BioThink E – Magazine, Vol. -3, Issue -1, January 2026
ISSN No. – 3048- 7943
www.biothink.in

Nano-fertilizers as an emerging tool for sustainable nutrient management in agriculture

Harshit Pareek✉, Sonali Rajput

Department of Seed Science and Technology, HNB Garhwal University

✉ pareekharshit2001@gmail.com

Abstract

Conventional fertilizers are less efficient and have hazardous impact on environment, hence scientists are looking for better ways to supply nutrients to the crop. In recent years, nano-fertilizers developed using nanotechnology have gained attention as a potential solution because they help plants use nutrients more efficiently while reducing environmental damage. These fertilizers deliver nutrients in very small particles or through nano-based materials, allowing nutrients to be released in a more controlled and targeted manner according to crop needs. This review discusses the basic concept of nano-fertilizers, their types, working mechanisms, advantages, limitations, and future possibilities. Special attention is given to India's experience with nano urea developed by IFFCO as an example of large-scale application. The article brings together findings from recent studies to evaluate the importance of nano-fertilizers in sustainable and precision agriculture.

Keywords: Nano-fertilizers, nanotechnology, nutrient use efficiency, sustainable agriculture, nano urea

1. Introduction

Modern agriculture relies heavily on mineral fertilizers to sustain crop productivity; however, the efficiency of these inputs remains suboptimal. A significant fraction of applied nutrients is lost through leaching, volatilization, and chemical fixation, leading to economic losses and environmental degradation (Kah *et al.*, 2018). Excessive use of fertilizer has also been linked to groundwater contamination, eutrophication of water bodies, and increased greenhouse gas emissions. These challenges highlight the need for innovative fertilizer technologies that can enhance nutrient efficiency while reducing adverse environmental impacts.

Nanotechnology has garnered significant attention in agricultural research due to its potential to manipulate materials at extremely small scales, thereby enhancing their functional properties. Within this framework, nano-

fertilizers have been proposed as advanced nutrient formulations capable of delivering nutrients more efficiently than conventional fertilizers (Raliya *et al*., 2018).

2. Concept and Characteristics of Nano-Fertilizers

Nano-fertilizers refer to nutrient formulations in which essential plant nutrients are either engineered into nanoscale particles or incorporated into nano-based delivery systems. These materials typically range in size from 1nm to 100nm and possess a large surface area relative to their volume, which enhances their reactivity and interaction with plant tissues (Demeke *et al*., 2025).

Unlike bulk fertilizers that release nutrients rapidly and uncontrollably, nano-fertilizers can be designed to release nutrients gradually or in response to specific environmental or physiological triggers. This property allows nutrients to be supplied in closer synchronization with plant requirements, improving nutrient use efficiency (Seleiman *et al*., 2021).

3. Classification of Nano-Fertilizers

Based on nutrient composition and delivery approach, nano-fertilizers can be categorized into three major groups. Nano-macronutrient fertilizers which supply primary nutrients such as nitrogen, phosphorus, and potassium in nanoscale forms. Nano-micronutrient fertilizers include elements like zinc, iron, and copper, which are essential in small quantities but often deficient in soils (Nongbet *et al*., 2022). A third category includes nano-carrier-based fertilizers, where nutrients are loaded onto nanomaterials such as nanoclays, mesoporous silica, or biodegradable polymers to regulate nutrient release (Raliya *et al*., 2018).

4. Mechanisms of Nutrient Delivery

The enhanced performance of nano-fertilizers is attributed to multiple physiological and physicochemical mechanisms. Due to their small size, nanoparticles can penetrate and enter plant tissues more effectively through root epidermis or leaf surfaces. Foliar-applied nano-fertilizers can enter plants through stomata or cuticular pathways, enabling rapid nutrient assimilation (Nongbet *et al*., 2022).

Additionally, nano-carriers protect nutrients from premature loss and improve their stability in soil environments. Controlled release from these carriers ensures sustained nutrient availability in the rhizosphere, reducing losses and enhancing uptake efficiency (Demeke *et al*., 2025).

5. Agronomic and Environmental Advantages

Nano-fertilizers offer many agronomic benefits, including improved nutrient use efficiency, enhanced crop growth, and stable yield performance. Efficient nutrient delivery supports key physiological processes such as photosynthesis, enzymatic activity, and protein synthesis, which collectively contribute to improved plant productivity (Seleiman *et al*., 2021).

From environmental perspective, reduced nutrient losses related with nano-fertilizer use can lower the risk of soil and water pollution. By minimizing excess nutrient application, nano-fertilizers contribute to environmentally responsible nutrient management and support the goals of sustainable agriculture (Kah *et al*., 2018).

6. Case Study: IFFCO Nano Urea in India

India has witnessed a significant development in nano-fertilizer adoption through the introduction of nano urea by Indian Farmers Fertiliser Cooperative Limited (IFFCO). IFFCO Nano Urea is formulated as a liquid fertilizer containing nitrogen in nanoscale form and is intended to improve nitrogen use efficiency while reducing reliance on conventional granular urea (IFFCO, 2021). The product is primarily applied as a foliar spray, enabling direct absorption of nitrogen through leaf tissues. This application method reduces nitrogen losses commonly associated with soil-applied urea and supports efficient nitrogen utilization within the plant system (Seleiman *et al*., 2021). Field demonstrations conducted across multiple agro-climatic zones have shown that nano-urea, when used in conjunction with reduced doses of conventional urea, can maintain crop yields in cereals, oilseeds, and vegetables (Yadav *et al*., 2023). The environmental implications of nano urea use include potential reductions in nitrogen runoff and gaseous emissions, which are major concerns in intensive agricultural systems. Furthermore, the reduced volume and weight of liquid nano fertilizers decrease transportation and storage requirements, indirectly lowering the carbon footprint of fertilizer distribution (Demeke *et al*., 2025).

However, the effectiveness of nano urea varies with crop type, growth stage, and management practices. Researchers highlights that nano urea should be integrated into balanced nutrient management strategies rather than used as a standalone fertilizer. Long-term studies evaluating soil health and ecological effects are essential to confirm its sustainability (Raliya *et al*., 2018).

7. Challenges and Research Gaps

Despite promising results, several challenges limit the widespread adoption of nano-fertilizers. High production costs, lack of standardized application guidelines, and limited awareness among farmers remain major constraints. In addition, the long-term behavior of nanoparticles in soil ecosystems and their interaction with

beneficial microorganisms require further investigation (Kah *et al*., 2018). Developing regulatory frameworks and safety assessment protocols is crucial to ensure responsible use of nano-fertilizers in agriculture (Demeke *et al*., 2025).

8. Future Prospects

The integration of nano-fertilizers with precision agriculture technologies offers significant opportunities for improving nutrient management. Advances in sensor-based monitoring, artificial intelligence, and decision-support systems could enable site-specific nutrient delivery using nano-enabled fertilizers. Future research should prioritize biodegradable nanomaterials and long-term field evaluations to enhance acceptance and scalability (Yadav *et al*., 2023).

9. Conclusion

Nano-fertilizers represent a promising advancement in agricultural nutrient management by addressing the inefficiencies associated with conventional fertilizers. Their ability to enhance nutrient use efficiency, reduce environmental losses, and support sustainable crop production highlights their potential role in future agricultural systems. The IFFCO nano urea initiative illustrates how nano-fertilizers can be translated from research to large-scale application, provided they are integrated into balanced and well-regulated nutrient management strategies.

References

Demeke, E. D., Benti, N. E., Terefe, M. G., & Tadesse, T. (2025). A comprehensive review on nano-fertilizers: Preparation, development, utilization, and prospects for sustainable agriculture. Nanoscale Advances, 7(6), 2131–2144. https://doi.org/10.1039/D4NA01068J

Indian Farmers Fertiliser Cooperative Limited. (2021). Nano urea: Product concept and application guidelines. IFFCO. https://www.iffco.in

Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nano-fertilizers and nano-pesticides against their conventional analogues. Nature Nanotechnology, 13(8), 677–684. https://doi.org/10.1038/s41565-018-0131-1

Nongbet, S. A., *et al*. (2022). Nanofertilizers: A smart and sustainable attribute to modern agriculture. Frontiers in Plant Science, 13, 1025457. https://doi.org/10.3389/fpls.2022.1025457

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

Seleiman, M. F., Al-Said, A. A., Khalil, H. E., & Abdel-Mawgoud, M. I. (2021). Nanofertilizers as a tool to improve crop productivity and nutrient use efficiency. Plants, 10(1), 2. https://doi.org/10.3390/plants10010002

Yadav, A., Kumar, V., Singh, S., & Singh, R. (2023). Nano-fertilizers: Types, delivery mechanisms, and their role in sustainable agriculture. Agrochemicals, 2(2), 179–198. https://doi.org/10.3390/agrochemicals2020019