale properties of the product from improvements which are due to increased total amount of nutrient supplied or differences in the application method. Thus, the increase in crop yield in one experiment is not enough to claim that the productive impact is sustainable (Maaz *et al*., 2025).

6.2. Environmental Dimension

The environmental benefits of nano-fertilizers, especially those developed for slow or controlled release, are associated with their potential to better match nutrient release with plant uptake. This can help to limit certain loss pathways, such as leaching into water bodies, or volatilization of nitrogenous compounds. However, these benefits are dependent on the specific formulation characteristics, the amount of dosage applied, the soil and climate conditions and the method of application. These benefits cannot be generalized to all types of nano-fertilizers. In addition, the environmental assessment should go beyond crop yield alone and incorporate possible effects on microorganisms, soil and water quality, nanomaterial fate after application, and the environmental impact of manufacturing, transportation and waste disposal. Hence, the environmental sustainability assessment should consider the agricultural benefits and possible risks during the life cycle of the product (Haydar *et al*., 2024; Maaz *et al*., 2025).

6.3. Water and Soil Management

In regions with water shortage, high soil salinity and low soil fertility, modern fertilization technologies are gaining importance. Increasing nutrient-use efficiency can help agricultural production, and optimize the use of inputs. However, the behavior of nanomaterials in soil is influenced by many factors such as pH, salinity, organic

matter content, ionic strength, and the intrinsic properties of the particles themselves, which can affect their solubility, aggregation, mobility, and interactions with soil components. Thus the best and safest use of nano-fertilizers requires their testing in the conditions of actual soil and irrigation water of the target region, taking into account the irrigation system and the characteristics of the root zone. The results of experiments conducted in different environments should not be used as a guide for local recommendations until their relevance to the specific agricultural conditions in question is confirmed (Sadiq *et al*., 2025).

6.4. Economic and Social Dimension

The efficiency of nano-fertilizers is determined not only by their agricultural efficiency, but also by their economic efficiency and practical applicability by farmers. Even when some formulations show promising agricultural results, the costs of raw materials, manufacturing, characterization and quality control may not allow them to compete with conventional fertilizers. Therefore, a feasibility study should take into account the net economic return, the cost per unit of nutrient, application costs, labor, transport and storage costs, the frequency of application and safety requirements. In addition, the product's ease of use and compatibility with the equipment that farmers already have should be considered. These technologies also face hurdles to commercial scale-up, including high costs, limited field data and the absence of standard evaluation methods, according to a new set of reviews. Thus, their application requires a comprehensive economic and environmental comparison with traditional fertilization programs (Maaz *et al*., 2025; Wang *et al*., 2025).

7. THE EFFECT OF NANO-FERTILIZERS ON SOIL AND MICROORGANISMS

The fate of nanomaterials after their application is decided by the soil in a paramount manner. Nanoparticles might clump together, adsorb to clay or organic matter, partially dissolve or convert to other compounds. These processes are affected by soil pH, salinity, composition, organic matter content and dissolved ions. While the binding of nanoparticles with soil components may restrict their mobility, it can also affect the bioavailability of the nutrients that they carry. In contrast, the degradation of these materials can increase the availability of nutrients, but also alters the original properties of the nanoparticles. Soil contains a range of bacteria, fungi and other microorganisms involved in nutrient cycling, breakdown of organic matter and plant growth promotion. Some nanomaterials can change the activity, composition, or functioning of these microbial communities, but the type of effect depends on the type of material, its concentration, how long the organisms are exposed to it, and the environmental conditions. However, the effect of nano-fertilizers on beneficial organisms such as root-associated microbes and mycorrhizal fungi should be studied instead of only focusing on the easily observed plant growth. In addition, the compatibility of nanomaterials with microorganisms in "nano-biofertilizers" needs to be evaluated to ensure the viability and functionality of the target organisms during manufacturing, storage, and application processes (Arora *et al*., 2024; Thangavelu *et al*., 2024).

8. RISKS AND CHALLENGES ASSOCIATED WITH NANO-FERTILIZERS

8.1. Phytotoxicity

Some nanomaterials in high concentrations or under improper conditions may have undesirable effects on plants. Such effects may be reflected in decreased germination, inhibition of root growth, changes in chlorophyll content, or increased markers of oxidative stress. The toxicity depends on the chemical composition, particle size, solubility, and dose, method of application and duration of exposure. Therefore, the effective and safe dosage range

for each specific formulation must be established; a dosage that has been shown to be suitable for one crop should not be generalized to others (Zhang *et al*., 2025; Zamora-Ledezma *et al*., 2025).

8.2. Environmental Fate and Accumulation

Long-term research is still needed to understand the environmental fate of nano-fertilizers, including their persistence in soil and water, the transformations they undergo and the potential for their translocation into plants and other living organisms. Nanoparticles can undergo processes such as dissolution, aggregation, adsorption, and interactions with organic matter or soil minerals that affect their mobility, bioavailability, and persistence in the environment. Such behaviors are related to the chemical composition of the nanomaterial, its surface properties and its solubility. Therefore, the results obtained for one nanomaterial cannot be extrapolated to another one, even if they are in the same class, e.g., metal oxides. Consequently, environmental safety assessments should include investigation of the effects of repeated applications over successive agricultural seasons, monitoring for possible build-up in the soil and the movement of substances into the edible portions of plants. These assessments should also consider effects on non-target organisms, especially soil biota and aquatic life. It is also recommended to carry out such assessments in conditions that resemble the real agricultural surroundings, as the results of short-term or laboratory-based experiments may fail to capture the long-term cumulative effects (Thangavelu *et al*., 2024; Haydar *et al*., 2025).

8.3. Effects of Microorganisms

The microorganisms in soil and rhizosphere are important for the sustainability of agricultural systems as they are engaged in nutrient cycling, organic matter decomposition, facilitation of nutrient uptake, and plant growth and resistance to pathogens. The growing use of nano-fertilizers necessitates the assessment of the interaction of nanomaterials with microbial communities. While some nanomaterials may stimulate the activity of certain microorganisms, others may inhibit the growth of different species or alter their diversity and biological functions. The nature of these effects depends on the chemical composition and concentration of the nanomaterial, soil characteristics, and the duration of exposure (Mgadi *et al*., 2024; Zhang *et al*., 2024). This issue is particularly significant when nano-fertilizers are combined with bio-fertilizers or biological control agents. The success of such combinations is dependent on the compatibility of the components and the ability of the beneficial micro-organisms to survive and function after mixing, storage and application. Therefore, it is important to evaluate the compatibility of nanomaterials with the target microorganisms, to determine the viability and functional activity of the latter and to monitor the changes that can occur in non-target microorganisms in the soil and rhizosphere. They are useful for determining formulations and dosages that provide agricultural benefits while maintaining the biological balance of the soil. 9.4 Standardization and Regulation

8.4. Standardization and Regulation

Standardization and regulation are essential prerequisites for the development of nano-fertilizers and for their efficient and safe use in sustainable agricultural systems. Variations in the characterization of nanoparticles, dosage measurements, experimental designs and results evaluations reduce the comparability of studies and hinder the definition of clear relationships between product properties and agricultural performance. Therefore, there is a strong need for unified protocols for characterization and testing, and for the documentation of experimental conditions in a manner that increases the reliability, reproducibility and comparability of results (OECD, 2025). Furthermore,

technical specifications for nano-fertilizers should include precise information regarding chemical composition, particle size and distribution, surface properties, nutrient content, release rates, and stability during storage and application with defined, acceptable limits for variation between production batches. From a regulatory perspective, claims concerning a product's efficacy and safety must be substantiated by reliable scientific evidence. Moreover, products should be subject to relevant risk assessments regarding the potential effects on humans, plants, and soil and non-target organisms in accordance with established regulatory requirements. Standardizing procedures for characterization and risk assessment is an important step to build confidence in these products and expand their responsible use in agriculture (OECD, 2022).

8.5. Cost and Industrial Scalability

Economic cost and industrial scalability are among the primary challenges facing the development and large-scale commercialization of nano-fertilizers (Table 2). Production costs for certain formulations can be higher than those of conventional fertilizers, driven by the need for specialized raw materials, precision manufacturing equipment, and advanced characterization and quality control processes. The transition from laboratory-level to industrial-level production may change the characteristics of the product, such as particle size and distribution, homogeneity, stability, and release rates of nutrients, which needs to be fully validated for product quality consistency between different production batches (Wang *et al*., 2025). Therefore, commercial scale-up feasibility should be based on a full economic assessment including the costs of raw materials, manufacture, characterization, storage, transport and application, and also considering the agricultural yields and improvements in nutrient-use efficiency over conventional fertilizers. In this regard, Maaz *et al*. (2025) stated that the lack of standardized field data, along with the necessity for additional evidence of the efficiency and environmental performance of these novel fertilizers, limits the evaluation of their commercial potential and the growth of their adoption. Therefore, the prerequisites for faster incorporation of these products in sustainable agriculture are demonstration of economic feasibility, assurance of product quality, and verification of performance under diverse field conditions.

Table (2) Comparison of Nutrient Uptake Efficiency among Conventional and Nano-fertilizers

Comparison Criteria	Conventional Fertilizers	Nano-fertilizers
Nutrient uptake efficiency	May be low to moderate, depending on the fertilizer type, soil, and crop	May be higher when appropriate formulations and concentrations are used
Nutrient losses through leaching	May be high, particularly for mobile nutrients	Can be reduced with some slow-release or controlled-release formulations
Nutrient availability to plants	Depends on fertilizer solubility and soil properties	Depends on particle size, composition, and nutrient release mechanisms
Rate of nutrient availability	Rapid for highly soluble fertilizers, but may vary depending on the type	Varies according to the formulation and application method
Required fertilizer quantity	May require larger quantities to achieve the desired response under certain conditions	May achieve a response at lower application rates in some cases, but not universally
Environmental impact	Potential for nutrient losses and accumulation when improperly applied	Some losses may be reduced, but the risks of toxicity and environmental accumulation remain
Effects on crop productivity	Depend on fertilization practices, crop type, and environmental conditions	May improve plant growth and productivity when the appropriate type and dose are selected
Major limitations	Use efficiency, nutrient losses, and soil properties	Dosage, particle size, stability, cost, and environmental safety

9. A PROPOSED FRAMEWORK FOR EVALUATING NANOFERTILIZERS BEFORE RECOMMENDING THEIR USE:

A multistage framework can be used to evaluate nano-fertilizers prior to making agricultural recommendations for

their use (Table 3). In assessing the feasibility of fertilizer reduction, experimental studies should include well-defined comparison treatments: conventional fertilizer at the recommended rate, nanofertilizer at a specific rate, an appropriate control treatment, and a reduced-rate conventional fertilizer treatment. When comparing the efficiency of different products the rates of nutrient application should be equalized for the amount of nutrient supplied. The soil properties, characteristics of irrigation water and weather conditions should also be recorded and appropriate experimental designs and statistical analyzes should be used. Also, it is necessary to publish the results that do not show statistically significant differences or adverse effects, as only positive results may lead to an overestimation of the effectiveness of this technology (Channab *et al*., 2024).

Table (3) Multistage framework can be used to evaluate nanofertilizers prior to making agricultural recommendations

Stage	Proposed Indicators	Objective
Physicochemical characterization	Particle size and distribution, morphology, composition, solubility, surface charge, and release rate	Characterize the product and determine its properties
Preliminary safety testing	Seed germination, root growth, toxicity symptoms, and stress indicators	Identify the effective and safe dose
Pot or greenhouse experiments	Plant growth, nutrient content, biomass, and soil properties	Evaluate responses under controlled conditions
Field trials	Crop yield, quality, nutrient use efficiency, and variation across locations and growing seasons	Verify the practical effectiveness of the product
Environmental assessment	Leaching and runoff, microorganisms, non-target organisms, and material residues	Assess potential environmental risks
Economic evaluation	Product and application costs, net returns, and comparison with alternatives	Determine economic feasibility for farmers
Regulatory assessment	Directions for use, labeling, storage, and waste disposal	Support responsible use

10. FUTURE RESEARCH PRIORITIES

To allow sustainable use of nanofertilizers, some gaps in scientific and practical knowledge should be filled. **First:** More field trials. Studies on nanofertilizers should be expanded to more locations and growing seasons, and compared with conventional fertilization programs at equivalent nutrient application rates. **Second**: harmonization of methods of characterization and evaluation. Establish clear protocols for determining particle size and size distribution, release rate and stability and standardize indicators of nutrient use efficiency. **Third**: Study of the long-term environmental fate. We need more information about how nanomaterials change in soil and water, their effects on microorganisms and non-target organisms, and whether they accumulate with repeated applications. **Fourth**: assessing economic viability, Cost per unit of nutrient supplied and net returns to farmers should be computed and compared with those obtained by conventional fertilization techniques and lower cost alternatives. **Fifth**: Integrated nutrient management with nanofertilizers. It may be less feasible to completely substitute conventional fertilizers than to apply them in a targeted and needs based way. This approach can encompass soil testing, balanced fertilization, irrigation management, use of organic matter, and application of nanofertilizers where proven benefits have been established. **Sixth**: Studying formulations of bio-based nanofertilizers. Compatibility of carrier materials and beneficial microorganisms must be tested and microbial viability and activity must be measured after storage and application. **Seventh**: Conduct life cycle assessments. Moreover, sustainability evaluation should take into account the environmental impacts of a product from raw material extraction, manufacturing, and transportation to the application and waste disposal, not only in terms of field performance. These priorities are in line with recent recommendations highlighting the need to invest in field trials, harmonized protocols, and research networks to address the gaps that limit the evaluation and implementation of novel fertilizers (Maaz *et al*., 2025).

CONCLUSIONS

Nanofertilizers are a new trend in the development of plant nutrition technologies as some formulations can improve nutrient availability, control nutrient release or reduce some forms of nutrient loss. However, these benefits are not universal for all products, crops, and environmental conditions as performance depends on chemical composition, physicochemical properties, application rate, application method, soil characteristics, and climate. The potential risks of phytotoxicity, effects on microorganisms, environmental fate, cost, and the lack of long-term field data are still major challenges to be addressed before their use can be expanded. Nanofertilizers can't be considered a universal replacement to traditional fertilizers right now. Instead, they are complementary technologies whose use must demonstrate agricultural efficacy, environmental safety and economic feasibility under the target conditions. Field trials should be conducted at different locations and growing seasons and characterization and evaluation methods should be standardized. Long-term environmental impacts should be studied. Nanotechnologies should be integrated into integrated nutrient management programs. The success of nanofertilizers for promoting sustainable agriculture will depend on the novelty of the technology, its ability to deliver reproducible agronomic benefits at affordable prices, with manageable and assessable risks while ensuring soil health, water resources and living organisms.

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