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Beyond the hype: unpacking the hidden challenges of nanofertilizers

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The application of nanotechnology in agriculture presents innovative solutions to improve crop production and food security, thus promoting sustainable practice. Nanofertilizers (NFs) derived from metal oxide nanoparticles (NPs) significantly improve soil quality by increasing the diversity and abundance of soil microbial communities, essential for nutrient cycling and soil health. They enhance nutrient uptake, stress resistance, and plant defense mechanisms leading to improved yield. The physical and chemical synthesis of NFs has a negative effect on the environment and human health due to the use of hazardous and toxic chemicals; thus, the green synthesis method is preferred as it is eco-friendly and cost effective. This work examines the evolving role of NFs in sustainable agricultural systems, exploring technological innovations, advantages, possible toxicity and limitations of NFs. It aims to provide a comprehensive overview of NFs' potential to promote soil health, plant productivity and environmental sustainability, while presenting recommendations for future research trajectories.

KEYWORDS

nanotechnology, plant productivity, soil health, sustainability, toxicity

1 Introduction

Nanotechnology, an evolving interdisciplinary field, holds the potential to revolutionize various areas of science including chemistry, physics, medicine, materials science, aeronautical, pharmaceutical, and agriculture (Toprak et al., 2014; Demirkiran et al., 2016; Pide et al., 2023). In agriculture, nanofertilizers (NFs) (1–100 nm) has emerged as an innovative and potential alternative for conventional mineral fertilizers and as an important strategy to increase crop productivity (Sharma et al., 2024), and reduce plant nutrient deficiencies and soil nutrient imbalances (Figure 1) (Lalitha et al., 2025). Nanofertilizers have unique physico-chemical properties such as small particle dimensions (<100 nm) and high surface area and surface area to volume ratio which promotes better adsorption and nutrient uptake by the root system, reducing the need for large volumes of conventional fertilizers and minimizing negative environmental impacts (Pide et al., 2023). The components of NFs include metal oxide nanoparticles (NPs), such as zinc oxide (ZnO), iron oxide (FeO) and titanium oxide (TiO_2) to provide symbiotic relation between microbes and plants (Yadav et al., 2023). The application of engineered NPs may increase the microbial flora while NPs such as ZnO help enhance nutrient uptake such as phosphorus and zinc, promoting plant growth and development, and combat pathogens (Saleem et al., 2023). Zinc oxide NPs facilitate the conversion of

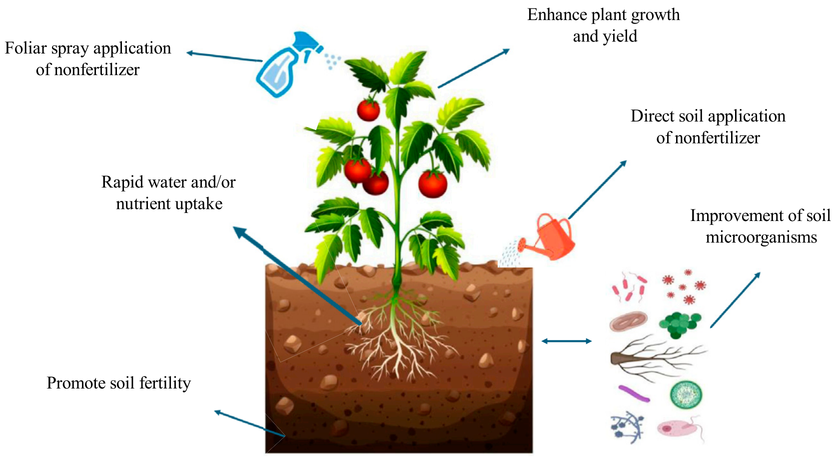

FIGURE 1
The basic role of nanofertilizers.

TABLE 1 Overview of nanofertilizer applications on soil and plants and their impacts.

Nanofertilizer synthesis method	Advantages	Disadvantages	References
Physical	Promote germination and shoot elongation, plant growth, development and yield	High energy consumption and environmental pollution. Reduce soil microbial diversity	Nisar et al. (2019), Sambangi et al. (2022)
Chemical	Improve seed germination, relative water content, growth, photosynthetic parameters and antioxidant enzymes activity	Use of hazardous chemicals, leading to ecotoxicity, genotoxicity, and cytotoxicity concerns	Nisar et al. (2019), Saurabh et al. (2024), Stojanova et al. (2025)
Biological	Enhance soil microbial activity, nutrient uptake, and bioactive compounds, leading to improved plant growth and yield. Environmentally friendly, cost-effective and reduces dependency on chemical fertilizers	Possible unintended effects on plant physiology and gene expression. Long-term impacts on plant health and soil ecosystems are not fully understood	Sambangi et al. (2022), Arora et al. (2024), Lalitha et al. (2025), Misu et al. (2025)

organic phosphorus into more readily absorbable forms, thereby increasing the availability of phosphorus to plants (Sharma et al., 2024).

Nanofertilizers are commonly synthesized using physical and chemical methods which are associated with the negative impact on the environment and human health (Nisar et al., 2019). Physical synthesis of NFs have some drawbacks such as high energy consumption and environmental pollution (Sambangi et al., 2022) while chemical methods involve the use of hazardous chemicals, leading to ecotoxicity, genotoxicity, and cytotoxicity concerns (Nisar et al., 2019). Hence, green synthesized NFs are increasingly preferred due to their eco-friendly nature, cost-effectiveness, and efficiency in enhancing crop productivity while minimizing environmental impact (Sambangi et al., 2022). Bionanofertilizers (BNFs) are synthesized using biological materials such as plant extracts, bacteria, fungi, and algae, which act as natural reducing and capping agents, making the process environmentally sustainable and reducing the need for agro-chemical (Arora et al., 2024). Although biosynthesized NFs are effective in improving soil fertility and plant yield, little is known about their long-term effect on soil health (Table 1).

2 Challenges and barriers to nanofertilizer development and application

2.1 Environmental and ecotoxicological concerns

Nanofertilizers are perceived as a solution to sustainable agriculture, as they are fabricated at the nanoscale to enhance uptake by plants (Saurabh et al., 2024), and are believed to leave negligible footprints in the environment (Sambangi et al., 2022). However, extensive application of NFs was found to have cumulative pollution in both aquatic and terrestrial environments (Stojanova et al., 2025). The degradation of aquatic microbial communities, and phyto and zooplanktons as a result of excessive level of NFs in the soil was observed in aquatic environments (Utazi et al., 2024). Nevertheless, different NPs showed to be effective NFs for different crops, with their toxicity barely studied over the past recent years. Nanofertilizers can induce plant toxicity through several molecular pathways including generation of reactive oxygen species, which causes oxidative stress (Chavan et al., 2020). This leads to cellular damage or disruption of cell membrane integrity, resulting in the release of toxic ions; interference with essential biomolecules such as proteins and deoxyribonucleic acid (Utazi et al., 2024). This ultimately results in altered gene expression and metabolic pathways; and physical disruption of cellular structures and organelles, affecting their function and consequently leading to reduced plant growth and yield (Kumari et al., 2009). Chavan et al. (2020) reported TiO_2 NFs inhibited plant growth by affecting the community composition of the plant growth-promoting bacteria in the soil. Moreover, due to their small sizes, silver NFs was found to easily enter the plant system, causing chromosomal breakage, metaphase disturbance and disruption on stages of cell division resulting in chromatin bridge (Kumari et al., 2009). Scientists are now preoccupied with the notion that NF is a sustainable solution; hence, a few recent studies on the exploration of toxicological effects of NFs on the environment. However, their potential to remain in the soil over a long period of time raises a concern. Also, there is scant information on the cumulative effect and predictive modelling of the behaviour of NFs (Table 1).

2.2 Regulatory and standardization issues

There is a considerable evidence on the potential toxicity of NPs in the environment. Difference in fabrication techniques influences the composition, which eventually affect their stability and biological compatibility (Yadav and Yadav, 2025). Other factors such as size, shape, chemical composition and surface modification affect the toxicity of NFs (Xuan et al., 2023). In the environment, the efficiency of NFs may also be influenced by the soil composition, local climate and the specific crop of interest (Stojanova et al., 2025). On the other hand, the application of NFs may be in foliar spray, soil application and seeds treatment (Saurabh et al., 2024). Given the dynamics governing the behaviour and fate in the environment, different application methods and their performance in enhancing nutrients uptake, there is a need for harmonized international legislations and guidelines on the use of NFs (Mishra et al., 2022). The Indian legislations were developed, which emphasized thorough examination of the application modes and frequency, efficiency, safety, improved crop yield and productivity before permission can be granted for application in the field (Yadav and Yadav, 2025). The United States Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and the United States Department of Agriculture (USDA) approved NFs, such as TiO_2, ZnO and FeO for utilization in food, with a little being said about the application in agricultural soil or on yield enhancement (Powell et al., 2016). Other countries such as Canada (Cepa, 2006), Europe (Efsasc, 2018) have made efforts to regulate manufacturing, transport, application, monitoring and management of nanoparticles used in several industries, and little has been said in the context of agriculture and their fate. It is evident that lack of harmonized fabrication methodology result in uncertainties on their behaviour, which impedes the approval by most authorities.

2.3 Production scalability

Scaling up the green synthesis of nanoparticles from a laboratory setting to industrial production presents significant challenges, despite the method's eco-friendly and cost-effective nature at smaller scales. A primary obstacle is ensuring product consistency. While precise control over reaction parameters such as temperature, mixing, and reactant concentrations is feasible in a laboratory, these conditions are difficult to replicate uniformly in large-scale reactors. This can result in batch-to-batch variability in nanoparticle size, morphology, and physicochemical properties, compromising quality control standards (Goyal et al., 2025). Furthermore, the economic viability of green synthesis can diminish at a larger scale. The sustainable sourcing of consistent quality plant extracts or microbial cultures becomes more complex, and the downstream purification and extraction processes can escalate in cost and complexity, offsetting the initial financial advantages (Nongbet et al., 2022). Addressing these scalability issues is crucial for the widespread commercial application of NFs.

2.4 Farmer adoption and awareness

A key obstacle to the widespread adoption of NFs is a lack of farmer awareness and the perception of high costs. Many farmers are unfamiliar with the specific benefits and proper handling of these advanced products, creating a knowledge gap that hinders their willingness to abandon traditional methods. This is often compounded by a lack of access to adequate training and educational resources, which are essential for safe and effective use (Nongbet et al., 2022). Furthermore, the higher upfront cost of NFs is a major deterrent for farmers, especially those with tight profit margins. While research suggests that the enhanced efficiency of nanoparticles could lead to lower total costs over time due to reduced application rates, this long-term economic benefit is not always clear to farmers. This perception of high initial cost creates a significant barrier to their widespread adoption (Yadav and Yadav, 2025).

2.5 Complexities of nanoparticle–soil–plant interactions

The unpredictable interactions of nanoparticles within complex soil ecosystems present a significant challenge to their effective and safe deployment. The unique properties of nanoparticles, such as their high surface area and reactivity, mean they do not behave like conventional fertilizers. Once applied, they can interact with a myriad of soil components, including organic matter, clay minerals, and native microbiomes, in ways that are difficult to predict. This can lead to unforeseen alterations in microbial community structure and function, potentially disrupting crucial ecosystem services such as nutrient cycling and soil health (Zhang et al., 2024). Furthermore, the response of various plant species to the same nanoparticle formulation can be highly variable, leading to inconsistent agricultural outcomes. For instance, a formulation that promotes growth in one crop might have neutral or even phytotoxic effects on another due to differences in root morphology, physiological pathways, and the plant's ability to take up and translocate the nanoparticles (Table 1) (Cheah et al., 2021). These complex and variable interactions underline the need for extensive research and careful application to ensure both efficacy and environmental safety.

3 Discussions

Although nanotechnology especially BNFs holds a significant potential for revolutionizing agriculture by improving crop productivity and sustainability (Figure 1), they are currently not completely adopted (Zhang et al., 2024). Challenges of BNFs include the need for production scalability, extensive field-testing, public acceptance, capacity building for stakeholders, standardization of production processes, application methods, and active participation from private organizations alongside suitable legislative enforcement (Sharma et al., 2024). Potential environmental impacts is another challenge of BNFs, hence there is a need for comprehensive research on long-term effects of BNFs on soil health and crop productivity to ensure sustainable agricultural practices (Table 1) (Lalitha et al., 2025). Despite these challenges, several studies have demonstrated that BNFs enhance plant resilience against biotic and abiotic stresses, leading to improved crop yields ranging from 17% to 54% depending on the crop and soil type (Arora et al., 2024; Misu et al., 2025).

4 Future prospects

The development of next-generation biofertilizers is significantly improved by integrating nanotechnology, genomics, and precision agriculture (Arora et al., 2024). The BNFs are promising eco-friendly alternative to synthetic fertilizers, leveraging nanotechnology and biotechnology or biofertilizers to enhance nutrient uptake by plants including nitrogen, phosphorus and potassium, enzyme activity, microbial populations, soil fertility, crop yield and resistance to diseases (Sambangi et al., 2022). In addition, genomic editing allows for the enhancement of biofertilizer efficiency by creating resilient microbial strains that can further promote plant growth (Table 1) (Misu et al., 2025). While BNFs are effective in improving plant growth and soil health by enhancing nutrient delivery and promoting sustainable agricultural practices, their long-term environmental and human health effects due to nanoparticle toxicity have not been fully explored, thus there is a need for future research on the regulatory frameworks, optimal formulations and application methods to ensure effective and safe use of BNFs.

Moreover, nanotechnology plays a significant role in real-time soil nutrient monitoring which can be achieved using nano-biosensors that detect nutrient levels, coupled with controlled nanoparticle release systems (Huang et al., 2021). These systems enable precise nutrient delivery, optimizing crop production while reducing environmental impact through reduced leaching and runoff. Furthermore, life cycle assessment (LCA) is a critical tool for quantifying the environmental impact of NFs and guiding their sustainable design (Nizam et al., 2021). By evaluating the entire life cycle of nanomaterials, from raw material acquisition to disposal, LCA helps identify key areas for environmental improvement (Rugani et al., 2023). However, most existing nano LCA studies focus on indirect impacts, mainly during production and manufacturing stages, often neglecting use and end-of-life considerations (Nizam et al., 2021). There is a critical need for comprehensive data on engineered nanomaterial (ENM) releases, fate, exposure, and effects to improve LCA methodologies and ensure responsible development of NFs, ultimately improving their sustainability and reducing environmental harm.

5 Conclusion

In conclusion, this review highlights the significant role of NFs including BNFs in enhancing soil microbial communities and plant tolerance to environmental stress by enabling efficient nutrient delivery, modulating phytohormonal signaling networks, and activating antioxidant defense mechanisms. These functions underscore the transformative potential of nanotechnology in advancing modern agricultural practices. However, challenges associated with NFs include high production costs, safety and toxicity concerns, regulatory frameworks, compatibility with existing infrastructure, and potential long-term effects on soil health. Furthermore, NPs can accumulate in soil and aquatic ecosystems, potentially harming soil microbes, algae, and biodiversity. The environmental risk assessment of NPs is in its infancy; hence, further research studies should investigate the application of different types and concentrations of NPs on microbial communities and function.

Author contributions

NMDB: Software, Writing – review and editing, Methodology, Formal Analysis, Investigation, Writing – original draft, Supervision, Visualization, Funding acquisition, Data curation, Conceptualization, Resources, Project administration, Validation. MCM: Resources, Visualization, Funding acquisition, Formal Analysis, Writing – original draft, Project administration, Conceptualization, Investigation, Data curation, Methodology, Validation, Writing – review and editing, Software, Supervision. JL: Funding acquisition, Validation, Writing – review and editing, Methodology, Formal Analysis, Supervision, Conceptualization, Project administration, Data curation, Software, Resources, Writing – original draft, Visualization, Investigation.

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Conflict of interest

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