Research Article

Journal of Environmental Nanotechnology

# Nano-fertilizers in Sustainable Agriculture: Advances, Mechanisms, Environmental Risks and Future Perspectives

R. Indhumathi[1], R. Saranya[2], Madhurima Joardar[2], D. Banupriya[2] and Divyaadharshini Mani[3]

[1]Department of Biomedical Engineering, SRM Institute of Science and Technology, Ramapuram Campus, Chennai, TN, India
[2]Department of Biotechnology, SRM Institute of Science and Technology, Ramapuram Campus, Chennai, TN, India
[3]Karlsruhe Institute of Technology, Institute of Biomedical Technology, Karlsruhe, BW, Germany
Received: 27.08.2026 Accepted: 29.09.2026 Published: xx.xx.xxxx
*banuprid@srmist.edu.in

## ABSTRACT

The rising need for sustainable agriculture has led to increased attention towards nano-fertilizers due to their usefulness as substitutes for traditional nutrient delivery systems. Nano-fertilizers have the unique ability to provide controlled release of nutrients, better availability of nutrients and enhanced efficiency in using nutrients. Yet, the observed benefits of nano-fertilizers depend on various factors: formulation, type of nutrient, type of crop, soil properties, method of application and environmental conditions in which nano-fertilizers are used. This paper aims to analyze the achievements in the field of nano-fertilizers, discussing their classification, production, formulation, mechanisms of action, application methods and their interaction in the soil-plant system. Despite reported benefits, their actual efficiency should be compared with traditional fertilizers in terms of crop productivity, nutrient use efficiency, losses, environmental impact, economic value and validation. This paper pays special attention to environmental outcomes, transformation of nanoparticles, their interaction with microorganisms present in soil, their phytotoxicity and persistence. Special attention is given to practical barriers to application.

**Keywords:** Nano-fertilizers; Nanotechnology; Nutrient-use efficiency; Controlled release; Sustainable agriculture; Environmental fate; Crop productivity; Ecotoxicity; Commercialization.

## 1. INTRODUCTION

Agriculture is under pressure to provide food for the growing population of the world while also ensuring that soil quality is preserved and no harm to the environment is done (Seleiman et al., 2021). Increased agricultural production brought about the increased use of fertilizers in agriculture. Farmers often rely on synthetic fertilizers that contain nitrogen (N), phosphorus (P), and potassium (K) (Kah *et al.*2018). However, improper usage of fertilizers can lead to a range of negative environmental effects. In particular, nutrient runoff is associated with the loss of nutrients that should be used by crops, thus making it hard to attain good results in the fields (Al-Mamun *et al.*2021). While traditional fertilizers allow nutrients to be available for plants in the dissolved state, they also leave room for nutrient losses. As a result, most of the nutrients applied cannot be used by plants. As a consequence, various methods have been developed in order to minimize nutrient losses and achieve effective crop fertilization (Toksha*et al.*2021).

The use of traditional fertilizers in correcting nutrient deficiencies is still very popular due to their cost-effectiveness, existing production facilities and formulations, availability, and predetermined composition. However, their high solubility and instant dissolution can lead to an overabundance of elements in the plant, exceeding its ability to absorb at certain stages of plant growth. This excess can later be leached from the soil, washed away with rain, evaporated, denitrified, or fixed in the soil. This means that loss of nitrogen leads to contamination of groundwater and atmospheric emissions, while phosphorus contributes to the process of eutrophication. Too frequent application of fertilizers can also be detrimental to soil composition and processes in it. All this has given rise to innovative fertilizers, such as slow-release, controlled-release, stabilized, and coated fertilizers (Jakhar et al., 2022).

In this regard, nanotechnology is regarded as a developing platform for modifying the methods of fertilizer and agricultural nutrient delivery and usage in agriculture (Usman et al., 2020). The term nano-fertilizers refers to fertilizers having nutrients at the nanoscale size, as well as fertilizers that (i) incorporate nutrients into nanostructured materials, (ii) coat them with nanostructured materials, or (iii) use nanostructured materials for delivering the nutrients. The nanoparticles have a very high surface-to-volume ratio, adjustable surface chemical structures, as well as

the ability to interact with biological organisms and soil. Depending on the formulation, the systems may either provide controlled nutrient release or enhance the availability of nutrients for plants. All these features have made it possible to initiate a wide range of studies of nano-enabled fertilizers, nanocomposite fertilizers, as well as fertilizers that are able to control the release of nutrients(Shang et al., 2019).

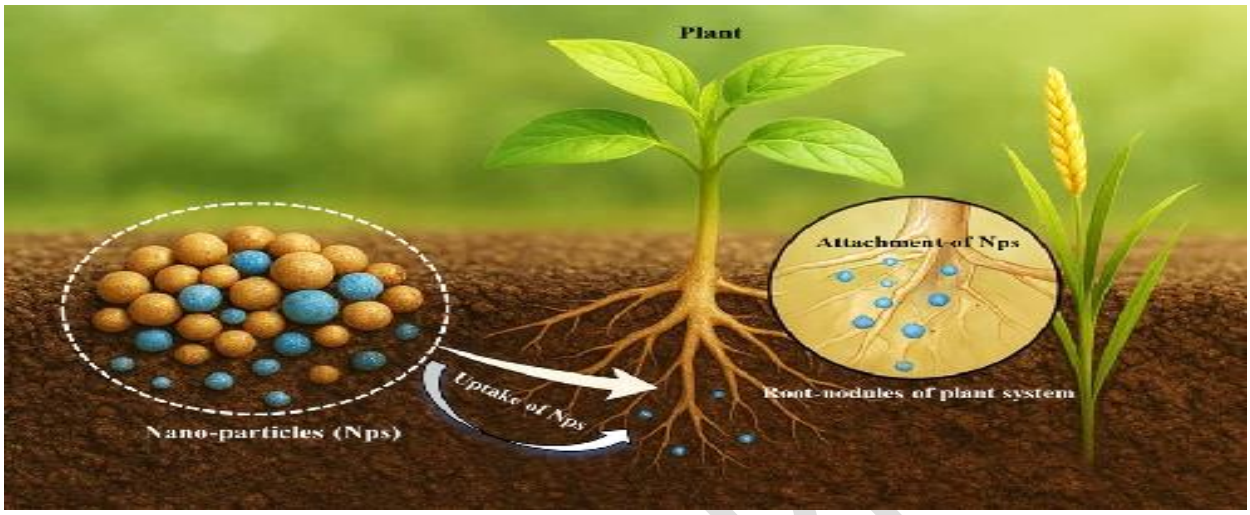



**Fig. 1: Schematic illustration of the nano-fertilizer–plant interaction pathway, showing nanoparticle attachment at the root interface, root uptake, and subsequent transport and interaction within the plant system**

The eco-friendliness of nano-fertilizers adds complexity to evaluating them. Regular fertilizers are mostly associated with environmental damage connected to nutrients, while nano-fertilizers present extra questions related to the behavior of the nano-element itself. After applying nano-fertilizers, nanoparticles either clump, break down, stick to something, undergo oxidation, or interact with the environment around them (Channab et al., 2024a; Chhipa, 2017). The behavior of the nanoparticles will also be changed, affecting their behavior, including mobility, nutrient release, persistence, and availability. Scientists need to discover how such nano-fertilizers interact with the soil, living organisms, plants, etc. Thus, even though a substance is able to minimize nutrient loss, it cannot be deemed environmentally friendly unless it does not cause persistent pollution or harm the environment in any other way.

Economic and technology-related aspects also add to the disparity between lab research and agricultural implementation. There may be additional steps in the production of nano-fertilizers, which may include reactions, surface modifications, encapsulation, stabilization, and characterization (Gupta et al., 2024; Dhlamini et al., 2022). These aspects may significantly impact production costs, possibilities for scaling up, stability in storage, and uniformity of production batches. Additionally, many studies published are limited to lab, hydroponic, pot, or greenhouse testing, whereas noticeably fewer studies are conducted in the field over time and in various locations. The lack of standardized characterization and testing methods and the absence of economic evaluations limit the possibility of formulating direct comparisons between formulations and negatively impact the situation with regulations (Kekeli et al., 2025).

Despite various literature reviews on the application of nano-fertilizers in terms of nutrient supply, formulation techniques, plant absorption and sustainable agricultural practices, there are still substantial gaps in bringing the claimed potential into agricultural practices. Most of the existing reviews emphasize enhanced nutrient efficiency and controlled nutrient release, while the actual performance of the mentioned benefits under real field conditions, their comparison with conventional fertilizers, and ecological and economic aspects still need thorough evaluation. More specifically, the differences in the composition and the surface properties of nanoparticles, formulation, dosing, soil characteristics, crop species and application methods make comparison across different studies challenging. On top of that, laboratory and greenhouse studies are much more numerous than long-term, multi-site field studies, showing that standardized characterization, cost-effectiveness analysis, regulatory framework and lifecycle data are still lacking.

The current review tries to reduce these gaps through a combined approach of the agronomic, environmental, technological, and commercial aspects of nano-fertilizers. With the help of this research, not only have the classification, production, formulation, action mechanism, and use of nano-fertilizers been

reviewed, but they have also been compared with conventional fertilizers in terms of their efficiency of nutrient use, nutrient loss, degree of crop production, optimal application, and efficiency, including effectiveness in the field. Moreover, the environmental stability, transformation rates, degree of environmental friendliness, action on soil microorganisms, life-cycle sustainability, scalability, standardization, requirements for regulation, and cost-effectiveness are described. Special attention is given to the difference between what is achieved when using nano-fertilizers and the parameters that should be achieved to use them successfully (Lowry et al., 2020).

The structure of this review is detailed in the following manner. Section 2 gives the classification and categorization of nano-fertilizers. The processes of nano-fertilizer production and formulation are explained in Section 3. Section 4 deals with the contribution of nano-fertilizers to crop nutrition and nutrient efficiency as well as in applying stress alleviation to crops. Section 5 presents a comparison of nano-fertilizers and common bulk fertilizers in terms of nutrient delivery, efficiency, losses, cost, and operation. The effects, dangers, and safety questions connected with the use of nano-fertilizers are considered in Section 6. Section 7 studies the applications of nano-fertilizers and the most essential points connected with their use, such as the technique of application, its volume, the growth stage of crops, and climate conditions. The issues related to the validation and commercialization of nano-fertilizers are highlighted in Section 8, where scaling, standardization, regulations, and profitability of nano-fertilizers are discussed. The review also regards the sustainability and lifecycle of nano-fertilizers in Section 9. Finally, Section 10 deals with the novelties and future of nanotechnology.

## 2. CLASSIFICATION AND TYPES OF NANO-FERTILIZERS

NF comprises nanosized particles, which are beneficial for plant absorption and enhance crop harvest. This means that this type of NF is produced using NT that, in theory, can be used in agriculture, but its taxonomic studies show certain discrepancies (Qin et al., 2025). Additionally, some definitions include other forms of the products, including nano-approaches and nano-biosensors. For example, NF is described both as part of NT and as a type of fertilizer. This dual nature of the term NF causes issues with the term's definition and classification, which can result in misunderstandings regarding NF use (Xiao et al., 2026; Chhipa, 2017). Moreover, NF can be categorized based on the raw material used in the production of NF. For example, some types of NF are made with carbon nanotubes, while others are produced with the use of polymers or metals. NF are distinguished from each other by the fact that they have different characteristics and can have different effects on plants. NF can also be classified by the type of nutrients they carry, the type of actions performed and their form (Guo et al.2018).

Action-based types of nano fertilizers (NF) can be divided into controlled-release, targeted delivery, growth stimulators, and loss preventers of nutrients. On the other hand, nutrient-based NF can be classified as hybrid, nutrient-coated, organic, or inorganic. Consistency-based NF types can include surface-coated, synthetic polymer-based, organic, or nano carrier. The aforementioned types of NF provide so many advantages such as increased efficiency of nutrient use, controlled release of nutrients, effective delivery of nutrients, improved growth, and reduced nutrient loss (Montalvo *et al.*2015).

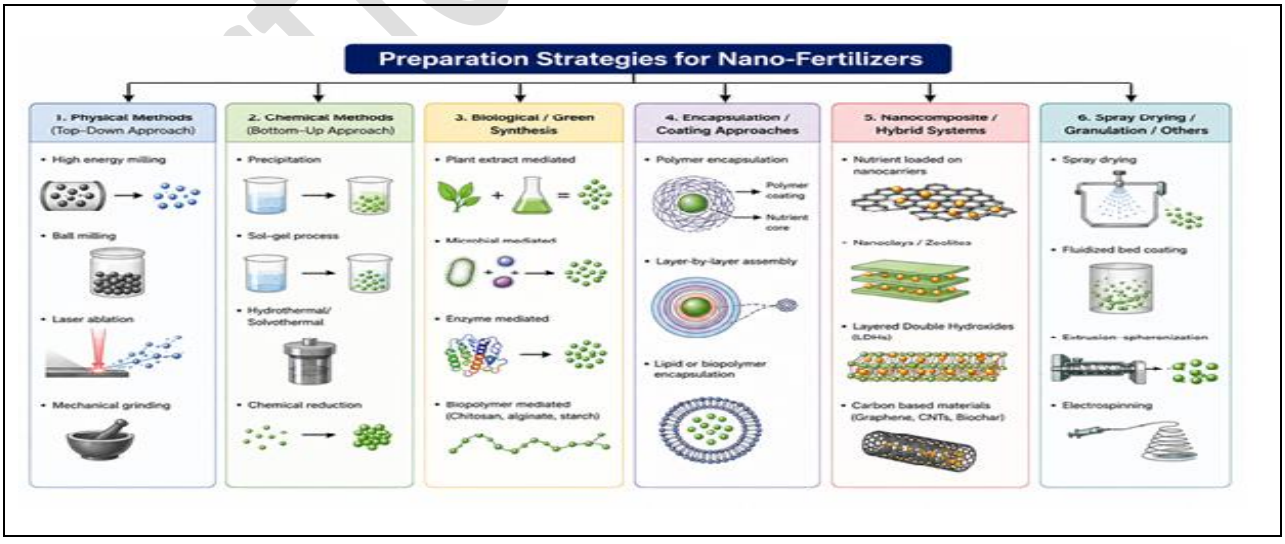



**Fig. 2: Comprehensive overview of preparation strategies for nano-fertilizers, encompassing physical and chemical synthesis, biological and green approaches, encapsulation and coating techniques, nanocomposite and hybrid systems, and advanced formulation methods for controlled nutrient delivery**

### 2.1 Nitrogen Nanofertilizer

Nitrogen (N) is an important macronutrient for plants, necessary for protein and amino acid synthesis, nucleic acid metabolism (etc.), and plant development. Plants obtain their nitrogen from the soil, dissolved as nitrate ($NO_3^-$) and ammonium ($NH_4^+$), and urea is an important fertilizer because it is easily converted into usable inorganic N forms in the soil (Raliya et al.2018). Though ammonia ($NH_3$) can be present in the soil-plant system, high levels of $NH_3$ volatilization imply loss rather than uptake of nitrogen by plants. Nitrous acid ($HNO_2$) and cyanide should not be taken as standard forms of available nitrogen in fertilizers. That is why the management of nitrogen fertilizers seeks to supply the needed nitrogen sources and minimize losses. Too much nitrogen fertilizer can cause loss of nutrients and environmental problems such as contamination of water sources with nitrates and release of nitrogen in the atmosphere (Dimkpa and Bindraban, 2018). Therefore, methods for regulating nitrogen supply and decreasing nutrient losses, including controlled-release formulations, coatings, stabilizers, and inhibitors of nitrification, have been developed (Jha et al.2023; Benício et al., 2017). Urea is one of the most popular fertilizers due to its high concentration of nitrogen and convenience in use (Mikhak et al., 2017).

To resolve the problem with nitrogen fertilizers, it is recommended to coat urea with polyolefins, neem, or sulfur to help control the release of nitrogen from Urea and nitrogen fertilizers. Coated and nanostructured formulations can be used to incorporate urea and nitrogen fertilizers and control the release of nutrients. Polymers, sulfur-based coatings, natural sources of materials, and nanostructured carriers need to be studied to monitor the dissolution of urea and nitrogen release. These systems work depending on the features of coatings, soil parameters, nutrient characteristics, and environmental conditions (Bernardo et al.2018; Jayara et al., 2023).

Zeolites are crystalline minerals of aluminosilicate nature, which are marked by their porous structure and cation exchange capacity. Owing to their ion-exchange properties, zeolites are able to store and exchange such cation nutrients as $NH_4^+$ and $K^+$, making them eligible nutrient carriers that enable controlled nutrient delivery (Sharma et al., 2022; Dhlamini et al.2022; Nongbet et al.2022). Deposits of natural zeolites include various zeolite minerals and the often-cited phrase stating that zeolites consist of over fifty minerals does not mean that one single natural sample may contain more than fifty minerals. Therefore, zeolite-based nanocomposites were studied as nutrient carriers and controlled release systems. Nonetheless, it should be mentioned that regular zeolites possess a poor capability to retain anionic substances such as nitrates and phosphates, which means that it is necessary to either modify their surface or add other materials in order to improve their properties (Nongbet et al., 2022).

### 2.2 Phosphorus Nanofertilizers

Phosphorus (P) is an important macronutrient used for growth and development of plants and also for energy transfer processes, nucleic acid metabolism, and membrane formation, as well as for the numerous processes occurring in plants. Adequate phosphorus availability ensures normal development of roots, other parts of plants, and formation of yield. On the other hand, phosphorus deficiency will result in suppressed plant growth and significant symptoms such as diminished growth and the accumulation of anthocyanin pigments, which makes their leaves and stems reddish or purplish.

Phosphorus availability in soil relies upon its chemical form, solubility, and interaction with soil minerals. In this regard, enhancing phosphorus availability and controlling its release needs consideration while developing phosphorus-based nanofertilizers. In this connection, research was carried out on the mixtures of rock phosphate and clinoptilolite saturated with $NH_4^+$ and $K^+$ ions to study cation exchange and phosphorus solubility. The results obtained indicated a possibility of using such mineral systems for improvement in phosphorus release and availability and thus for considering application of controlled or slow-release phosphorus fertilization (Padhan et al., 2024; Benício et al., 2017). However, the efficacy of phosphorus release depends on the composition of the materials and soil conditions and cannot be generalized to all phosphorus nanofertilizers.

### 2.3 Potash Nanofertilizers

Phosphorus (P) represents an essential macronutrient in energy acquisition and provides key functions in nucleic acid metabolism; formation of cell membranes; photosynthesis; and processes regulating plant growth and development. Phosphorus availability favors root growth and development, the formation of flowers and fruits, and the accumulation of biomass. The deficiency of phosphorus may impede plant development and can be manifested in characteristic biochemical and visual manifestations, including the higher formation of soluble sugars and anthocyanin pigments. The intensity and manifestations of the symptoms can vary based on the level of phosphorus deficiency.

Phosphorus availability in the soil is affected by its form and its interaction with soil minerals. The uptake of phosphates is hindered by adsorption and precipitation of this nutrient due to iron, aluminum, or calcium in certain soil conditions. In order to overcome phosphorus availability issues, phosphorus-containing

Article in Press

materials can be used in some carriers such as clinoptilolite-based formulations, making it possible to control phosphorus release from the carrier system. Generally, these formulations lead to the maintenance of plant-available phosphorus in the soil, yet the effectiveness of the systems is determined by the soil properties, carrier composition, and treatment technology (Yadav *et al*.2023).

Research has observed an enhancement in phosphorus-related responses of crops such as cluster bean and pearl millet under arid conditions through foliar application of nanoscale phosphorus at around 640 mg ha-1. Notably, this value indicates work regarding the application of nano-phosphorus, which is indeed incomparable with the application of nano-potassium in harvesting. The study outcomes indicate that nanotechnology could be effectively used in stable fertilizer production for agricultural use. Leucite is classified as a potassium aluminosilicate with a chemical formula approximated as $KAlSi_2O_6$ ($K[AlSi_2O_6]$). The unique nature of leucite compounds sparked a lot of interest in these materials as carriers of controlled-release fertilizers, as they can interact with nutrients contained in nutrient ions (Sharma et al., 2022).

### 2.4 Calcium Nanofertilizers

Ca is another important macronutrient that is involved in cell wall formation and plant development regulation. Being part of the cell wall, Ca provides structural integrity as it forms cross-linkages in the pectin-polysaccharide matrix. Ca helps protect and cure plants from diseases (both bacterial and viral). Use of nano-Ca proved to successfully promote development and physical growth of the plants. Although there is a handful of publications on the influence of nano-Ca on plants, which manifested good prospects for its application in fertilizers (Channab et al., 2024a).

### 2.5 Magnesium Nanofertilizers

Magnesium (Mg) is a significant macronutrient that takes part in photosynthesis, production of chlorophyll, enzyme activation, protein synthesis and energy metabolism. Thus, magnesium deficiency can lead to reduced efficiency of photosynthesis and growth of plants. Therefore, the studies concerning soil and foliar application of magnesium can be useful for enhancing the performance of plants (Verma *et al.*2024).

Using nano-Mg formulations can also be one of the ways to improve the distribution of nutrients. However, the outcomes of such experiments heavily depend on a number of factors such as the form of chemicals, properties of the particles, concentration of application, species of plants and the environmental conditions. As a result, the evaluations of nano-Mg influence should be done with the help of crop-specific studies rather than general ones. According to some research, the yield of cowpea was improved by 13.4% with the use of 0.5 g L-1 of salt Fe + 0.5 g L-1 of salt Mg (Shirsat and Suthindhiran, 2024).

### 2.6 Zinc Nanofertilizers

Zinc (Zn) is a vital micronutrient that contributes to enzyme activity, protein metabolism, membrane functioning, and the growth of plants. Deficiencies in Zn can negatively influence the processes in the plant's physiology and productivity. Therefore, work is being done to explore the use of Nano-Zn formulations to improve the supply of Zn and the level of Zn in plants. In the pomegranate (Punica granatum cv. Ardestani), the effect of the foliar application of nano-Zn chelate fertilizer was studied at 0, 60, and 120 mg Zn $L^{-1}$ along with nano-B treatment. It was discovered that applying nano-Zn and nano-B improved the yield of fruits. It was realized that the response was mainly due to the increase in the number of fruits on each tree. However, the effect of the treatment depended on the technique used, with Zn treatment producing lower results compared to the application of B (Davarpanah et al., 2016).

### 2.7 Nano Porous Zeolites

Nanoporous zeolites are highly porous aluminosilicate compounds that possess a large surface area, significant ion-exchange capacity, and controlled pore structure. All these characteristics make them ideal candidates for the creation of systems for nutrient carrier and controlled-release fertilizers. In practice, zeolite-based materials can serve as sorption or ion-exchange sites for nutrients; thus, these materials can affect the nutrient release and retention in soils. A range of synthesis and modification techniques has been explored to generate zeolite materials with specific pore structures and surface characteristics, such as templating and post-synthesis modifications. Their performance as nano-fertilizer carriers relies on various factors such as the pore structure, particle size, surface chemistry, nutrient loading, release kinetics, and interactions with soil (Sharma et al., 2022; Davarpanahet al.2016; Abdel-Aziz et al.2016). While zeolites have been extensively used in catalysis and adsorption, the catalytic applications of zeolites are out of the scope of this review. Therefore, the present discussion observes only the zeolites' capability for nutrient retention, controlled nutrient release, and nano-fertilizer delivery.

## 3. PREPARATION STRATEGIES FOR NANO-FERTILIZERS

Article in Press

Various methods are available for the production of nano-fertilizers, such as top-down, bottom-up, encapsulation, biological, and hybrid techniques as shown in Figure 2. The option that is picked will have an effect on the particle size, morphology, surface chemistry, nutrient load, formulation stability and nutrient release. Since the definition of nano-fertilizer includes not only nutrient nanoparticles but also nano-encapsulated fertilizers, nanocomposites, and nanocarrier systems, it is important to consider the preparation methods, the formulation and the mechanism of nutrient delivery rather than particle size (Sharma *et al.*2020).

### 3.1 Top-down Approaches

Top-down processing relies on transforming bulk fertilizer materials into nanoscale structures through the introduction of various forces. Effective techniques that exemplify this process are high-energy ball milling, ultrasonication, homogenization, and laser ablation. High-energy ball milling is one of the top-down techniques that has received a lot of attention for bulk materials. The appropriateness of this method depends on the type of raw material, desired characteristics of the final product, energy consumption, risk of contamination, and feasibility of scaling up the process (Pandorf *et al.*2020). In addition, a decrease in particle size does not guarantee better effectiveness of fertilizers since nutrient-use efficiency is determined by the composition of the particles, dissolution or release rates, surface chemistry, dose of application, properties of soil, and response of plants (Haydar *et al.*2024).

### 3.2 Bottom-up Chemical Approaches

Bottom-up techniques revolve around the synthesis of nanoparticles from ions or molecules through regulated nucleation and growth. Some of the most popular methods in this category include co-precipitation, sol-gel and hydro-solvothermal treatment, chemical reduction and crystallization. Co-precipitation is one of the most applied methods for the synthesis of nanoparticles of inorganic fertilizers, because it enables control over many features of nanoparticle production, such as pH, concentration of precursor, temperature, ionic strength, and length of the reaction (Mohammed, 2021).

Hydro- and solvothermal techniques guarantee a higher product quality and morphology of nanoparticles with respect to the methods mentioned above, however, higher temperature and pressure several may complicate the process. Chemical methods guarantee a higher level of control over size, shape, composition, and crystallinity of the particles. However, overall issues with phytotoxicity and accumulation in soil should be taken into consideration in the process of developing nanoparticle fertilizers, which makes it important to think about purification of the final product (Zulfiqar *et al.*2019).

### 3.3 Encapsulation and Nanocarrier-based Approaches

Encapsulation is a major advancement in that it allows not just the realization of nanoparticles that consist of only nutrients. Instead, engineered nutrient delivery systems are created. Such systems arise when nutrients are trapped within nanoscale carriers that are made from chitosan, alginates, starches, cellulose derivatives, lipid systems, nanoclays, mesoporous silica, and others. Polymeric nanocarriers allow for controlled release of the nutrients by regulating diffusion, polymer degradation, swelling, or matrix destruction. Therefore, chitosan-based systems may provide simultaneous encapsulation of nutrients and biodegradable properties (Kumar et al., 2023; Delgado-López et al., 2020; Dhlamini et al., 2022). Nanoclay and mesoporous carriers offer large surface areas and the ability for adsorption, thus minimizing nutrient losses by dissolution or leaching. However, such systems pose additional challenges in terms of design, namely encapsulation efficiency, loading capacity, degradation of the carrier, interaction of the nutrients and the carrier, release mechanisms, as well as residual accumulation of the carrier. This means that the agricultural outcome has to be assessed in terms of the cost of the carrier material and processing (Sahoo et al.2024).

### 3.4 Ionic Gelation

Ionic gelation is significant for the preparation of polymer-based nanofertilizers, in particular from chitosan. The principle of ionic gelation is in the attachment of ionic polymer to an ionic crosslinker, which gives rise to the formation of nanoparticles at low temperatures and mild conditions. The process can be considered to be advantageous because of the fact that it allows water-based processing and does not require the application of extreme temperatures. At the same time, ionic gelation is highly dependent on several factors such as the molecular weight of the polymer, chitosan deacetylation, polymer/crosslinker ratio, pH, ionic strength, and mixing conditions (Kumalasari*et al.*2022).

### 3.5 Green and Biological Synthesis

Green synthesis has developed as a method to replace traditional chemical methods since bio-materials may serve different functions and proceed chemical reactions in benign ways. The application of plant extracts and certain living organisms like microbes, algae, enzymes, proteins, and biopolymers has been widely studied for using nanoparticles with specific nutrients as materials. Plants have been employed in the production of nanomaterials and have become of interest to researchers, as plants seem to be able to

Article in Press

generate biologically active compounds (plant metabolites) such as polyphenolic compounds, flavonoids, proteins, and carbohydrates, which can be deemed crucial for the process of the production and stabilization of nanoparticles. Yet, species of plants used in the process, extraction methods, the set of phytochemical compounds, and other processing parameters can cause variable properties of the produced nanoparticles (Guo et al., 2018). Nonetheless, despite the fact that biological processes have some evidence of environmental advantage, the main problem is that their outcomes cannot be identical. Changes in the species of plants, conditions of their growth and extraction, strains of microorganisms, kinds of metabolites, and the conditions of any chemical reaction can lead to differences in nanoparticles. Thus, the idea that "green" synthesis is effective must be confirmed by the quantification of the whole process.

## 3.6 Nanoemulsion and High-energy Dispersion Methods

Nanoemulsion techniques use high-shear mixing, ultrasonication, microfluidization, or high-pressure homogenization in the development of nanosized droplets or prepared nutrient formulations (Ayenew et al., 2025). These methods are particularly important when nutrients and bioactive compounds have limitations regarding water solubility. The resulting nanosized droplets can improve dispersion of poorly soluble components and may influence interactions with plant surfaces. Nevertheless, nanoemulsion stability is highly dependent on the size distribution of drops, concentration of surfactant, zeta potential, ionic strength, temperature, and storage conditions.

## 3.7 Spray Drying and Freeze Drying

Spray drying and freeze-drying are predominantly downstream formulation and drying processes rather than the primary nanoparticle synthesis methods. Spray drying converts nanoparticle suspension or formulation into dry powders through the process of atomization and rapid solvent removal, while freeze-drying removes water through sublimation under reduced pressure. While these processes will aid in terms of storage, transport, and handling, drying may bring about aggregation, change in surface characteristics, and incomplete redispersion of the dried material. Hence, the size of the particles and redispersibility must be assessed before and after drying.

## 3.8 Hybrid and Multifunctional Approaches

New developments in nanofertilizers often seek to integrate various production methods to enhance controlled release of nutrients, stability, and plant absorption. Some examples of recent achievements in this field are nutrient-rich polymer-nanoclay composites, inorganic nanoparticle compounds coated with biopolymers, and hybrid systems, which have the main benefit of the possibility to separately engineer all four stages of the fertilizing process: nutrient loading, protection, transportation, and release. However, with the complexity of the compositions, there may be an increase in the cost of regulatory processes, production, and evaluation of environmental risks of the product (Ayenew et al., 2025). Table 1 gives a summary of the main methods of preparing nanomaterials and nano-based delivery systems, noting their merits, demerits, and several important features needing improvement. All these features offer a foundation for choosing and perfecting appropriate preparation techniques with respect to the required properties of the particles and the effectiveness of their delivery system.

**Table 1: Comparative overview of nanomaterial preparation approaches: advantages, limitations, and key optimization parameters**

| Preparation Approach | Major Advantage | Major Limitation | Key Parameters Requiring Optimization |
|---|---|---|---|
| Top-down milling | Simple and scalable concept | High energy use; broad size distribution | Milling time, energy, particle size |
| Ultrasonication | Good dispersion and size reduction | Possible aggregation/re-agglomeration | Sonication time, amplitude, concentration |
| Co-precipitation | Simple chemical synthesis; compositional control | Aggregation and residual chemicals | pH, precursor ratio, temperature |
| Sol–gel | Good control over structure | Multiple processing steps | Precursor concentration, pH, aging |
| Hydrothermal | High crystallinity and morphology control | High temperature/pressure | Temperature, pressure, reaction time |
| Ionic gelation | Mild and aqueous processing | Sensitive to formulation conditions | Polymer/crosslinker ratio, pH |
| Green synthesis | Reduced reliance on harsh chemicals | Poor reproducibility | Extract composition, pH, temperature |
| Encapsulation | Controlled nutrient release | Additional carrier complexity | Loading, encapsulation efficiency, release rate |
| Nanoemulsion | Improved dispersion of poorly soluble compounds | Stability problems | Droplet size, surfactant, zeta potential |

Article in Press

| Preparation Approach | Major Advantage | Major Limitation | Key Parameters Requiring Optimization |
|---|---|---|---|
| Spray/freeze drying | Improved storage and handling | Possible aggregation | Drying conditions, redispersion |
| Hybrid systems | Multifunctional delivery | Higher complexity and cost | Component interactions, release kinetics |

## 4. NANO FERTILIZER ROLE IN CROP NUTRITION

### 4.1 Nutrient Availability and Nutrient-use Efficiency

The concept of nano-fertilizers is that they can enhance the synchronization of nutrient availability and plant requirements, thereby overcoming the problem of low nutrient-use efficiency that has always accompanied the traditional application of fertilizers. In traditional systems, the increased solubility of the fertilizers leads to a situation where plants get more nutrients than they are able to use and will thus lose excess nutrients in the forms of leaching, volatilization, runoff, fixation, and immobilization. Nano-fertilizer formulations influence these processes of nutrient loss by changing the way they dissolve in soil and adsorb to its surfaces, by encapsulating fertilizers and controlling their release, and by affecting the soil constituents. Thus, the main advantage of nano fertilizers is not so much in their size as in the possibility to control the timing and geographical range of nutrient supply (Rico *et al.*2011).

The use of nanostructured formulations for nitrogen, phosphorus, and potassium has been studied with the goal of achieving optimum nutrient recovery rates and minimizing losses. The development of nano-enabled nitrogen systems may allow for slow and controlled release of nitrogen with a view to reducing losses due to nitrification and volatilization. The problems encountered with phosphorus are slightly different, as the phosphate ions can be easily immobilized due to adsorption and precipitation processes, especially in soil featuring high concentrations of iron, aluminum, or calcium (Kekeli et al., 2025). Nanocarriers as well as slow-release phosphorus fertilizers may play a key role in altering phosphorus dissolution rates and ensuring sustainable levels of plant-available phosphorus. Similarly, nano-potassium fertilizers may perform better than potassium salts due to their capacity to control the release rates of potassium salts, with their specific performance being highly dependent upon soil type, cation-exchange capacity, moisture regime, and chemistry of the formulations in question (Sharma et al., 2022; Yadav et al., 2023).

### 4.2 Plant Uptake, Translocation and Physiological Responses

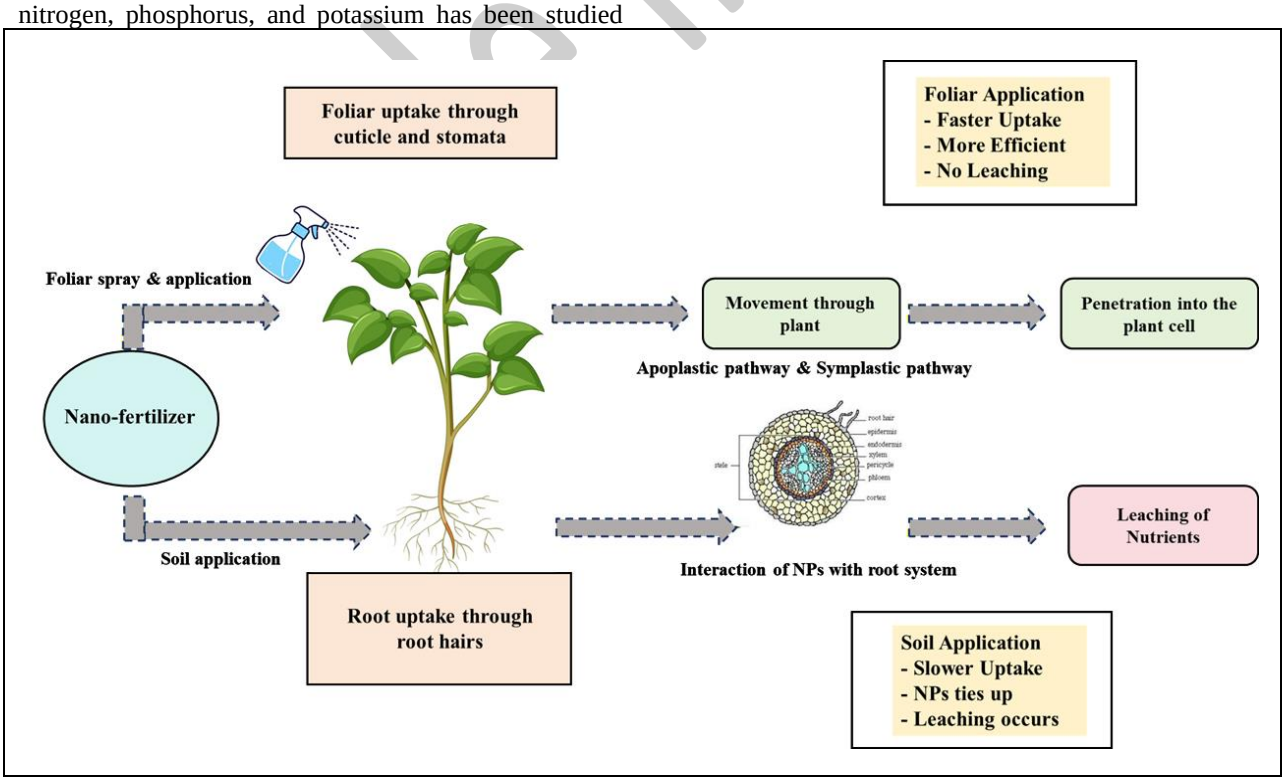



**Fig. 3: Schematic representation of nano-fertilizer application modes and plant uptake pathways, detailing foliar penetration (cuticle and stomata), root hair uptake, and internal translocation via apoplastic and symplastic pathways into plant cells (adapted with reference to Channab et al. al. 2024a)**

In Press

The nutrients can travel in the plant via apoplastic and symplastic pathways and can be transported via xylem and phloem, as shown in Figure 3. Nonetheless, just because nutrients started accumulating doesn't mean that the nanoparticle particles were absorbed. In fact, in some formulations, what we see as a nutritional response is mostly due to the slow dissolution of nutrients from the nanoparticle or nanocarrier. This means that we must prove nanoparticle-specific uptake using some imaging, elemental mapping, or tracer approach. Better nutrient delivery will promote chlorophyll synthesis, photosynthetic activity, enzyme function, antioxidant defense, biomass accumulation, etc. The use of nano-formulations with Zn, Fe, Mn, and so forth can have an impact on processes related to photosynthesis and oxidative stress regulation. At the same time, chemical responses depend on the amount of substance introduced (Channab et al., 2024b; Singh et al., 2023b).

### 4.3 Rhizosphere Interactions and Stress Mitigation

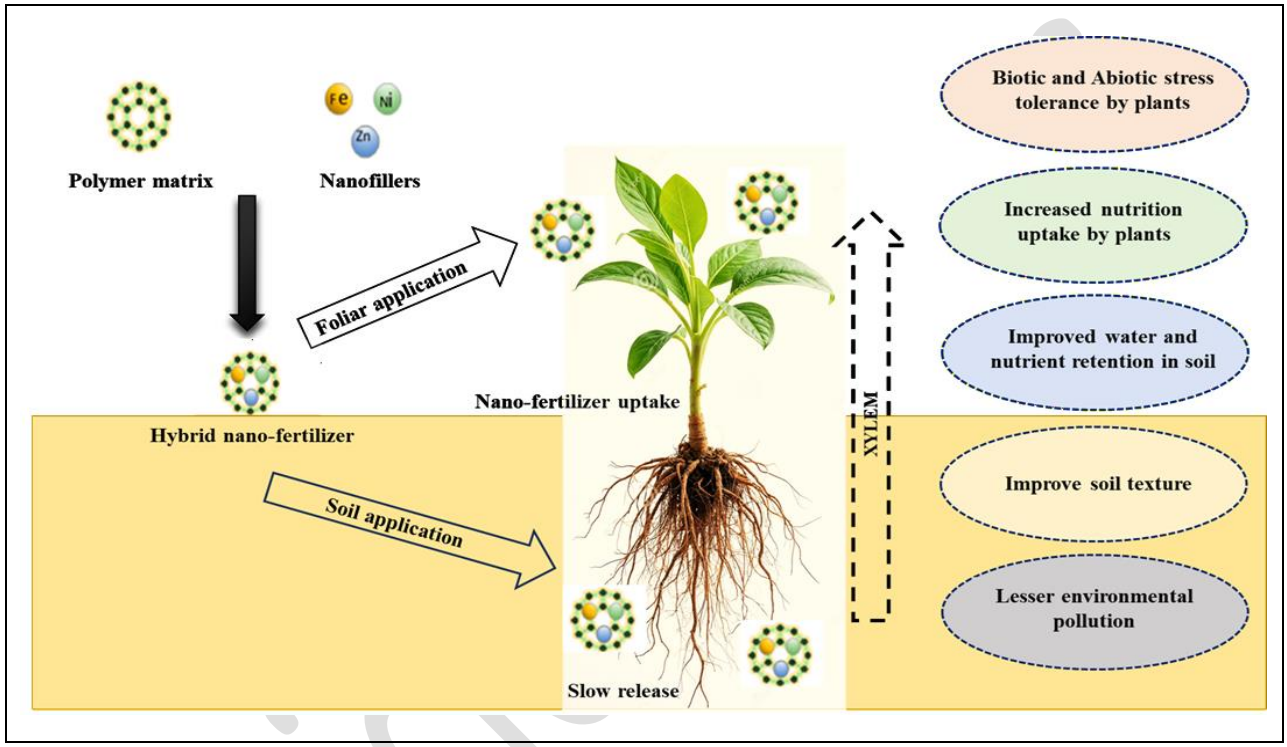



**Fig. 4: Schematic representation of the potential role of hybrid nano-fertilizers in controlled nutrient release, plant nutrient uptake, soil nutrient retention, and mitigation of biotic and abiotic stresses**

Nano-fertilizers do not serve solely as nutrient providers; their effect on rhizosphere, soil minerals, organic matter, microorganisms, and root exudates can significantly affect nutrient availability and plant behavior. Nanoparticles can have an impact on nutrient adsorption-desorption, microbial activity, and nutrient transformations and affect the process of nutrients migrating towards the root, as shown in Figure 4. Nevertheless, this interaction is highly dependent on soil characteristics such as pH, clay and organic matter levels, moisture content, and microorganisms' composition, which makes it challenging to evaluate its field performance (Liu et al., 2015; Khardia et al., 2022).

Nano-fertilizers can also provide plants with increased drought, salinity, oxidative stress, and temperature stress resistance by improving access to the needed nutrients for antioxidant defense (Saravana et al., 2024; Avila-Quezada et al., 2022). For instance, the application of nano-fertilizers for delivering Zn, Fe, Mn, or Si can provide support to the functioning of antioxidant enzymes and allow for maintaining cellular redox balance under stress. Improvement in nutrient availability may also play a role in enhancing root development, which can assist in acquiring nutrients and water (Saravana et al., 2024; Avila-Quezada et al., 2022). The ability of nanoparticles to decrease stress may change depending on the amount of nanoparticles used as well as the surrounding conditions during application. High amounts of nanoparticles can lead to oxidative stress or harm to beneficial bacteria in soil. Therefore, the benefits of nano-fertilizers should be compared to their potential harm (de França Bettencourt et al., 2020).

## 5. NANO-FERTILIZERS VS. CONVENTIONAL BULK FERTILIZERS

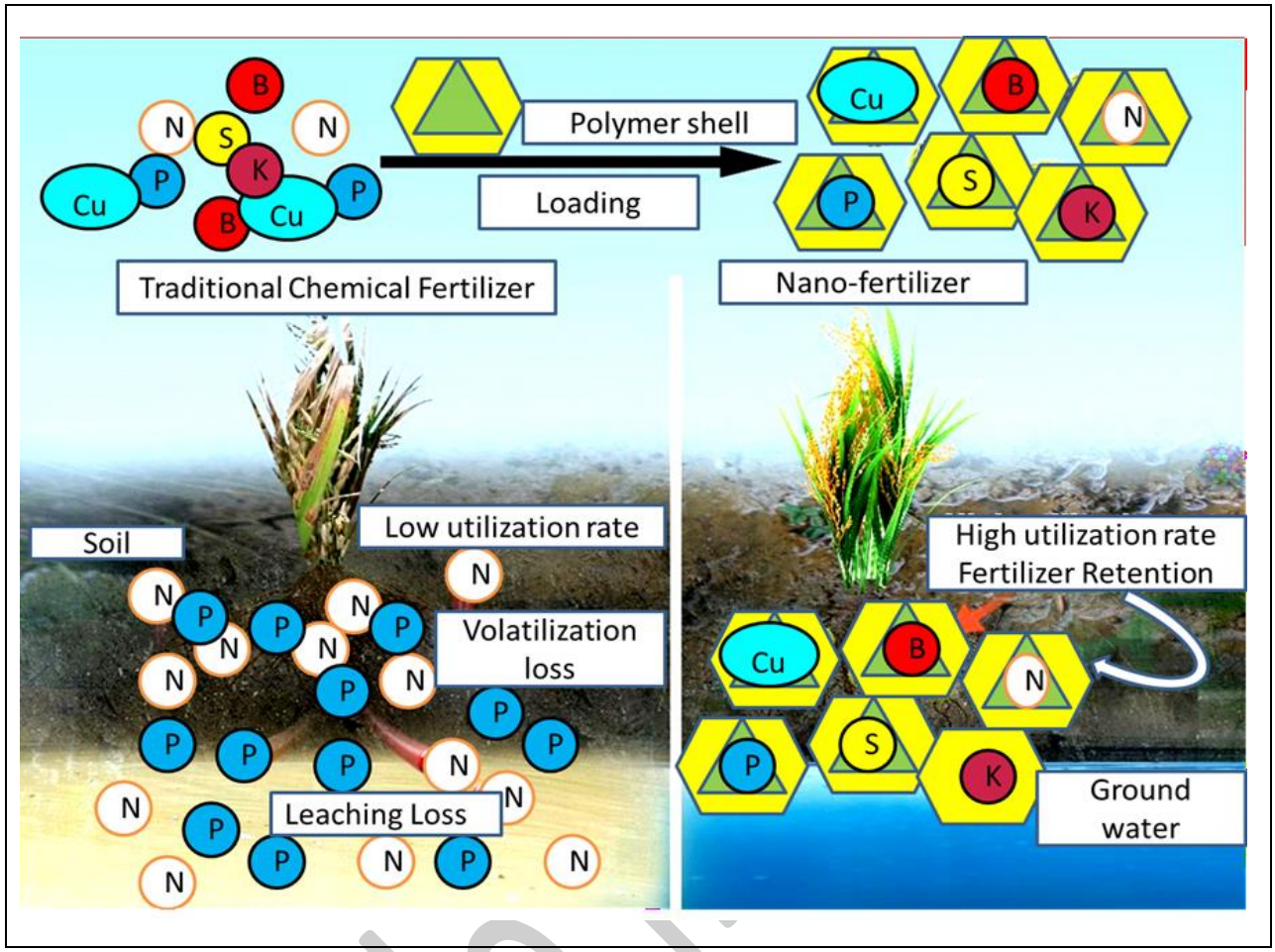



**Fig. 5: Comparative representation of conventional and nano-fertilizer systems illustrating nutrient loading, controlled release, improved fertilizer retention, and reduced nutrient losses**

**Table 2: Comparative analysis of key operational, performance, and environmental characteristics between conventional bulk fertilizers and nano-fertilizers**

| Parameter | Conventional Bulk Fertilizers | Nano-fertilizers |
|---|---|---|
| Nutrient release | Generally rapid | Controlled or sustained |
| Nutrient-use efficiency | Often moderate | Potentially higher |
| Nutrient losses | Leaching, runoff, volatilization | Potentially reduced |
| Application quantity | Relatively high | Potentially lower |
| Nutrient delivery | Mainly through dissolution | Controlled dissolution/carrier-mediated delivery |
| Nutrient retention | Can be affected by fixation | Can be engineered for improved availability |
| Environmental impact | Higher risk of nutrient losses | Potentially lower, but nanoparticle risks require assessment |
| Formulation complexity | Relatively simple | Generally higher |
| Production cost | Usually lower | Often higher |
| Field validation | Well established | Still comparatively limited |
| Long-term soil effects | Relatively well understood | Require further investigation |

Table 2 illustrates the difference between standard bulk fertilizers and nano-fertilizers with regard to their nutrient release, effectiveness, loss of nutrients, impact on the environment, formulation, cost and testing. It underlines the benefits of the use of nano-fertilizers and indicates that studies on the safety of nanoparticles, as well as their effects on the soil over time, are required. The primary benefit of nano-fertilizers is their ability to regulate nutrient availability and reduce their wastage, rather than their small size. However, the benefit does not hold true in all scenarios (Sadati et al., 2021). The effectiveness of nano-fertilizers is dependent on various crop species, soil properties, type of nutrient, characteristics of extracted particles, dosage, and application method. In addition, a lower application rate does not automatically imply better performance of the fertilizers, and it must be proven through other results (Esmaeil et al., 2020).

Despite promising laboratory and greenhouse results, conventional fertilizers are still widely used because of their cost-efficiency, well-established production technique, predictable nutrient composition, and multiple validations in the field. Using nano-fertilizers is also associated with a number of challenges such as stability and reproducibility of formulations, production on a large scale, regulatory approval, and uncertainty regarding long-term accumulation of nano-fertilizers in soils(Mehta *et al.*, 2024). Therefore, the focus should move from questioning whether nano-fertilizers are better than traditional fertilizers to looking for conditions under which the use of nano-fertilizers can be justified. Future research can compare the two types of fertilizers under normal nutrient input conditions following criteria such as efficiency of nutrient utilization (Khalkhal et al., 2020).

## 6. ENVIRONMENTAL FATE, TOXICITY AND BIOSAFETY OF NANO-FERTILIZERS

The environmental features of nano-fertilizers cannot be assessed just on the basis of their ability to enhance nutrient-use efficiency. The application of nanomaterials causes different changes, such as dissolution, aggregation, adsorption, surface alteration and interaction with organic matter, soil minerals, microorganisms and roots that affect their mobility and availability (Demeke et al., 2025). Soil pH, ionic strength, clay, organic matter, humidity and redox levels influence these processes critically. Therefore, the physicochemical features of a nano-fertilizer before application differ from its performance in the real agricultural environment (Mehta et al., 2024).

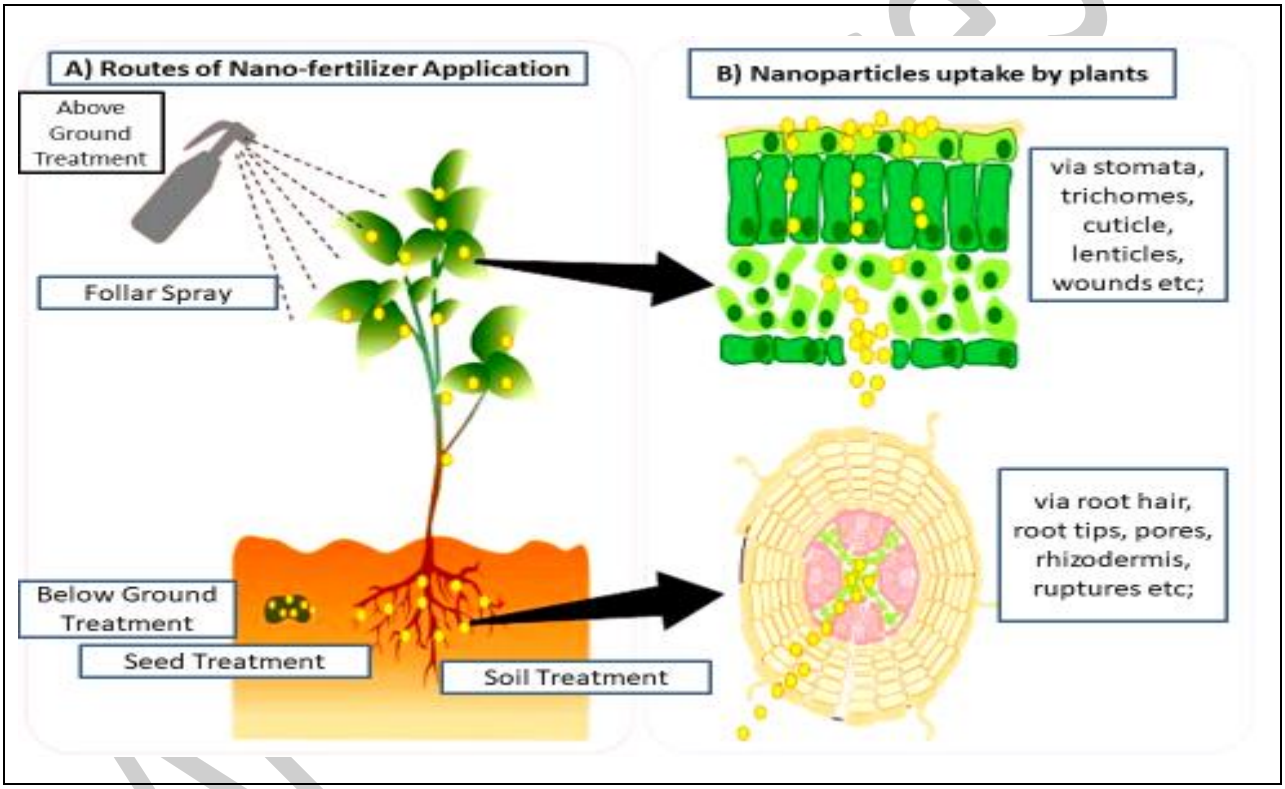



**Fig. 6: Major application routes of nano-fertilizers and corresponding nanoparticle uptake pathways through foliar and root interfaces in plants**

The interaction of nanofertilizers with the rhizosphere plays a significant role in both the nutrient cycle and the structure and operation of the soil microbes. The effect of nanofertilizers depends on such factors as the type of nanomaterial, its concentration, time of exposure, and environmental conditions. The action of nanoparticles is also dependent on the dose of the applied nanofertilizer. At high doses, certain nanomaterials can cause oxidative stress, damage to membranes, hindering root development, and changes in photosynthesis (Saravana et al., 2024; Babu et al., 2022; Khardia et al., 2022). Hence, when assessing the toxicity of nanoparticles, it is important to take into consideration factors such as concentration of the substance, its particle size, surface chemistry, dissolution rate, type of coating, the duration of exposure, genotype of the crops subjected to the treatment, and soil conditions (Avila-Quezada et al.2022).

Another issue is the possibility of the accumulation and transfer of the elements from nanoparticles in plant tissues meant for human consumption. Increased accumulation of the elements in

plants cannot be automatically viewed as the uptake of nanoparticles in the pure form, as there may be an important contribution from the ions of the nutrients that have dissolved in water. Therefore, it is crucial to use various methods such as elemental mapping, isotopic tracing, and specific analysis techniques on nanoparticles to distinguish these processes especially when it comes to food crops. In addition, repeated use of such nanoparticles in practice may result in environmental effects that cannot be determined as a result of short-term greenhouse experiments, including changes in the communities of microorganisms, cycling of nutrients, the persistence of nanoparticles, and physicochemical properties of soils (Saurabh *et al.* 2024).

A major limitation of the current evidence is the inconsistency between controlled experimental results and the behavior of nanoparticles in the environment of real-life farming. The differences in chemical composition, surface modification, particle size, dosage, type of soil, and the timing of application may have a great deal of impact on the properties and biological traits of the nanoparticles, thus making comparison of data between the studies very complicated (Sharma et al., 2022). Thus, it is impossible to extrapolate the use of nano-fertilizers from their characteristics in the agricultural field. Sustainability can be assessed only when used wisely, considering the parameters of efficiency of nutrient usage, persistence in the environment, soil-microbial interaction, accumulation by plants, and toxicity (Xiao et al., 2026).

## 7. APPLICATION STRATEGIES AND FACTORS AFFECTING NANO-FERTILIZER EFFICIENCY

The use of nanofertilizers is greatly determined by the method of use and the relationship between the characteristics of the nanofertilizer and the agricultural environment. Unlike traditional fertilizers, nanofertilizers can be used through various methods, such as soil application, foliar application, seed treatment, or root-zone application. The success of every method relies on the type of nutrient, properties of the particles, plant growth stage, properties of soil, and environmental conditions (Yin et al., 2023).

Soil application allows the easy dissemination of the fertilizers into the root systems of plants and is particularly adapted to the use of fertilizers that are designed to have a slow and steady delivery of nutrients. However, it is possible that some nanoparticles can be agglomerated and adsorbed in the soil, which can affect their mobility, nutrient availability, and the effectiveness in the delivery of nutrients to plants. At the same time, foliar application helps to reduce soil contact, but the reaction of the leaf cuticle and the size of nanoparticles should be taken into consideration. Seed coating and seed priming are other effective methods of application, which make it possible to supply nutrients immediately after germination (Rajput et al., 2020).

The effectiveness of nano-fertilizers is determined by different factors of formulation and environment. Among the factors affecting the functioning of nanoparticles are the particle size, physical and chemical characteristics, form of the nutrient, time of dissolution of the particle, and the nature of the coating (Babu et al., 2022). At the same time, the pH, presence of organic substance, quantity of clay, soil moisture conditions, temperature, and activity of microorganisms influence the changes in nanoparticles and the release of nutrients. Importantly, the kind of crop and its growing phase also play a role in determining crop needs for nutrients (Hong et al., 2021).

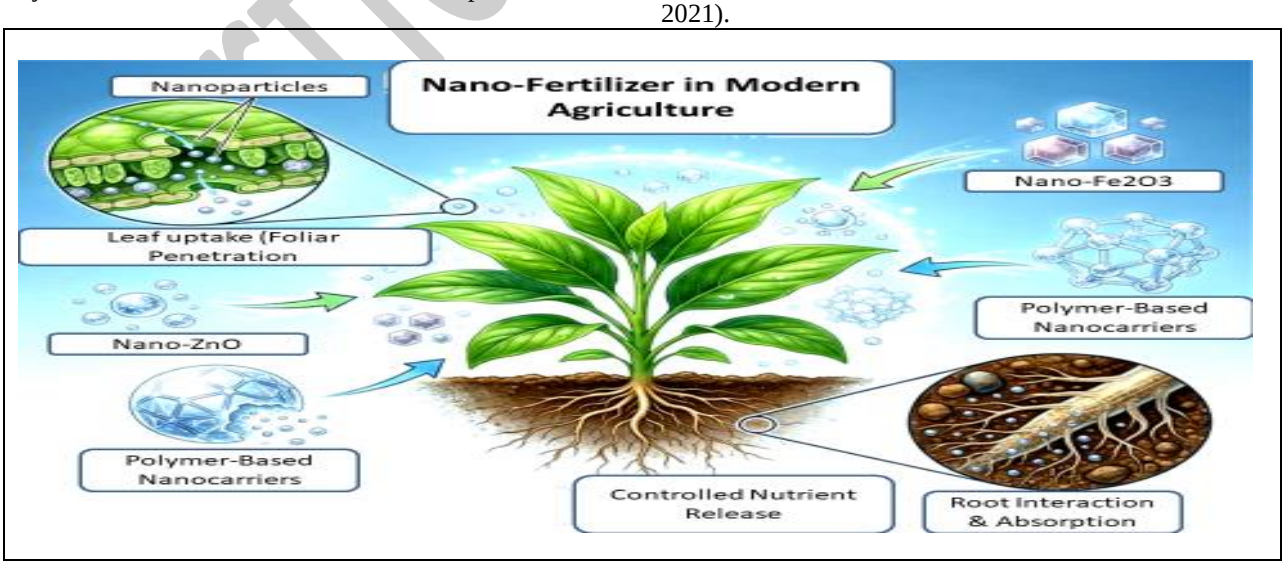



**Fig. 7: Schematic representation of nano-fertilizer-mediated nutrient delivery in modern agriculture, illustrating controlled nutrient release, root interaction and absorption, foliar uptake, and nanocarrier-assisted nutrient transport**

Article in Press

The dosage of nano-fertilizers is another major factor which should be taken into account. It does not follow that bigger quantities are better in terms of stimulating plant growth or improve plant nutrition. The plant response may rise up to a certain level, after which there will be no more benefits or the possibility of the occurrence of phytotoxicity. Hence, it is better to concentrate on dose-effect relations rather than using a particular amount.

## 8. FIELD VALIDATION AND COMMERCIALIZATION CHALLENGES

Laboratory-based research and greenhouse trials provide good results but translating results from laboratory to field conditions proves to be difficult. Field conditions provide a lot of variability in terms of soil characteristics, temperature, moisture conditions, microorganisms, type of plants and their nutrient needs, all of which can affect the properties of nanoparticles. As a result, results obtained under controlled conditions do not always replicate in the field. Reviews of literature similarly show that validation in the field is only produced for limited types of nano-fertilizers (Pourzahedi *et al.* 2018).

Another important matter related to nano-fertilizer production is the profitability of the process and manufacturing on a large scale. As far as laboratory experiments allow control of parameters like particle size, shape, chemical composition, and nutrient composition in an accurate way, mass production may cause interference with maintaining the accuracy of these parameters. Thus, different qualities of initial raw materials, synthesis conditions, refinement processes, and operational parameters will influence the costs of the production process as well as the characteristics of the final products. Therefore, it is necessary to ensure the production process is stable and cost-efficient in case of mass production (Kumar *et al.* 2023).

The standardization process is critical to ensure that nano-fertilizers are evaluated and compared reliably. Differences in measuring methods for parameters such as particle size and shape, nutrient loading, method of application, nutrient-release properties, and toxicity evaluation complicate the process of formulation comparison. Thus, there is unanimous agreement among experts that application-specific standardization methods are essential for enhancing the consistency of the produced materials, controlling their quality, and achieving compliance with regulations for nanomaterials.

The commercialization of nano fertilizers can be influenced by regulatory aspects. The regulations regarding the product may vary due to the type of raw materials used, their applications, formulations, and regions of sale. In some jurisdictions, agricultural products using nanotechnology may not be subject to one particular regulation covering nano fertilizers but fall under existing laws governing fertilizers and agrochemicals instead. Such regulations complicate the registration and testing of the products for their safety. Hence, introducing a uniform set of rules and procedures concerning the product characterization will facilitate the development of responsible products.

Economic feasibility is another important aspect of commercialization. Besides the raw material costs, the total cost of the nanofertilizer may include costs for the synthesis, purification, formulation, quality control, packing, storage, transport, and regulatory compliance. Thus, the economic feasibility of the product is determined not only by its agronomic parameters but also by the fact that the extra costs of its production and application must be compensated for by measurable benefits such as higher efficiency of nutrients application, lower fertilizer consumption, and higher productivity. Therefore, techno-economic assessments and field cost-benefit analyses should be conducted in order to estimate the practical feasibility of nanofertilizers for different agricultural practices. (Nejatzadeh, 2024) Table 3 outlines the key difficulties involved in bringing nano-fertilizers to market, taking into account the technology, finance, regulations, environmental features, and field performance. By establishing universal testing, developing scalable manufacturing, carrying out field validation over an extended period of time, and ensuring safety assessment, it is possible to resolve these issues.

**Table 3. Commercialization factors, current limitations, and practical implications for scaled nanomaterial deployment in agriculture**

| Commercialization Factor | Current Limitation | Implication |
|---|---|---|
| Field efficacy | Limited multi-location and long-term field trials | Uncertain consistency across agricultural conditions |
| Scale-up | Laboratory methods may be difficult to reproduce at larger scale | Batch-to-batch variability |
| Production cost | Complex synthesis, purification, and processing requirements | Potentially higher production cost |
| Storage stability | Aggregation or formulation changes during storage | Reduced product stability and shelf life |
| Standardization | Differences in characterization and testing protocols | Difficult product comparison and quality assessment |
| Regulation | Variation in regulatory requirements and limited harmonization of nano-specific assessment approaches | Greater complexity in product registration and safety evaluation |

Article in Press

| | | |
|---|---|---|
| Economic return | Limited field-based techno-economic and cost–benefit data | Uncertain economic feasibility under different farming conditions |
| Environmental safety | Limited long-term data on environmental fate and non-target effects | Uncertainty regarding long-term environmental implications |
| Commercialization | Limited evidence on large-scale manufacturing, market performance, and economic viability | Greater uncertainty for investment and large-scale deployment |

## 9. SUSTAINABILITY AND LIFE-CYCLE CONSIDERATIONS

The sustainability of nano-fertilizers has to be assessed over the entire life cycle of nano-fertilizers and across all stages of their life cycle, including resource extraction, production, usage, environmental fate, and further disposal of the product. It is true that nano-fertilizers can make fertilizer production more efficient and reduce some fertilizer use in farmers' fields, but it is also necessary to take into account the assessment of how much energy, water, chemicals, and raw materials are used in the production of nano-fertilizers. It should be noted that the production of nanomaterials may create additional environmental issues and burdens when compared to conventional fertilizer production. Thus, the sustainability of a nano-fertilizer will depend on its composition, production technology, required resources for production, and agricultural performance.

The assessment of nano fertilizer sustainability must extend from resource extraction right through their use, environmental fate, and eventual disposal or degradation. Although nano fertilizers are likely to enhance nutrient use efficiency and to reduce the scope of nutrient losses, these aspects have to be weighed against consumption of energy, water, chemicals, and materials involved in the production of nanoparticles. Life-cycle assessment (LCA) provides a systematic framework for evaluating the environmental effects of nano-fertilizers in comparison with ordinary fertilizers concerning various stages of their life-cycle. Some of the parameters that can be assessed may include energy and resource consumption, emissions of greenhouse gases, water usage, material inputs, waste loss, and other emissions into the environment. However, the employment of LCA in the case of agricultural products utilizing nanotechnology is a complicated task since data on large-scale manufacturing, material flow, environmental impact, and properties of nanomaterials are absent. The gaps in data and uncertainty connected with it can influence the reliability and comparability of LCA results.

Achieving high effectiveness in agronomy does not assure sustainability of the environment. In evaluating the ecological effect of nanofertilizers, both agricultural factors and environmental features of production, utilization and disposal must be considered. A life-cycle perspective can help decide whether an increase in nutrient efficiency is connected with a lesser effect on the environment or whether the advantages are diminished by higher consumption of resources accompanying nanomaterial manufacturing and application.

## 10. EMERGING TECHNOLOGIES AND FUTURE PERSPECTIVES

The exploration in nano-fertilizers has progressed from just the creation of nutrient compounds of the nano size into discovering ways to build multifunctional delivery systems. New innovative formulas could include innovation in controlled-release coating technology, the use of biodegradable polymers, or development of new types of nanoclays that control the delivery of nutrients related to weather conditions and crop requirements. One of the newest trends in this area is the development of technologies that combine application of nano-fertilizer with the use of precision farming technologies. Such technologies can incorporate the use of soil sensors, remote sensing technologies, and crop monitoring, which will allow the application of fertilizers at the right place and at the right time (Al-Mamun *et al.* 2021). Data-driven approaches based on machine learning can also be used to correlate the properties of nano-fertilizer formula to soil conditions, leading to the perfect fertilizer dose. However, at the moment, all of the technologies are studied mainly as an additional tool for fertilizer use, although it has been established that these methods would have to be tested in real agricultural conditions before they could be fully integrated (Zafar et al., 2024).

The employment of bio-based and biodegradable nanocarriers has become popular since the application of this technology would help to eliminate the concerns related to adverse effects of ongoing alkali metals. Simultaneously, the utilization of nanofertilizers together with microorganisms or other biosystems represents a novel approach in terms of enhancing nutrient contribution in agriculture. This technology will enable the combination of the opportunities provided by nanotechnology with bio-transformation of nutrients and collaboration between plants and microorganisms (Chandana *et al.* 2021). As a result, it is reasonable to assume the growth of the number of functionalities of nanofertilizers along with increased effectiveness of nutrient utilization, biological compatibility and ecological nature of the end product rather than changing the dimensions of nanoparticles.

Article in Press

## 11. CONCLUSIONS

The utilization of nano fertilizers offers a potentially efficient way of delivering nutrients in agriculture. Compared to conventional large fertilizers, nano fertilizers can not only regulate the release of nutrients and enhance their availability, but also minimize the loss of nutrients. Nevertheless, the success of the use of nano fertilizers is not solely determined by the size of the nanoparticles; instead, the results also depend on the chemical composition of the fertilizers, methods of application, type of crops grown, characteristics of the soil, and other environmental factors. The analysis presented in this review indicates that laboratory and greenhouse experiments have reported higher rates of nutrient absorption, use of nutrients by plants, and overall efficiency of these fertilizers. However, it cannot be said that these results hold true for field conditions unless the experimental procedures are repeated in real-life farms. Simultaneously, the transformation of the environment and sustainment of nanoparticles, their interactions with microbes, possible effects on plants, manufacturing costs, scalability and lack of regulation must be taken into account in their utilization. The development of future nano-fertilizers should not only reduce the usage of fertilizers but also include controlled release, compatibility with biology, scalability and eco-friendly manufacturing. Successful use of nano-fertilizers depends upon proving that they can do better than regular methods of fertilization concerning cost-efficiency, crop yield and eco-friendliness, as provable through field testing results. Combining nanotechnology with precision farming and sustainable materials may help develop nano-fertilizers.

## FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

## COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).



## REFERENCES

Abdel-Aziz, H. M. M., Hasaneen, M. N. A. and Omer, A. M., Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil, *Span. J. Agri. Res*., 14(1), e0902 (2016). https://doi.org/10.5424/sjar/2016141-8205

Al-Mamun, M. R., Hasan, M. R., Ahommed, M. S., Bacchu, M. S., Ali, M. R. and Khan, M. Z. H., Nanofertilizers towards sustainable agriculture and environment, Environ. Technol. Innov., 23, 101658 (2021). https://doi.org/10.1016/j.eti.2021.101658

Avila-Quezada, G. D., Ingle, A. P., Golińska, P. and Rai, M., Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks, *Nanotechnol. Rev.*, 11, 2123–2140 (2022). https://doi.org/10.1515/ntrev-2022-0126

Ayenew, B. M., Satheesh, N., Zegeye, Z. B. and Kassie, D. A., A review on the production of nanofertilizers and its application in agriculture, Heliyon, 11(1), e41243 (2025). https://doi.org/10.1016/j.heliyon.2024.e41243

Babu, S., Singh, R., Yadav, D., Rathore, S. S., Raj, R., Avasthe, R., Yadav, S. K., Das, A., Yadav, V., Yadav, B., Shekhawat, K., Upadhyay, P. K., Yadav, D. K. and Singh, V. K., Nanofertilizers for agricultural and environmental sustainability, Chemosphere, 292, 133451 (2022). https://doi.org/10.1016/j.chemosphere.2021.133451

Benício, L. P. F., Constantino, V. R. L., Pinto, F. G., Vergütz, L., Tronto, J. and da Costa, L. M., Layered double hydroxides: New technology in phosphate fertilizers based on nanostructured materials, ACS Sustain. Chem. Eng., 5(1), 399–409 (2017). https://doi.org/10.1021/acssuschemeng.6b01784

Bernardo, M. P., Guimarães, G. G. F., Majaron, V. F. and Ribeiro, C., Controlled release of phosphate from layered double hydroxide structures: Dynamics in soil and application as smart fertilizer, ACS Sustain. Chem. Eng., 6(4), 5152–5161 (2018). https://doi.org/10.1021/acssuschemeng.7b04806

Chandana, P., Latha, K., Chinnamuthu, C., Malarvizhi, P. and Lakshmanan, A., Impact of foliar application of nano nitrogen, zinc and copper on yield and nutrient uptake of rice, *Int. J. Plant Soil Sci.*, 33, 276–282 (2021). https://doi.org/10.9734/ijpss/2021/v33i2430778

Channab, B. E., El Idrissi, A., Ammar, A., Dardari, O., Marrane, S. E., El Gharrak, A., Akil, A., Essemlali, Y. and Zahouily, M., Recent advances in nano-fertilizers: Synthesis, crop yield impact, and economic analysis, Nanoscale, 16, 4484–4513 (2024a). https://doi.org/10.1039/D3NR05012B

Channab, B. E., El Idrissi, A., Ammar, A., Dardari, O., Marrane, S. E., El Gharrak, A., Akil, A., Essemlali, Y. and Zahouily, M., Correction: Recent advances in

Article in Press

nano-fertilizers: Synthesis, crop yield impact, and economic analysis, Nanoscale, 16, 4920 (2024b). https://doi.org/10.1039/D4NR90042A

Chhipa, H., Nanofertilizers and nanopesticides for agriculture, *Environ. Chem. Lett*., 15, 15–22 (2017). https://doi.org/10.1007/s10311-016-0589-3

Davarpanah, S., Tehranifar, A., Davarynejad, G.H., Abadía, J. and Khorasani, R., Effects of foliar applications of zinc and boron nano-fertilizers on pomegranate (Punica granatum cv. Ardestani) fruit yield and quality, *Scientia Horticul*., 210, 57–64 (2016). https://doi.org/10.1016/j.scienta.2016.07.003

de França Bettencourt, G. M., Degenhardt, J., Zevallos Torres, L. A., de Andrade Tanobe, V. O. and Soccol, C. R., Green biosynthesis of single and bimetallic nanoparticles of iron and manganese using bacterial auxin complex to act as plant bio-fertilizer, Biocatal. Agric. Biotechnol., 30, 101822 (2020). https://doi.org/10.1016/j.bcab.2020.101822

Ramírez-Rodríguez, G. B., Dal Sasso, G., Carmona, F. J., Miguel-Rojas, C., Pérez-de-Luque, A., Masciocchi, N., Guagliardi, A. and Delgado-López, J. M., Engineering biomimetic calcium phosphate nanoparticles: A green synthesis of slow-release multinutrient (NPK) nanofertilizers, ACS Appl. Bio Mater., 3(3), 1344–1353 (2020). https://doi.org/10.1021/acsabm.9b00937

Demeke, E. D., Benti, N. E., Terefe, M. G., Anbessa, T. T., Mengistu, W. M. and Mekonnen, Y. S., A comprehensive review on nano-fertilizers: Preparation, development, utilization, and prospects for sustainable agriculture in Ethiopia, *Nanoscale Adv*., 7(8), 2131–2144 (2025) https://doi.org/10.1039/d4na01068j

Dhlamini, B., Paumo, H. K., Kamdem, B. P., Katata-Seru, L. and Bahadur, I., Nano-engineering metal-based fertilizers using biopolymers: An innovative strategy for a more sustainable agriculture, *J. Environ. Chem. Eng.*, 10, 107729 (2022). https://doi.org/10.1016/j.jece.2022.107729

Dimkpa, C. O. and Bindraban, P. S., Nanofertilizers: New products for the industry?, J. Agric. Food Chem., 66(26), 6462–6473 (2018). https://doi.org/10.1021/acs.jafc.7b02150

Esmaeil, M., Abd Elghany, S., Fattah, A. A. and Arafat, A., Assessment of the effect of nano sulfur on some soil properties and maize productivity in saline soil, *Curr. Sci. Int.*, 9(4), 656–665 (2020). https://doi.org/10.36632/csi/2020.9.4.59

Guo, H., White, J. C., Wang, Z. and Xing, B., Nano-enabled fertilizers to control the release and use efficiency of nutrients, *Curr. Opinion Environ.Sci.Hea.*, 6, 77–83 (2018). https://doi.org/10.1016/j.coesh.2018.07.009

Gupta, S., Gupta, G. S., Parvati, M., Kumar, M. A. and Tiwari, S., Nano fertilizers for sustaining future farming: A review, *Biocatal. Agri. Biotechnol*., 62, 103446 (2024). https://doi.org/10.1016/j.bcab.2024.103446

Haydar, M. S., Ghosh, D. and Roy, S., Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns, *Plant Nano Biol*., 7, 100058 (2024). https://doi.org/10.1016/j.plana.2024.100058

Hong, J., Wang, C., Wagner, D.C., Gardea-Torresdey, J. L., He, F. and Rico, C. M., Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts, *Environ. Sci. Nano*, 8(5), 1196–1210 (2021). https://doi.org/10.1039/D0EN01129K

Jakhar, A. M., Aziz, I., Kaleri, A. R., Hasnain, M., Haider, G., Ma, J. and Abideen, Z., Nano-fertilizers: A sustainable technology for improving crop nutrition and food security, NanoImpact, 27, 100411 (2022). https://doi.org/10.1016/j.impact.2022.100411

Jha, A., Pathania, D., Damathia, B., Raizada, P., Rustagi, S., Singh, P., Rani, G. M. and Chaudhary, V., Panorama of biogenic nano-fertilizers: A road to sustainable agriculture, *Environ. Res.*, 235, 116456 (2023). https://doi.org/10.1016/j.envres.2023.116456

Kah, M., Singh, K. R., Gogos, A. and Daniel, B. T., A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues, *Nat. Nanotechnol*., 13(8), 677–684 (2018). https://doi.org/10.1038/s41565-018-0131-1

Kekeli, M. A., Wang, Q. and Rui, Y., The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality, *Plants*, 14(4), 554 (2025). https://doi.org/10.3390/plants14040554

Khalkhal, K., Asgari, L. B. and Mansour, G., An overview on the effect of soil physicochemical properties on the immobilization of biogenic nanoparticles, *Bio. Nano-Part. Use Agro-Ecosyst*., 133-160 (2020). https://doi.org/10.1007/978-981-15-2985-6_8

Khardia, N., Meena, R., Jat, G., Sharma, S., Kumawat, H., Dhayal, S., Meena, A.K., Sharma, K. Soil properties influenced by the foliar application of nano fertilizers in maize (*Zea mays* L.) Crop. *Int. J. Plant Soil Sci.* 2022, *34*, 99–111. https://doi.org/10.9734/ijpss/2022/v34i1430996

Kumalasari, R., Hanuddin, E. and Nurudin, M., Increasing Growth and Yield of Shallot Using Nano Zeolite and Nano Crab Shell Encapsulated NK Fertilizer in Entisols and Inceptisols, *Planta Tropika*, 10(2), 140–151 (2022). https://doi.org/10.18196/pt.v10i2.12945

Kumar, N., Samota, S. R., Venkatesh, K. and Tripathi, S. C., Global trends in use of nano-fertilizers for crop production: Advantages and constraints—A review, *Soil Tillage Res*., 228, 105645 (2023). https://doi.org/10.1016/j.still.2023.105645

Article in press

Liu, R. and Lal, R., Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions, Sci. Total Environ., 514, 131–139 (2015). https://doi.org/10.1016/j.scitotenv.2015.01.104

Gilbertson, L. M., Pourzahedi, L., Laughton, S., Gao, X., Zimmerman, J. B., Theis, T. L., Westerhoff, P. and Lowry, G. V., Guiding the design space for nanotechnology to advance sustainable crop production, Nat. Nanotechnol., 15, 801–810 (2020). https://doi.org/10.1038/s41565-020-0706-5

Mehta, S., Thakur, A., Kurbah, I., Chauhan, N. and Thakur, R., Nanotechnology in plant nutrition: Ensuring sustainable agriculture through nanofertilizers, J. Plant Nutr. Soil Sci., 187(5), 589–603 (2024). https://doi.org/10.1002/jpln.202300288

Mikhak, A., Sohrabi, M. Z., Kassaee, M. and Feizian, Synthetic nanozeolite/nanohydroxyapatite as a phosphorus fertilizer for German chamomile (Matricaria chamomilla L.), *Indus. Crops Prod*., 95, 444–452 (2017). https://doi.org/10.1016/j.indcrop.2016.10.054

Mohammed, M. M., Disadvantages of using Nano-particles as fertilizers in Iraq, *IOP Conf. Ser. Earth Environ. Sci.*, 735(1), 012043 (2021). https://doi.org/10.1088/1755-1315/735/1/012043

Montalvo, D., McLaughlin, M. J. and Degryse, F., Efficacy of hydroxyapatite nanoparticles as phosphorus fertilizer in Andisols and Oxisols, Soil Sci. Soc. Am. J., 79(2), 551–558 (2015). https://doi.org/10.2136/sssaj2014.09.0373

Nejatzadeh, F., Effect of foliar application frequency and different levels of nano fertilizer on growth and development of coriander (*Coriandrum sativum* L.), *Heliyon*, 10(11), e31732 (2024). https://doi.org/10.1016/j.heliyon.2024.e31732

Nongbet, A., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Ray, M. K., Khan, M., Baek, K. H. and Chakrabartty, I., Nanofertilizers: A smart and sustainable attribute to modern agriculture, Plants, 11(19), 2587 (2022). https://doi.org/10.3390/plants11192587

Padhan, S. R., Kar, I., Mohanty, A. and Kumar, P. K., Nanofertilizers: Types, synthesis, methods, and mechanisms, *Springer Nat. Switzerland*, 61–98 (2024). https://doi.org/10.1007/978-3-031-41329-2_3

Pandorf, M., Pourzahedi, L., Gilbertson, L., Lowry, G. V., Herckes, P. and Westerhoff, P., Graphite nanoparticle addition to fertilizers reduces nitrate leaching in growth of lettuce (*Lactuca sativa*), *Environ. Sci. Nano*, 7(1), 127–138 (2020). https://doi.org/10.1039/C9EN00890J

Pourzahedi, L., Pandrof, M., Ravikumar, D., Julie, Z. B., Thomas, S. P., Paul, W., Leanne, G. M. and Lowry, G. V., Life cycle considerations of nano-enabled agrochemicals: Are today's tools up to the task?,*Environ. Sci. Nano*, 5(5), 1057–1069 (2018). https://doi.org/10.1039/C7EN01166K

Qin, Q., Wang, Q., Chen, Y., Tang, Y., Ding, Y. and Rui, Y., Enhancing crop yields and quality of agricultural products: Research progress in nanofertilizer applications, *Environ. Sci. Nano*., 12(4), 2193–2207 (2025). https://doi.org/10.1039/D5EN00075K

Rajput, V., Minkina, T., Mazarji, M., Shende, S., Sushkova, S., Mandzhieva, S., Burachevskaya, M., Chaplygin, V., Singh, A. and Jatav, H., Accumulation of nanoparticles in the soil-plant systems and their effects on human health, *Ann. Agric. Sci.*, 65(2), 137–143 (2020). https://doi.org/10.1016/j.aoas.2020.08.001

Raliya, R., Saharan, V., Dimkpa, C. and Biswas, P., Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives, J. Agric. Food Chem., 66(26), 6487–6503 (2018). https://doi.org/10.1021/acs.jafc.7b02178

Rico, C. M., Majumdar, S., Maria, D. G., Jose, P. V. R. and Garde, T. J. L., Interaction of nanoparticles with edible plants and their possible implications in the food chain, *J. Agri. Food Chem.*, 59(8), 3485–3498(2011). https://doi.org/10.1021/jf104517j

Sadati, V. S. T., Niknejad, Y., Fallah, A. H. and Barari, T. D., Response of rice yield and quality to nano-fertilizers in comparison with conventional fertilizers, *J. Plant Nutr.*, 44, 1971–1981 (2021). https://doi.org/10.1080/01904167.2021.1884701

Sahoo, B. R., Dash, A. K., Mohapatra, K. K., Mohanty, S., Sahu, S. G., Sahoo, B. R., Prusty, M. and Priyadarshini, E., Strategic management of nano-fertilizers for sustainable rice yield, grain quality, and soil health, *Front. Environ. Sci.*, 12, 1420505 (2024). https://doi.org/10.3389/fenvs.2024.1420505

Saravana, K. P., Ramkumar, S., Seethalaxmi, M., Rekha, T., Abiyoga, M., Baskar, V. and Sureshkumar, S., Biofortification of crops with nutrients by the application of nanofertilizers for effective agriculture, *Plant Physiol. Biochem*., 212 108772 (2024). https://doi.org/10.1016/j.plaphy.2024.108772

Saurabh, K., Ved, P., Dubey, A. K., Ghosh, S., Arti, K., Prem, S. K., Jeet, P., Sarkar, B., Upadhyaya, A., Das, A., Kumar, S., Govind, M., Kumar, U., Kumar, A. and Singh, R. R., Enhancing sustainability in agriculture with nanofertilizers, *Discover Appl. Sci.*, 6(11), 559 (2024). https://doi.org/10.1007/s42452-024-06267-5

Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A. and Battaglia, M. L., Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use?, Plants, 10(1), 2 (2021). https://doi.org/10.3390/plants10010002

Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H. and Zhou, J., Applications of nanotechnology in plant growth and crop protection: A review, Molecules, 24(14), 2558 (2019). https://doi.org/10.3390/molecules24142558

Sharma, G., Kumar, A., Devi, K. A., Deepa, B., Pal, A., Raliya, R., Biswas, P. and Vinod, S., Chitosan nanofertilizer to foster source activity in maize, *Int. J. Biol. Macromol.*, 145, 226–234 (2020). https://doi.org/10.1016/j.ijbiomac.2019.12.155

Sharma, V., Javed, B., Byrne, H., Curtin, J. and Tian, F., Zeolites as carriers of nano-fertilizers: From structures and principles to prospects and challenges, Appl. Nano, 3(3), 163–186 (2022). https://doi.org/10.3390/applnano3030013

Shirsat, S. and Suthindhiran, K., Iron oxide nanoparticles as iron micronutrient fertilizer—Opportunities and limitations, *J. Plant Nutri. Soil Sci.*, 187(5), 565–588 (2024). https://doi.org/10.1002/jpln.202300203

Jayara, A. S., Kumar, R. and Pandey, P., Nanofertilizers in wheat crop nutrition: A review, J. Cereal Res., 15(1), 24–30 (2023). https://doi.org/10.25174/2582-2675/2023/128120

Singh, L., Sadawarti, R. K., Shaifali, Menon, S., Minkina, T., Sushkova, S. and Rajput, V. D., Impact of nano-fertilizers and nutrient management on growth and yield of strawberry, Russ. J. Earth Sci., 23(5), ES0215 (2023). https://doi.org/10.2205/2023ES02SI15

Toksha, B., Sonawale, V. A. M., Vanarase, A., Bornare, D., Tonde, S., Hazra, C., Kundu, D., Satdive, A., Tayde, S. and Chatterjee, A., Nanofertilizers: A review on synthesis and impact of their use on crop yield and environment, Environ. Technol. Innov., 24, 101986 (2021). https://doi.org/10.1016/j.eti.2021.101986

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S.A., Rehman, H. U., Ashraf, I., Sanaullah, M., Nanotechnology in agriculture: Current status, challenges and future opportunities, *Sci. Tot. Environ.*, 721, 137778 (2020). https://doi.org/10.1016/j.scitotenv.2020.137778

Verma, S. K., Rana, N., Verma, A., Roy, S., Shukla, A. and Kumar, A., Effect of Foliar Application of Nano and Non-Nano Fertilizers on Growth and Nutrient Use Efficiency of Indian Mustard [*Brassica juncea* (L.) Czern and Coss], *J. Sci. Res. Rep.*, 30(5), 868–878 (2024). https://doi.org/10.9734/jsrr/2024/v30i52004

Xiao, Z., White, J. C., Kah, M., Cao, X., Yue, L., Dai, Y., Wang, C., Zhang, L., Ma, L., Bai, Z., Wang, X., Rasmann, S., Wang, Z. and Xing, B., Nano-agrochemical use in sustainable agriculture and environmental protection, Nat. Rev. Earth Environ., 7, 447–468 (2026). https://doi.org/10.1038/s43017-026-00796-w

Yadav, A., Yadav, K. and Abd-Elsalam, K. A., Nanofertilizers: Types, delivery and advantages in agricultural sustainability, Agrochemicals, 2(2), 296–336 (2023). https://doi.org/10.3390/agrochemicals2020019

Yin, J., Su, X., Yan, S. and Shen, J., Multifunctional nanoparticles and nanopesticides in agricultural application, *Nanomater.*, 13(7), 1255 (2023) https://doi.org/10.3390/nano13071255

Zafar, S., Bilal, M., Ali, M. F., Mahmood, A., Kijsomporn, J., Wong, L. S., Kumar, V. and Alotaibi, S. S., Nano-biofertilizer: An eco-friendly and sustainable approach for the improvement of crops under abiotic stresses, *Environ. Sustain. Indic.*, 24, 100470 (2024) https://doi.org/10.1016/j.indic.2024.100470

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A. and Munné-Bosch, S., Nanofertilizer use for sustainable agriculture: Advantages and limitations, *Plant Sci.*, 289, 110270 (2019) https://doi.org/10.1016/j.plantsci.2019.110270

Article in Press