Nanofertilizers on Agriculture

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Introduction

The Food and Agriculture Organization (FAO) estimates that by 2050, grain output must increase by 70% to meet the increased demand due to the growing world population (Bernard and Lux, 2017). Agricultural productivity faces numerous challenges, including reduction of arable land, nutrient deficiencies, soil degradation, disease outbreaks, pest infestations, and inefficient fertilizer management (Prost, 2021). As expanding farmland is no longer feasible, optimizing nutrient management, disease control, and stress mitigation emerges as a critical solution to boost crop yields (Elemike et al., 2019). For decades, chemical fertilizers and pesticides have been the primary tools for these purposes. However, recent advancements in nanoscience and nanotechnology offer a promising avenue for revolutionizing agriculture (Mittal et al., 2020). Currently, nano-fertilizers are most popular and newly advanced technology for better nutrient application to plants (Salama et al., 2019). Nanoscience and nano-based technologies are emerging as transformative forces in the agricultural sector, presenting a robust potential to enhance various agricultural practices (Mittal et al., 2020). Notably, nanoparticles developed into "nano-fertilizers" have shown significant benefits across multiple facets of agriculture, including seed germination, plant growth, development, yield enhancement, nutritional fortification, disease resistance, and stress management in plants. The unique properties of nano fertilizers, characterized by their small size (typically ranging from 1 to 100 nm) and high surface area, facilitate their penetration into plant systems, thereby improving plant productivity while achieving high fertilizer use efficiency and cost-effectiveness (Haydar et al., 2024).

Classification of Nano-Fertilizers

The classification of nano-fertilizers is presented in Figure 1.

1. Based on mineral nutrients: There are two primary categories of nanonutrient fertilizers: Macro nanofertilizers and Micro nanofertilizers.

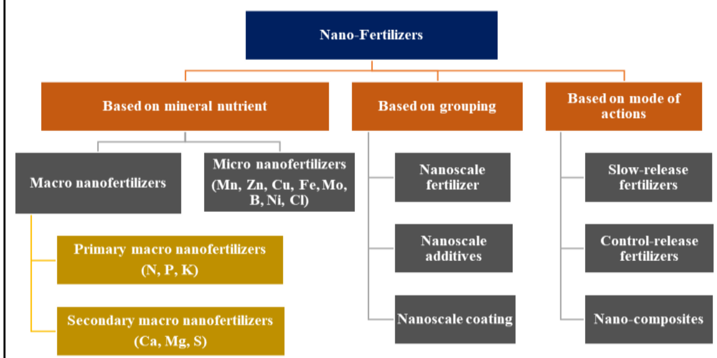

Fig. 1. Classification of nanofertilizers

Macro nanofertilizer

Macronutrient nanofertilizers are composed of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) that are required in significant quantities for plant growth. Conventional fertilizers often result in substantial nutrient losses—ranging from 40% to 90% for N, P, and K—which leads to resource wastage and environmental issues, including nutrient runoff into water bodies that disrupt aquatic ecosystems (Zulfiqar et al., 2019). Given the projected increase in global macronutrient fertilizer consumption from 175.5 million tons to 263 million tons by 2050, there is a pressing need for efficient and environmentally friendly macronutrient nanofertilizers to enhance sustainable food production. Macronutrient nanofertilizers provide numerous advantages over traditional fertilizers, including improved crop growth and yield efficiency, reduced nutrient losses, and minimized environmental impacts. They can effectively deliver nutrients in encapsulated forms with specific nanoparticles, which facilitate better uptake through plant root systems (Al-Mamun et al., 2021).

A study reported by Sharma et al., 2022 showed the efficacy of urea nanohybrids (including hydroxyapatite-urea, magnesium-infused hydroxyapatite-urea, and zinc-infused hydroxyapatite-urea), when applied at nitrogen doses equivalent to 25% and 50% of the standard recommendation compared to a control of 150 kg/ha of conventional urea. This application significantly increased growth and yield in wheat (*Triticum aestivum* L.) and enhanced the plant's uptake of essential nutrient elements, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and iron (Fe). Additionally, the grain exhibited higher levels of protein and phospholipid content as a result of these treatments.

Micro nanofertilizers

Micronutrient nanofertilizers, required in minimal quantities (≤100 ppm), are crucial for various metabolic processes in plants. Key micronutrients include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and molybdenum (Mo). These micronutrients are often incorporated into NPK fertilizers in soluble forms to enhance crop uptake and performance (Zulfiqar et al., 2019). In mungbean, Kareem et al., (2022) found that the application of zinc oxide nanoparticles (ZnO-NPs) under high temperature stress resulted in increased chlorophyll content, improved gas exchange parameters, and a well-balanced enzymatic response. These enhancements led to higher pod counts, larger pod sizes, and an overall increase in total grain yield. Similarly, Thakur et al., (2021) reported that in wheat seedlings subjected to heat stress, the application of ZnO and titanium dioxide nanoparticles (TiO_2 NPs) enhanced membrane stability and improved antioxidant defense mechanisms in both the root and shoot. In the case of tomatoes, Ahmed et al., (2023) reported that a foliar application of 100 ppm ZnO-NPs produced the most favorable results for growth parameters, physiological traits, yield attributes, and fruit quality. This treatment also maximized nutrient uptake and resulted in a remarkable yield increase of 200% compared to the control group. Overall, these findings indicate that foliar application of ZnO-NPs is more effective than conventional zinc fertilizers, with the recommendation to use 100 ppm ZnO-NPs to improve both the quantity and quality of tomato crops grown in control conditions.

Based on grouping

Nano-fertilizers are categorized into three types based on grouping: nanoscale fertilizers, nanoscale additive fertilizers, and nanoscale coating fertilizers. Nanoscale fertilizers consist of nanoparticles that are rich in nutrients, while nanoscale additive fertilizers incorporate traditional fertilizers enhanced with nanoscale additives. Conversely, nanoscale coating fertilizers are traditional fertilizers that have been coated or loaded with nanoparticles. The application of nanoscale fertilizers has garnered significant interest, leading to the development and initial industrial-scale production of various nano-based fertilizers. However, this field is still in its early developmental stages, necessitating considerable time and effort to fully commercialize new NFs (Mejias et al., 2021).

Based on mode of action

Slow- and controlled-release nanofertilizers (SRNFs and CRNFs) offer advanced solutions compared to conventional nanoparticles for addressing nutrient delivery challenges in agriculture. These fertilizers either utilize coatings (as in CRNFs) or composite materials (as in SRNFs) to release nutrients in a precise, regulated manner, thereby mitigating the risks of leaching and ensuring more effective delivery of essential macro and micronutrients (Haydar et al., 2024). SRNFs are primarily composed of nanocomposite-based fertilizers, wherein a complex polymer matrix encapsulates the nutrients. In contrast, CRNFs are defined as coated fertilizers, where the external coatings meticulously control the release of the nutrients. The preparation methods for CRNFs can vary, employing a range of encapsulation and coating techniques, while SRNFs can be developed using various composite materials, including hydroxyapatite, hydrogel, chitosan, and alginate, etc. (Elsayed et al., 2022; Chouhan et al., 2022).

SRNF (Slow-Release Nutrient Fertilizer) can be synthesized as a condensation product of urea-aldehyde compounds, super granules, or other fertilizers with a physical barrier. Whereas CRNF is mainly coated material containing the source of nutrients (water soluble), the efficacy of these coatings is critical, as they regulate the rate and pattern of nutrient release. Controlled-Release Nutrient Fertilizers, also known as coated fertilizers, delayed-release fertilizers, or metered fertilizers, are the fertilizers in which factors determining the rate, duration, and pattern of nutrient release can be fully controlled during preparation (Liu et al., 2021). The materials used to prepare CRNF or SRNF coatings and matrices can be either inorganic—such as phosphogypsum, bentonite, and sulfur—or organic, which can be synthetic (e.g., polyethylene, polyurethane, alkyd resin) or natural (e.g., chitosan, starch, cellulose) (Lawrencia et al., 2021a; Lawrencia et al., 2021b). These slow-release nanofertilizers possess optimal properties for effective agricultural use, they are one of the most efficient methods for nutrient delivery to plants. They possess an effective concentration for controlled delivery in response to specific stimuli to a particular target with reduced ecotoxicity (Guo et al., 2018). Additionally, nano-encapsulated products have been found effective for transporting agro-molecules owing to their capacity for slow release and protection of the core molecules. The encapsulated cargo is frequently surrounded by a hydrophilic shell that swells upon moisture absorption, leading to dissolution and the gradual release of nutrients through diffusion (Hueppe et al., 2023).

Currently, nano-based controlled release fertilizers represent a cutting-edge innovation in sustainable agriculture, offering a more precise and efficient approach to nutrient delivery, in a relatively preliminary stage holds immense potential to revolutionize farming practices. Applying superhydrophobic bio-based polymer-coated urea extended the duration of nitrogen release (Zhang et al., 2021). Polyhydroxyalkanoate (PHA)-based fertilizers mitigated nutrient loss and fostered beneficial plant-microbe interactions (Murugan et al., 2020). Additionally, the implementation of cassava starch and bagasse composite urea-based controlled-release nanofertilizers (CRNFs) enhanced nitrogen use efficiency (NUE) in plants (Versino et al., 2020).

References

Ahmed, R., Uddin, M. K., Quddus, M. A., Samad, M. Y. A., Hossain, M. M. and 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.

Ali, M., Cheng, Z. H., Hayat, S., Ahmad, H., Ghani, M. I. and Tao, L. I. U. (2019). Foliar spraying of aqueous garlic bulb extract stimulates growth and antioxidant enzyme activity in eggplant (Solanum melongena L.). Journal of Integrative Agriculture. 18(5), 1001-1013.

Al-Mamun, M. R., Hasan, M. R., Ahommed, M. S., Bacchu, M. S., Ali, M. R. and Khan, M. Z. H. (2021). Nanofertilizers towards sustainable agriculture and environment. Environmental Technology & Innovation. 23, 101658.

Baloch, R. A., Baloch, S. U., Baloch, S. K., Baloch, A. B., Baloch, H. N., Bashir, W., ... and Shakoor Ru, A. (2015). Effect of zinc and boron in combination with NPK on sunflower (Helianthus annuus L.) growth and yield. Journal of Biology, Agriculture and Healthcare. 5(19), 101-107.

Bernard, B. and Lux, A. (2017). How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. Regional Environmental Change. 17(5), 1279-1290.

Chouhan, D., Dutta, A., Kumar, A., Mandal, P. and Choudhuri, C. (2022). Application of nickel chitosan nanoconjugate as an antifungal agent for combating Fusarium rot of wheat. Scientific Reports. 12(1), 14518.

Elemike, E. E., Uzoh, I. M., Onwudiwe, D. C. and Babalola, O. O. (2019). The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. Applied Sciences. 9(3), 499.

Elsayed, A. A., Ahmed, E. G., Taha, Z. K., Farag, H. M., Hussein, M. S. and AbouAitah, K. (2022). Hydroxyapatite nanoparticles as novel nano-fertilizer for production of rosemary plants. Scientia Horticulturae. 295, 110851.

Guo, H., White, J. C., Wang, Z. and Xing, B. (2018). Nano-enabled fertilizers to control the release and use efficiency of nutrients. Current Opinion in Environmental Science & Health. 6, 77-83. N.

Handayati, W. and Sihombing, D. (2019, July). Study of NPK fertilizer effect on sunflower growth and yield. In AIP conference proceedings (Vol. 2120, No. 1). AIP Publishing.

Haydar, M. S., Ghosh, D. and Roy, S. (2024). Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. Plant Nano Biology. 100058.

Hueppe, N., Wurm, F. R. and Landfester, K. (2023). Nanocarriers with multiple cargo load—a comprehensive preparation guideline using orthogonal strategies. Macromolecular rapid communications, 44(16), 2200611.

Kareem, H. A., Hassan, M. U., Zain, M., Irshad, A., Shakoor, N., Saleem, S., ... and Wang, Q. (2022). Nanosized zinc oxide (n-ZnO) particles pretreatment to alfalfa seedlings alleviate heat-induced morpho-physiological and ultrastructural damages. Environmental Pollution. 303, 119069.

Laoung-On, J., Jaikang, C., Saenphet, K. and Sudwan, P. (2021). Phytochemical screening, antioxidant and sperm viability of Nelumbo nucifera petal extracts. Plants. 10(7), 1375.

Lawrencia, D., Wong, S. K., Low, D. Y. S., Goh, B. H., Goh, J. K., Ruktanonchai, U. R., ... and Tang, S. Y. (2021). Controlled release fertilizers: A review on coating materials and mechanism of release. Plants. 10(2), 238.

Liu, G., Zotarelli, L., Li, Y., Dinkins, D., Wang, Q. and Ozores-Hampton, M. (2021). Controlled-release and slow-release fertilizers as nutrient management tools. USA: US Department of Agriculture, UF/IFAS Extension Service, University of Florida, IFAS.

Maghsoodi, M. R., Ghodszad, L. and Lajayer, B. A. (2020). Dilemma of hydroxyapatite nanoparticles as phosphorus fertilizer: Potentials, challenges and effects on plants. Environmental Technology & Innovation, 19, 100869.

Mejías, J. H., Salazar, F., Pérez Amaro, L., Hube, S., Rodriguez, M. and Alfaro, M. (2021). Nanofertilizers: A cutting-edge approach to increase nitrogen use efficiency in grasslands. Frontiers in Environmental Science. 9, 635114.

Mittal, D., Kaur, G., Singh, P., Yadav, K. and Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. Frontiers in Nanotechnology. 2, 579954.

Prost, L. (2021). Revitalizing agricultural sciences with design sciences. Agricultural Systems. *193*, 103225.

Salama, D. M., Osman, S. A., Abd El-Aziz, M. E., Abd Elwahed, M. S. and Shaaban, E. A. (2019). Effect of zinc oxide nanoparticles on the growth, genomic DNA, production and the quality of common dry bean (Phaseolus vulgaris). Biocatalysis and Agricultural Biotechnology. 18, 101083.

Sharma, B., Afonso, L. O., Singh, M. P., Soni, U. and Cahill, D. M. (2022). Zinc-and magnesium-doped hydroxyapatite-urea nanohybrids enhance wheat growth and nitrogen uptake. Scientific Reports. 12(1), 19506.

Thakur, S., Asthir, B., Kaur, G., Kalia, A. and Sharma, A. (2021). Zinc oxide and titanium dioxide nanoparticles influence heat stress tolerance mediated by antioxidant defense system in wheat. Cereal Research Communications. 1-12.

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A. and Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. Plant science. 289, 110270.

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