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Exploring nanofertilizers: innovations for precision agriculture and nutrient management

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ABSTRACT

Nanofertilizers mark a significant breakthrough in agricultural practices, offering innovative solutions for nutrient transport and regulation from the soil to plants. Essential nutrients like nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, manganese, copper, zinc, iron, and molybdenum promote healthy plant growth and ensure successful crop production. Fertilization has been a core agricultural practice since its origins, driven by the need to boost crop yield and quality. The advent of nanofertilizers introduces a transformative shift, paving the way for next-generation fertilizers. These advanced solutions are not only cost-efficient but also enhance soil's chemical and physical properties, such as improving water retention. Additionally, plants treated with nanofertilizers demonstrate increased yields, superior quality, and enhanced resilience to both biotic and abiotic stress factors. This review aims to underscore the significance of nanofertilizers in modern agricultural practices by comparing them with conventional fertilizers, emphasizing their advantages, their role in improving crop quality and productivity, and their potential contribution to environmental sustainability.

Keywords: *nanofertilizers, nanotechnology in agriculture, sustainable agricultural production, next-generation fertilizers, nutrient transport.*

INTRODUCTION

Plant nutrients, commonly supplied through fertilizers, are essential for plant growth and development, as they provide the necessary elements for metabolic processes. However, the excessive and indiscriminate use of conventional fertilizers has led to a decline in soil fertility by disrupting beneficial microbial communities, necessitating the search for alternative, eco-friendly solutions. In this regard, nanofertilizers (NFs) represent a significant advancement in agricultural technology, offering a sustainable approach to nutrient management (Abobatta, 2018). Unlike traditional fertilizers, nanofertilizers enable crops to absorb nutrients according to their specific needs, minimizing nutrient loss and reducing harmful environmental effects (Preetha and Balakrishnan, 2017). The enhanced surface area of nanomaterials facilitates various metabolic reactions, including improved photosynthesis, ultimately leading to increased agricultural productivity.

While conventional fertilizers have played a crucial role in ensuring food security, their inefficiency in nutrient uptake and negative environmental impacts highlight the urgent need for more sustainable and effective alternatives (Su et al., 2022). Nanofertilizers, which consist of nutrients encapsulated or coated with nanomaterials, have emerged as a promising solution in this context. The application of nanotechnology in fertilizer synthesis is a pioneering step toward sustainable agriculture, offering the potential to address food scarcity while promoting environmental resilience in the face of climate change (Qureshi et al., 2018). Nanomaterials, with particle sizes ranging from 1 to 100 nanometers, enable precise nutrient delivery, reducing ecotoxicity and preventing nutrient loss to soil and groundwater (Hussain et al., 2016; Gade et al., 2023).

Nanofertilizers are either chemically synthesized or derived from traditional fertilizers, bulk materials, or plant extracts, modified using nanotechnology to enhance soil fertility, productivity, and crop quality. By regulating nutrient release, these fertilizers ensure that crops receive the optimal amount of nutrients in the right proportions, thereby improving yield while mitigating environmental degradation (Agnihotri and Tyagi, 2023). Additionally, nanofertilizers offer a targeted approach to nutrient delivery, ensuring that nutrients are supplied precisely where they are needed, whether in the form of micronutrients or macronutrients (Popko et al., 2018).

Despite the promising advantages of nanofertilizers, research gaps persist, particularly concerning their long-term environmental impact, potential toxicity, and large-scale field applications. Further studies are needed to assess their interactions with soil microorganisms, possible bioaccumulation, and economic feasibility compared to conventional fertilizers. Additionally, standardization and regulatory frameworks for nanofertilizer production and application remain underdeveloped, necessitating further interdisciplinary research.

This review aims to provide a comprehensive analysis of the role of nanofertilizers in agricultural production, comparing them with traditional fertilizers, highlighting their benefits in enhancing yield quality and quantity, and exploring their potential contributions to environmental sustainability. By addressing existing research gaps, this paper seeks to advance the understanding of nanofertilizer applications and encourage further innovation in sustainable agricultural practices.

MINERAL FERTILIZERS AND THEIR DRAWBACKS

The application of fertilizers, whether mineral or organic, is essential for improving soil properties and supporting plant growth by influencing key physiological and biochemical processes, such as metabolic reactions, photosynthesis, and respiration (Stojanova, 2022). However, conventional mineral fertilizers have significant inefficiencies, including low nutrient uptake and high losses due to inadequate agronomic practices and climate change. (Stojanova, 2018; Yadav et al., 2023).

Excessive and unregulated use of phosphorus and potassium fertilizers contributes to soil degradation, leading to compaction, salinization, and nutrient imbalances. These effects not only impact soil health but also pose risks to human and animal populations through the consumption of contaminated crops. Moreover, the overuse of phosphorus fertilizers is directly linked to eutrophication and heavy metal accumulation, both of which have severe ecological and public health consequences (Stojanova, 2018).

A key drawback of conventional fertilizers is their low bioavailability, as many macronutrients in chemical fertilizers exhibit poor solubility in soil, leading to inefficient plant absorption. To compensate, farmers apply fertilizers repeatedly, increasing production costs and environmental damage. Over time, excessive fertilizer application disrupts microbial communities, destabilizes mineral cycles, and depletes soil structure, causing irreversible degradation. Furthermore, nitrogen and phosphorus fertilizers are major contributors to eutrophication on a global scale, highlighting the urgent need for more sustainable solutions (Rahman and Zhang, 2018).

Beyond environmental concerns, the economic viability of conventional fertilizers is also declining. Their high nutrient release rates result in poor nutrient use efficiency (NUE), leading to significant losses through runoff and volatilization. This inefficiency increases production costs for farmers, who must use larger quantities of fertilizers to achieve desired yields (Verma et al., 2022a). Additionally, factors such as limited arable land, water scarcity, and a growing global population further drive reliance on chemical fertilizers, despite their long-term negative impacts (Shuqin and Fang, 2018).

Given these challenges, a transition toward sustainable fertilization strategies is imperative. Innovative alternatives such as nanofertilizers offer promising solutions to enhance nutrient efficiency while reducing environmental harm. Additionally, stronger regulatory frameworks and sustainable agricultural policies must be implemented to mitigate the adverse effects of conventional fertilizers. Only through an integrated approach that combines technological advancements, ecological awareness, and policy intervention can the agricultural sector move toward a more resilient and sustainable future.

BENEFITS OF NANO FERTILIZERS IN AGRICULTURE

As the global population continues to grow, the demand for food security and sustainable agricultural practices is increasing rapidly. Traditional agricultural methods, though effective to some extent, often fall short of maximizing output while preserving environmental health. Enter nano-fertilizers – a convergence of nanotechnology and agriculture – offering a range of benefits that may provide solutions to many contemporary agricultural challenges (Mahesha et al., 2023).

Emerging technologies are continuously advancing, particularly in modern agriculture. Environmental concerns must be a central consideration, given the growing scarcity of natural resources and the worsening effects of climate change exacerbated by human activity. The pursuit of progress and the growth of the global population have generated significant demands, such as the need for high food production in smaller areas and shorter time frames. In this context, the use of nanofertilizers in agriculture can serve as a valuable ally in achieving sustainability.

In recent years, the food sector has undergone significant advances, particularly in the development of technologies used in crops to supply essential nutrients often lacking in the human diet, largely due to the rise of fast food and the declining consumption of fruits and vegetables. As a result, the use of nanotechnology in the development of agrochemicals has led to the emergence of nanofertilizers (da Silva Júnior et al., 2020).

Nanofertilizers are innovative agricultural inputs designed to release nutrients into the soil gradually and in a controlled manner. This not only minimizes environmental damage but also enhances crop growth and productivity (El-Ghamry et al., 2018).

Key advantages of nanofertilizers

The development and application of nanofertilizers align with the need for a sustainable, nutrient-efficient, and environmentally friendly alternative to traditional chemical fertilizers. Their benefits include:

1. **Enhanced soil fertility and crop quality** – Nanofertilizers improve soil health, enhance crop yield, and maintain high-quality produce. They are non-toxic, environmentally safer, and significantly reduce the ecological footprint of agricultural activities. By increasing nutrient use efficiency, nanofertilizers contribute to both environmental protection and economic savings (Qureshi, 2018). Unlike conventional fertilizers, which release nutrients rapidly, nanofertilizers ensure a gradual and controlled nutrient supply to plants.
2. **Improved nutrient uptake and absorption efficiency** – Nanofertilizers exhibit higher nutrient efficiency. Their nanoscale properties enhance soil retention, ensuring a steady and sustained nutrient supply to crops over time.
3. **Enhanced nutrient transport mechanisms** – Due to their extremely small size, nanoparticles can easily pass through nanosized pores, root exudates, and molecular transporters. They also utilize specific ion channels, which facilitate higher nutrient uptake in plants. Once inside the plant, nanoparticles can move through plasmodesmata, ensuring effective nutrient delivery to key metabolic sites.
4. **Minimized nutrient losses** – Traditional fertilizers require frequent application because a significant portion of their nutrients is lost through leaching and volatilization. Nanofertilizers, in contrast, exhibit significantly lower losses, allowing for smaller application amounts while maintaining nutrient availability for crops. This reduces excessive fertilizer use and mitigates associated environmental concerns.
5. **Reduced environmental pollution** – The lower nutrient loss rate of nanofertilizers significantly minimizes the risk of soil and water pollution. By preventing excessive nitrogen and phosphorus runoff into water bodies, nanofertilizers help combat water eutrophication and the associated decline in aquatic ecosystems.
6. **Higher solubility and diffusion efficiency** – Compared to conventional synthetic fertilizers, nanofertilizers display superior solubility and diffusion rates. This ensures that nutrients remain bioavailable for plant uptake, enhancing agricultural productivity.
7. **Smart nutrient release mechanisms** – Advanced nanofertilizers, such as polymer-coated formulations, prevent premature nutrient interaction with soil and water. The encapsulated nanoparticles release nutrients only when plant roots are ready to absorb them, thereby reducing waste and improving efficiency. This contrasts with conventional fertilizers, which often result in nutrient losses due to uncontrolled release.
8. **Increased crop resilience and growth** – Nanofertilizers enhance plant adaptability under stressful environmental conditions, including drought, salinity, and temperature fluctuations. This contributes to improved crop resilience and higher agricultural yields (Babu et al., 2022).
9. **Mitigation of environmental degradation** – By improving nutrient use efficiency (NUE), nanofertilizers reduce soil degradation and water contamination. Their slow-release properties also help minimize greenhouse gas emissions, such as nitrous oxide and methane, which are commonly associated with conventional fertilizers (Mohanraj et al., 2019).

10. **Cost-effectiveness and economic viability** – Since the total cost of fertilizers correlates directly with application rates, nanofertilizers present a cost-efficient alternative due to their lower dosage requirements. Their higher efficiency in nutrient delivery also translates to increased revenue potential for farmers. Small-scale farmers, in particular, can benefit from the reduced input costs associated with nanofertilizer use (Ude et al., 2024).

The Role of Nanofertilizers in Sustainable Agriculture

Despite the availability of various mineral and chelated fertilizer sources, as well as multiple application methods (such as soil incorporation, foliar spraying, or a combination of both), the efficiency of nutrient use from traditional fertilizers often does not exceed 5% of the applied amount. Nano fertilizers play an important role in plant nutrition, whether applied via foliar sprays or soil treatments. They are distinguished by their higher solubility and greater reactivity compared to conventional fertilizer particles (Figure 1).

Nano fertilizers deliver nutrients to plants through one of three primary mechanisms: 1. Encapsulation of mineral nutrients within nanomaterials such as nanotubes; 2. Use of materials with open nanoporous structures that are coated with a thin film of protective polymer; 3. Delivery in the form of nanoparticles or nano-emulsions, which, due to their extremely high surface area relative to volume, exhibit enhanced efficiency.

This nanoscale efficiency can surpass even that of modern polymer-coated fertilizers, which themselves have seen significant improvements in recent years. Today, various essential macro- and micronutrients, such as nitrogen, phosphorus, potassium, iron, zinc, and calcium, are available in nanoscale formulations. These can be applied across a wide range of crops, including both field crops and horticultural products (Huda and Aljanabi, 2021).

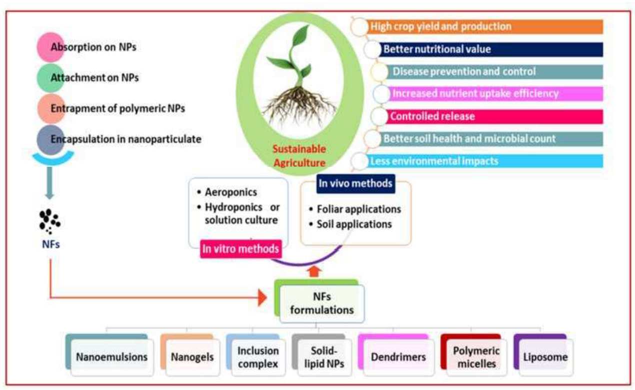

Figure 1. An overview of nano-fertilizer application in agriculture (Verma et al., 2022b)

Nano-fertilizers play a vital role in modern agriculture by utilizing appropriate formulations and delivery mechanisms to ensure optimal nutrient uptake and use in plants (Mittal et al., 2022). These nanoscale fertilizers help reduce nutrient losses due to leaching and minimize chemical transformations, thereby enhancing nutrient use efficiency (NUE) and contributing to better environmental quality. This is achieved through the application of nanoparticles (NPs) based on various metals and metal oxides. The use of nano-enabled fertilizers has been shown to improve nutrient delivery efficiency in plants (Chhipa, 2017). Additionally, nano-fertilizers enhance productivity by enabling targeted delivery and gradual nutrient release, which allows for reduced fertilizer usage while increasing NUE (Verma et al., 2022b).

Beyond fertilization, nanotechnology is proving to be a transformative force in sustainable agriculture (Figure 2).

Whether used alone or in combination with synthetic or organic fertilizers, nanofertilizers exhibit a controlled-release mechanism. Unlike conventional mineral fertilizers, which typically release nutrients over a period of 4 to 10 days, nanofertilizers can sustain nutrient release for an extended duration of 40 to 50 days (Seleiman et al., 2021).

Nanofertilizers are specifically designed to release active ingredients in response to biological and environmental requirements. Nano NPK fertilizers play a crucial role in increasing agricultural productivity, as they promote plant growth while minimizing environmental pollution (Table 1). This makes them a promising and sustainable alternative to traditional chemical fertilizers (Agnihotri and Tyagi, 2023).

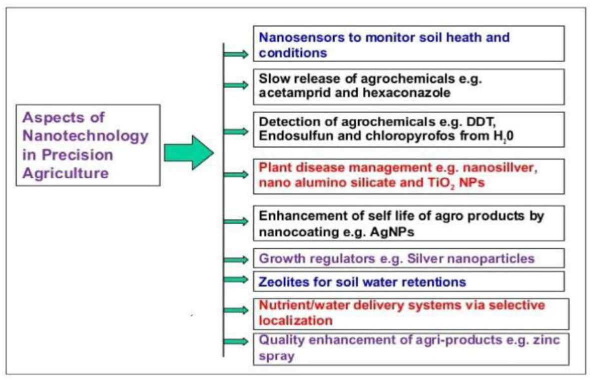

Figure 2. Key elements of nanotechnology in precision agriculture (Glotra et al., 2023)

Table 1. Distinct characteristics of nanofertilizers vs. traditional fertilizers (Gade et al., 2023)

Properties	Nanofertilizers	Traditional Fertilizers
Solubility and Dispersion of the mineral nutrients.	Nano-sized advantages the mineral nutrient by improving solubility, and dispersion, and can achieve enhanced bioavailability.	Due to large-sized particles, it can show limited solubility and dispersion hence leading to poor bioavailability to the plants.
Deprivation rate of Nutrients in Fertilizer.	Nano-sized enables the retention of soil particles for a prolonged period.	Significantly leached, rain-off, and drifts can occur in the methods.
Superintend releasing Mode.	The release rate and pattern of nutrients can be precisely controlled by encapsulating the nanofertilizers in the polymer matrix, supporting sustainable practices.	Direct exposure to fertilizers might be toxic in excess dosage and can also damage the ecosystem associated with the crop field.
Nutrient Uptake Efficiency.	Nanostructured Fertilizers can save the excess use and increase the efficiency in uptake ratio during controlled cultivation.	Large-sized Chemical Composite is difficult to uptake by plants hence reducing efficiency and resource utilization.
Prolongation of effective nutrient release.	The nanostructured formulation can extend the nutrient supply to the plant for a prolonged time by controlled released efficiency.	Readily available at the time of delivery or foliar leading to the loss of rest nutrients into the soil, forming insoluble salts.

CATEGORIES OF NANOFERTILIZERS

With the global population on the rise and an increasing demand for food production, sustainable agricultural solutions have become essential. Among these, nutrient-based nanofertilizers have emerged as an innovative approach to improving nutrient availability, uptake, and utilization in plants (Yadav et al., 2023).

Nanofertilizers can be classified into various categories, one of which is based on their nutrient composition. Broadly, they are divided into macronutrient and micronutrient nanofertilizers.

Macronutrient-Based Nanofertilizers

Macronutrients are essential for plant growth and development, including nitrogen, phosphorus, potassium, calcium, sulfur, magnesium, carbon, oxygen, and hydrogen. Nanofertilizers incorporating these macronutrients enhance nutrient availability while reducing bulk application and cultivation costs (Kumar et al., 2022). Traditional fertilizers, such as urea, often suffer from volatilization and leaching, leading to inefficiencies. In contrast, nitrogen-based nanofertilizers improve uptake and mitigate chlorosis caused by nitrogen deficiency (Manzoor et al., 2024). Alongside nitrogen, phosphorus and potassium are crucial for plant health and productivity (Stojanova, 2020; Khatri and Bhateria, 2022).

Phosphorus plays a key role in photosynthesis, respiration, and nutrient transport, directly impacting fruit ripening and quality (Stojanova et al., 2024). However, conventional phosphate fertilizers often bind to the soil, limiting plant absorption. Apatite nanoparticles and other phosphorus-based nanofertilizers offer improved efficiency and reduce the risk of eutrophication by enhancing root uptake (Bhardwaj et al., 2022; Ardali et al., 2024).

Potassium is essential for enzyme activation and biomolecule synthesis. Nano-potassium fertilizers promote root and shoot development while increasing the absorption of nitrogen, calcium, and magnesium. Due to their high solubility and reduced leaching, these fertilizers ensure sustained nutrient availability (Khatri and Bhateria, 2023; Yadav et al., 2023). Similarly, sulfur-based nanofertilizers, such as sulfate nanoparticles and nano-zeolite, enhance nutrient absorption and improve crop productivity, benefiting crops like groundnut (Khatri and Bhateria, 2023).

Calcium is critical for cell division, enzyme activity, and maintaining cell membrane stability. It supports mitosis and metabolic processes, significantly influencing plant health (Kumar et al., 2021; Stojanova et al., 2024). Magnesium, another vital nutrient, contributes to chlorophyll synthesis, enzyme activation, and energy transfer reactions. Magnesium deficiency results in stunted growth and delayed reproductive phases (Saleem et al., 2019). Magnesium-based nanofertilizers, derived from magnesium oxide or magnesium sulfate, have proven effective in enhancing crop growth, improving nutritional quality, and strengthening plant resistance to pests and diseases. They have demonstrated particular success in crops like rice, sugarcane, tomatoes, and potatoes (Liao et al., 2021).

By integrating nanotechnology into fertilizer formulations, these macronutrient-based nanofertilizers enhance plant nutrition, minimize environmental impact, and improve overall agricultural sustainability.

Micronutrient-Based Nanofertilizers

Micronutrients, though required in smaller quantities than macronutrients, are essential for plant growth and productivity. Even minor deficiencies can significantly impact crop physiology. Micronutrient-based nanofertilizers enhance nutrient uptake, improve yields, and strengthen resistance to biotic and abiotic stresses (Yadav et al., 2023). These fertilizers contain trace elements such as zinc, iron, boron, and copper, which are crucial for metabolic and physiological processes (Ahmed et al., 2023). Nanoparticle formulations improve solubility, enhance soil distribution, and reduce fixation, increasing nutrient availability and boosting crop quality.

Iron, despite its abundance in soil, often remains inaccessible due to pH constraints. Its deficiency leads to poor growth, reduced leaf production, and lower chlorophyll content. Iron nanofertilizers improve nutrient distribution and metabolism, but optimal concentrations are crucial to avoid toxicity (Khatri and Bhateria, 2022). Similarly, manganese plays a key role in enzymatic processes, photosynthesis, ATP synthesis, chlorophyll production, and secondary metabolite formation, aiding plants in environmental stress adaptation (Nongbet et al., 2022).

Copper nanoparticles demonstrate superior efficiency over conventional fertilizers. Copper is vital for plant enzymes and proteins that support growth. Van Nguyen et al. (2022) highlighted its role in improving maize's drought stress tolerance. Likewise, boron is essential for cell wall formation, pollen development, and nutrient translocation, enhancing flower and fruit growth. Ibrahim and Farttoosi (2019) studied boron nanoparticle foliar application in mung beans, showing its positive effects on plant growth and yield.

Zinc is crucial for enzyme activation, carbohydrate synthesis, and protein metabolism. Its deficiency results in stunted growth and chlorophyll reduction. Zinc oxide nanofertilizers improve bioavailability, enhancing crop productivity while reducing leaching and environmental risks (Yadav et al., 2023). Awan et al. (2021) synthesized zinc oxide nanofertilizers using zinc sulfate and black seed extract, demonstrating their effectiveness in increasing seed germination, plant height, and leaf development in broccoli.

Nanofertilizers can be applied through multiple methods, including soil application (Taiz and Zeiger, 2010), foliar spraying (Dutta and Bera, 2021), seed nanopriming (Yadav et al., 2023), aeroponic treatment, and hydroponic treatment (Glotra et al., 2023).

MECHANISMS OF NANOFERTILIZER UPTAKE BY PLANTS

The most significant advantage of nanofertilizers is their improved effectiveness in delivering nutrients directly into plant cells. This targeted delivery ensures that plants receive the nutrients they need without excess nutrients accumulating in the soil or running off into nearby water bodies, such as lakes and streams – an issue that can lead to environmental damage from nitrogen or phosphorus pollution. Furthermore, the adoption of nanotechnology-based products results in reduced costs for farmers and a lower overall environmental impact. This is because nanofertilizers are more efficient in delivering essential nutrients compared to conventional fertilizer products (Gade et al., 2023).

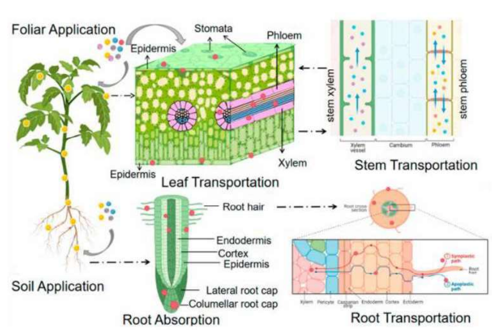

Figure 3. Nanoparticle pathways through roots and leaves (Wang et al., 2023)

Efficient uptake of nanoparticles by plant tissues is essential for their bioavailability and subsequent utilization in metabolic processes. Various pathways and mechanisms influence how nanoparticles enter plant systems, with particle size playing a crucial role. Root absorption is one primary route, where nanoparticles pass through the epidermal layers and enter the xylem for distribution to aerial parts of the plant. Another major pathway is foliar uptake, wherein nanoparticles penetrate the plant surface through stomatal openings or cuticular pores (Azim et al., 2023). The efficiency of nanoparticle uptake depends on their size, which determines their movement within the plant via mechanisms such as inner attraction, free translocation, outer wrapping, and embedment (Figure 3).

A direct correlation exists between nanoparticle size and nutrient absorption efficiency, with smaller nanoparticles being more readily taken up compared to larger ones. Table 2 illustrates how smaller particles enhance nutrient uptake in plants. The reduced particle size of nanofertilizers enables them to enter plant systems more effectively and support essential biochemical and physiological functions (Madlala et al., 2024).

Nanoparticles adhere easily to plant surfaces and are absorbed through natural openings at the nano- to micrometer scale. Different pathways facilitate nanoparticle uptake, with the absorption rate largely influenced by particle size and surface properties. While extremely small nanoparticles can penetrate directly through the cuticle, larger nanoparticles enter via non-cuticular regions such as stomata, hydathodes, and flower stigmas. For nanoparticles to reach the protoplast of plant cells, they must first traverse the cell wall. Studies indicate that nanoparticles smaller than 5 nm in diameter are particularly effective in crossing the intact cell wall and reaching intracellular compartments (Rana et al., 2021).

Table 2. Correlation between particle size and plant uptake (Madlala et al., 2024)

Crop type	Nanoparticle type	Nanoparticle size	Effect on nutrient uptake
Watermelon	AgNPs	20 nm	63.8%of the NPs were absorbed 38.2%werefoundontheoutersurface of the leaves
		60 nm	21.7% of the NPs were absorbed 8.3% accumulated on the outside surface
Soybean	CuONPs	25 nm	Exhibited high nutrient uptake
		50 nm	Demonstrated lower nutrient uptake compared to the CuONPs 25 nm
Wheat	SeNPs	40 nm	The absorption was 1.8–2.2 times higher than SeNPs 140 nm and 240 nm.
		140 nm	The absorption was1.8–2.2 times lower than SeNPs 40 nm
Cucumber	Ceria NPs	7 nm	Exhibited higher uptake of ceria NPs
		25 nm	Demonstrated lower uptake of ceria NPs
Allium porrum	Water-suspended fluorescent polystyrene NPs	43 nm	The NPs were able to penetrate through the stomatal pores
		1100 nm	The NPs were not able to penetrate; They accumulated on the outer surface

Enhanced Nutrient Use Efficiency and Yield

Nano-fertilizers significantly improve various growth parameters, including plant height, leaf area, number of leaves, chlorophyll synthesis, and photosynthetic activity, ultimately leading to higher yields compared to conventional fertilizers (Table 3).

As noted by Cui et al. (2010), nanostructured fertilizer formulations enhance nutrient absorption efficiency, and optimize fertilizer utilization, contributing to improved crop productivity while conserving resources.

The foliar application of nano-fertilizers containing nitrogen (N), phosphorus (P), and potassium (K) at lower concentrations has been shown to enhance wheat growth and yield parameters (Abdel-Aziz et al., 2016). Moreover, substituting ammonium sulfate with ammonium-loaded zeolite in sandy soils helps mitigate nitrogen leaching while sustaining sweet corn growth and improving nitrogen use efficiency. Pourjafar et al. (2016) reported that applying foliar sprays of nano-micronutrients, specifically iron and manganese, resulted in increased canola grain yields. Among the treatments, plants sprayed with a combination of iron sulfate (1:1,000) and manganese sulfate (1.5:1,000) exhibited the highest grain production (Glotra et al., 2023).

Table 3. Macro and micronutrient NF and their impact on various crops (Khatri and Bhateria, 2022)

Nutrients	Plant	Output	Additional effect
Macronutrients			
Nitrogen (N)	Sugarcane	Improved sugar production	Prevented leaching
Potassium (K)	Peanut	Highly significant increase in plant parameters, with the highest increase in the chlorophyll content	Overall biomass increased
Magnesium (Mg)	Green gram, Groundnut	Antioxidants are released to enhance chlorophyll production	Stabilizes chloroplast
Sulfur (S)	Groundnut	Improved productivity in terms of root, shoot, kernel, and shell growth	Improved seed germination Seed germination
Micronutrients			
Iron (Fe)	Maize	At low and medium concentrations showed optimum growth	Acted as a growth regulator and antimicrobial agent
Zinc (Zn)	Broccoli	Increased seed germination, root length, shoot length, the weight of seedlings, the count of leaves, plant height, and leaf surface	Antimicrobial property
Copper (Cu)	Maize	Positively regulates drought stress responses	Disease management
Boron (B)	Mung bean	Improved plant height, pods per plant, and total seed growth	N/A

OPPORTUNITIES AND FUTURE TRENDS

The application of nanotechnology in agriculture represents a transformative step toward sustainable farming by enhancing resource efficiency, minimizing environmental contamination, and preserving ecosystems. A key advancement is the use of nano-sensors in precision agriculture, which enables real-time monitoring of crop health, soil conditions, and environmental factors. This data-driven approach allows farmers to optimize fertilizer and water usage, reducing waste and minimizing the ecological footprint. Additionally, biodegradable and eco-friendly nanomaterials ensure that nanotechnology aligns with sustainability goals. By improving nutrient efficiency and reducing reliance on chemical fertilizers, nanotechnology contributes to soil conservation, lowers water contamination, preserves biodiversity, and decreases greenhouse gas emissions (Rana et al., 2024).

Despite its potential across multiple sectors, concerns persist regarding the environmental and biological implications of nanoparticle reactivity. The unique properties of nanoparticles, including their small size and high surface area, raise questions about their long-term effects in agricultural systems. While research is ongoing, the lack of standardized global regulations governing nanofertilizer application remains a major challenge. Critical issues include determining optimal application rates, assessing toxicity risks, and evaluating environmental impacts. As fertilizers are essential to soil fertility and agricultural productivity, ensuring their responsible application and safe disposal is crucial (Ardali et al., 2024).

Further research is needed to understand nanofertilizer characteristics, mechanisms of action, and plant-specific applications. While nanofertilizers can enhance crop growth and yield, excessive concentrations may lead to toxicity or growth inhibition. Establishing precise dosage recommendations is essential. A systematic evaluation of nanomaterial clearance, health implications, and environmental interactions will help refine nanofertilizer formulations and expand their commercial applications. Future research should prioritize field application guidelines that balance agronomic benefits with safety considerations. Additionally, technological advancements must align with farmer-centric recommendations to ensure practical usability (Gade et al., 2023).

Nanotechnology presents an innovative solution for meeting modern agriculture’s nutrient demands, traditionally reliant on inorganic fertilizers. By improving nutrient absorption efficiency and overcoming the limitations of conventional fertilizers, nanofertilizers offer benefits such as enhanced drought resistance, improved soil health, and higher crop yields. These attributes make them a promising tool for advancing sustainable agricultural practices (Mahesha et al., 2023; Babu et al., 2024).

For large-scale adoption, an integrated assessment of nanofertilizers' environmental, economic, and agronomic impacts is essential. Slow-release nanofertilizers could revolutionize nutrient delivery, reducing pollution and optimizing resource use. Research should focus on improving production processes, identifying cost-effective biodegradable materials, and minimizing risks associated with nanoparticle accumulation. Advancing these areas will help ensure nanofertilizers support global food security while aligning with sustainable agricultural principles (Gade et al., 2023).

CONCLUSION

In conclusion, the growing challenges to food security, driven by population growth and environmental concerns, necessitate innovative and sustainable agricultural practices. Chemical fertilizers, while essential for crop production, have limitations such as low nutrient efficiency and high environmental impact. These challenges highlight the need for alternatives that enhance yields while minimizing ecological harm. Nanofertilizers offer a promising solution by improving seed germination, photosynthesis, nutrient metabolism, and stress tolerance. Their high nutrient use efficiency allows for smaller application quantities compared to conventional fertilizers, reducing pollution and optimizing nutrient delivery to plants.

Beyond improving crop productivity, nanotechnology also contributes to reducing post-harvest losses and enhancing the quality of fruits and vegetables. By ensuring more efficient resource utilization, nanofertilizers can decrease reliance on chemical pesticides and fertilizers, fostering a more sustainable agricultural system. However, despite their advantages, improper or excessive use of nanofertilizers could lead to phytotoxicity, environmental harm, and unintended ecological consequences. Therefore, their application must be carefully regulated and supported by thorough research and risk assessments to prevent negative impacts on soil health, ecosystems, and food safety.

While nanotechnology presents a transformative tool for increasing crop yields, improving food quality, and reducing agricultural costs, its success depends on responsible implementation. The adoption of nanofertilizers could revolutionize agriculture, making it more efficient and environmentally sustainable. However, continued research, regulatory oversight, and cautious application are essential to fully harness their benefits while mitigating potential risks. By balancing innovation with sustainability, nanotechnology can play a crucial role in addressing global food security challenges and promoting a more resilient agricultural future.

REFERENCES

Abdel-Aziz, H.M.M., Hassaneen, M.N.A., & Omer, A.M. (2016). Nano chitosan-NPK fertilize enhances the growth and productivity of wheat plants grown in sandy soil. *Spanish Journal of Agricultural Research, 14,* 1–9.

Abobatta, W.F. (2018). Over view of nano-fertilizers. *Asian J. Ethnopharma. Med. Foods, 4,* 17–20.

Agnihotri, R., & Tyagi, D.B. (2023). *Effect of nano-fertilizer and conventional fertilizer on the growth, yield and yield attributes of sesame (Sesamum indicum L.).* Lambert Academic Publishing. UK.

Ahmed, R., Uddin, M.K., Quddus, M.A., Samad, M.Y.A., Hossain, M.M., & Haque, A.N.A., (2023). Impact of foliar application of Zinc and Zinc oxide nanoparticles on growth, yield, nutrient uptake and quality of Tomato. *Horticulturae, 9*(2)*,* 162.

Ardali T. R., Soleimanpour L., Ma'mani L., & Chorom M. (2024). Opportunities and future perspective of nanofertilizers and controlled release nanofertilizers in agriculture. *J. Water Environ. Nanotechnol., 9*(2)*,* 223–247. https://doi.org/10.22090/jwent.2024.02.08

Awan, S., Shahzadi, K., Javad, S., Tariq, A., Ahmad, A., & Ilyas, S. (2021). A preliminary study of the influence of zinc oxide nanoparticles on growth parameters of Brassica oleracea var italic. *J. Saudi Soc. Agric. Sci., 20*(1)*,* 18–24.

Azim, Z., Singh, N.B., Singh, A., Amist, N., Niharika Khare, S., Yadav, R.K., Bano, C., & Yadav, V. (2023). A review summarizing uptake, translocation and accumulation of nanoparticles within the plants: Current status and future prospectus. *J. Plant Biochem. Biotechnol. 32,* 211–224.

Babu, S.R., Joseph, M., Hemalatha, M., Bhuvaneswaei, J., Srinivasan, S., & Leninraja, D. (2024). Nano-fertilizers: The future of nutrient approaches for cereals. *Indian Journal of Agricultural Sciences, 94*(11): 1155–1164. https://doi.org/10.56093/ijas.v94i11.150587

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., & Singh, V. K. (2022). Nanofertilizers for agricultural and environmental sustainability. *Chemosphere, 292,* 133451. https://doi.org/10.1016/ j.chemosphe re.2021.133451

Bhardwaj, A.K., Arya, G., Kumar, R., Hamed, L., Pirasteh-Anosheh, H., Jasrotia, P., & Singh, G.P. (2022). Switching to nano nutrients for sustaining agroecosystems and environment: the challenges and benefits of moving from ionic to particle feeding. *J. Nanobiotechnol., 20(1),* 1–28.

Chhipa, H. (2017). Nanofertilizers and nanopesticides for agriculture. *Environ. Chem. Lett., 15,* 15–22. https://doi.org/10.1007/s10311-016-0600-4

Cui, H.X., Sun, C.J., Liu, Q., Jiang, J., & Gu, W. (2010). Applications of nanotechnology in agrochemical formulation: perspectives, challenges and strategies. In *International Conference on Nanoagri*, Sao Pedro, Brazil. pp 28–33.

da Silva Júnior, A.H., Mulinari, J., Reichert Júnior, F.W., & de Oliveira, C.R.S. (2020). Nanofertilizers: an overview. In *International Agribusiness Congress. Proceedings Book.* https://doi.org/10.31692/ ICIAGRO.2020.0041

Debashis, D., & Anurag, B. (2021). Nano fertilizer on sustainable agriculture - a review. *International Journal of Environment and Climate Change, 11*(8)*,* 1– 5.

El-Ghamry, A., Mosa, A., Alshaal, T., & El-Ramady, H. (2018). Nanofertilizers vs. biofertilizers: new insights. *Environment, Biodiversity and Soil Security, 2,* 51–72. https://doi.org/10.21608/ jenvbs.2018.3880.1029

Gade, A., Ingle, P., Nimbalkar, U., Rai, M., Raut, R., Vedpathak, M., Jagtap, P., & Abd Elsalam, K.A. (2023). Nanofertilizers: the next generation of agrochemicals for long-term impact on sustainability in farming systems. *Agrochemicals, 2,* 257–278. https://doi.org/10.3390/agrochemicals2020017

Glotra, A., Singh, M., & Maneesha. (2023). Nanofertilizers: A Review on the Futuristic Technology of Nutrient Management in Agriculture. *Agricultural Reviews, 44*(2)*,* 238–244. https://cabidigitallibrary. org.by77.29.82.145

Huda, A., & Aljanabi, Y. (2021). Effects of nano fertilizers technology on agriculture production. *Annals of R.S.C.B., 25*(4)*,* 6728 – 6739.

Hussain, I., Singh, N.B., Singh, A., Singh, H. & Singh, S.C. (2016). Green synthesis of nanoparticles and its potential application. *Biotechnol. Lett., 38*(4)*,* 545– 560.

Ibrahim, N.K., & Al Farttoosi, H.A.K. (2019). Response of mung bean to boron nanoparticles and spraying stages (*Vigna radiata* L.). *Plant Arch., 19*(2)*,* 712–715.

Iqbal, M.A. (2019). Nano-fertilizers for sustainable crop production under changing climate: A global perspective. In M. Hasanuzzaman, M.C.M. Teixeira Filho, M. Fujita, & T.A. Rodrigues Nogueira (Eds.), *Sustainable crop production*. IntechOpen. http://dx.doi.org/10.5772/intechopen.89089

Khatri, A., & Bhateria, R. (2022). Efficacy of nanofertilizers over chemical fertilizers in boosting agronomic production. Nature environment and pollution technology. *An International Quarterly Scientific Journal.* 22, 767–776. https://doi.org/10.46488/NEPT.v22i02.019

Kumar, A., Singh, K., Verma, P., Singh, O., Panwar, A., Singh, T., Kumar, Y., & Raliya, R. (2022). Efect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. *Scientifc Reports 12,* 6938. https://doi.org/10.1038/s41598-022-10843-3

Madlala, N.C., Khanyile, N., & Masenya, A. (2024). Examining the correlation between the inorganic nano-fertilizer physical properties and their impact on crop performance and nutrient uptake efficiency. *Nanomaterials, 14,* 1263. https://doi.org/10.3390/ nano14151263

Manzoor, M.A., Xu, Y., Iv, Z., Xu, J., Wang, Y., Sun, W., Liu, X., Wang, L., Usman, Jiyuan, M., Wang, Liu, R., Whiting, D.M., Songtao, J., & Zhan, C. (2024). Nanotechnology-based approaches for promoting horticulture crop growth, antioxidant response and abiotic stresses tolerance. *Plant Stress, 11,* 100337. https://doi.org/10.1016/j.stress.100337

Mahesha, K.N., Singh, N.K., Amarshettiwar, S.B., Singh, G., Gulaiya, S., Das, H., & Kumar, J. (2023). Entering a new agricultural era through the impact of nano-fertilizers on crop development: a review. *International Journal of Plant & Soil Science, 35*(20)*,* 94–102. https://doi.org/10.9734/IJPSS/ 2023/v35i203789

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S.A. (2020). Nanoparticle-based sustainable agriculture and food science: recent advances and future outlook. *Front. Nanotechnol, 2*(10)*.* https://doi.org/10.3389/fnano.2020.579954

Mohanraj, J., Subramanian, K., & Lakshmanan, A. (2019). Role of nano-fertilizer on greenhouse gas emission in rice soil ecosystem. *Madras Agricultural Journal, 106.* https://doi.org/10.29321/ MAJ.2019.000327

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

Pourjafar, L., Zahedi, H., & Sharghi, Y. (2016). Effect of foliar application of nano iron and manganese chelated on yield and yield component of canola (*Brassica napus* L.) under water deficit stress at different plant growth stages. *Agricultural Science Digest. 36*(3)*, 172*–178.

Popko, M., Michalak, I., Wilk, R., Gramza, M., Chojnacka, K., & Górecki, H. (2018). Effect of the new plant growth biostimulants based on amino acids on yield and grain quality of winter wheat. *Molecules, 23*(2)*,* 470.

Preetha, P.S, & Balakrishnan, N. (2017). A review of nano fertilizers and their use and functions in soil. *Int. J. Curr. Microbiol. Appl. Sci., 6*, 3117–3133.

Qureshi, A., Singh, D.K. & Dwivedi, S. (2018). Nano-fertilizers: A novel way for enhancing nutrient use efficiency and crop productivity. *Int. J. Curr. Microbiol. App. Sci., 7*(2)*,* 3325–3335.

Rana, L., Kumar, M., Rajput, J., Kumar, N., Sow, S., Kumar, S., Kumar, A., Singh, S.N., Jha, C.K., Singh, A.K., Ranjan, Ritwik, S., Samanta, D., Nath, D., Panday, R., & Raiga, B.L. (2024). Nexus between nanotechnology and agricultural production systems: challenges and future prospects. *Discover Applied Sciences*. https://doi.org/10.1007/s42452-024-06265-7.

Rana, R.A., Siddiqui, M.N., Skalicky, M., Brestic, M., Hossain, A., Kayesh, E., Popov, M., Hejnak, V., Gupta, D.R., Mahmud, N.U., et al. (2021). Prospects of nanotechnology in improving the productivity and quality of horticultural crops. *Horticulturae, 7,* 332. https:// doi.org/10.3390/horticulturae7100332.

Rahman, K.M.A., & Zhang, D. (2018). Effects of fertilizer broadcasting on the excessive use of inorganic fertilizers and environmental sustainability. *Sustainability, 10*, 759.

Shuqin, J., & Fang, Z. (2018). Zero growth of chemical fertilizer and pesticide use: China's objectives, progress and challenges. *J. Resour. Ecol., 9(1),* 50–58.

Stojanova, T.M., Djukic, D.A., Stojanova, M., Boskovic, I. (2024). Effect of foliar calcium amplifiers on the chemical composition of sweet paper. In *Full text book*, International Congress of High Value-Added Agcicultural Products, Iğdır University, Türkiye, pp. 178–185.

Stojanova, T.M. (2020). *Fruits Nutrition*. Academic Press, Skopje.

Stojanova, T.M. (2022). *Nutrition of Horticultural Plants*. Academic Press, Skopje.

Stojanova, T.M. (2018). *Plant Nutrition*. Academic Press, Skopje.

Su, Y., Zhou, X., Meng, H., Xia, T., Liu, H., Rolshausen, P., Roper, C., McLean, J. E., Zhang, Y., Keller, A. A., & Jassby, D. (2022). Cost–benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. *Nature Food, 3*(12)*,* 1020–1030. https://doi.org/10.1038/s43016-022-00647-z

Taiz, L., & Zeiger, E. (2010). *Plant Physiology*. 5th Edition, Sinauer Associates. Publisher Sunderland, 781–785.

Wang,X., Xie, H., Wang, P., & Yin, H. (2023). Nanoparticles in plants: uptake, transport and physiological activity in leaf and root. *Materials. 16*, 3097.

Van Nguyen, D., Nguyen, H.M., Le, N.T., Nguyen, K.H., Nguyen, H.T., Le, H.M., & Van Ha, C. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought-stress conditions. *Plant Growth Regul., 41*(1)*,* 364–375.

Verma, K.K., Song, X.P., Joshi, A., Rajput, V.D., Singh, M., Sharma, A., Singh, R.K., Li, D.M., Arora, J., Minkina, T., et al. (2022a). Nanofertilizer possibilities for healthy soil, water, and food in future: an overview. *Front. Plant Sci. 13,* 865048.

Verma, K.K., Song, X.P., Joshi, A., Tian, D.D., Rajput, V.D., Singh, M., Arora, J., Minkina, T., & Li, Y.R. (2022b). Recent trends in nano fertilizers for sustainable agriculture under climate change for global food security. *Nanomaterials, 12,* 173. https://doi.org/10.3390/nano12010173

Ude, R., Kujiper, I., Takiguchi, T., & Bußman, J. P. (2024). *Nanofertilizers: A Green Window of Opportunity for Food Security in Sub-Saharan Africa*. Science-Policy Brief for the Multistakeholder Forum on Science, Technology and Innovation for the SDGs.

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: advantages and limitations. *Plant Science, 289,* 110270. https://doi.org/https://doi.org/10.1016/j.plantsci.20 19.110270

Yadav, A., Yadav, K., & Abd-Elsalam, K.A. (2023). Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability. *Agrochemicals, 2,* 296–336. https://doi.org/10.3390/ agrochemicals2020019.