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Review Article

NANO-BIOFERTILIZERS AS NEXT-GENERATION NUTRIENT DELIVERY SYSTEMS FOR SUSTAINABLE AND CLIMATE-SMART AGRICULTURE: A COMPREHENSIVE REVIEW

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ABSTRACT

Nano-biofertilizers represent a cutting-edge innovation at the convergence of nanotechnology and biological nutrient management, offering a sustainable and efficient alternative to conventional agrochemical fertilizers. These advanced formulations combine beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing microbes, and plant growth–promoting rhizobacteria with nanoscale nutrient carriers to enhance the precision, efficiency, and sustainability of crop nutrition. In contrast to traditional fertilizers, which often experience significant nutrient losses through leaching, volatilization, and runoff, nano-biofertilizers are designed to deliver nutrients in a controlled and targeted manner, thereby substantially improving nutrient use efficiency (NUE) and reducing environmental contamination. Recent research (2023–2025) highlights the effectiveness of nanocarrier systems derived from chitosan, alginate, silica, and biodegradable polymers in encapsulating nutrients and microbial inoculants. These systems protect bioactive components from adverse soil conditions and enable their gradual release in alignment with plant nutrient demand. Such controlled delivery enhances nutrient uptake while fostering a stable and biologically active rhizosphere. The synergistic interaction between nanoparticles and microbial consortia has been shown to improve plant physiological performance, including enhanced root development, increased chlorophyll content, elevated enzymatic activity, and greater tolerance to abiotic stresses such as drought, salinity, and nutrient deficiency. From a sustainability standpoint, nano-biofertilizers reduce dependence on synthetic fertilizers, lower greenhouse gas emissions, and mitigate nutrient pollution in terrestrial and aquatic ecosystems. Their application aligns with climate-smart and precision agriculture strategies by supporting site-specific and dose-efficient nutrient management. Although promising, challenges related to large-scale production, regulatory frameworks, long-term ecological impacts, and economic feasibility remain. Addressing these issues will be crucial for the widespread adoption of nano-biofertilizers as a transformative solution for sustainable agriculture and global food security.

Keywords: Nano-biofertilizers, Nanocarriers, Nutrient use efficiency, Sustainable agriculture, Pollution.

INTRODUCTION

Global agriculture is confronting unprecedented pressures that stem from the imperative to increase food production for a rapidly expanding population while simultaneously reducing the environmental degradation caused by intensive agrochemical use. The global population is projected to reach nearly 9.7 billion by 2050, a surge that necessitates as much as a 50–70 % increase in food production compared with current levels to ensure food security and nutritional adequacy worldwide (Turner *et al.*, 2024). However, traditional agricultural practices, particularly the heavy reliance on synthetic chemical fertilizers, pose significant environmental and ecological consequences. A substantial proportion of the nutrients supplied by conventional fertilizers especially nitrogen and phosphorus is not assimilated by crops but is instead lost to the environment through pathways such as leaching, volatilization, and runoff, which contribute to soil degradation, water pollution, eutrophication, and greenhouse gas emissions (Das & Kim, 2023; Khan *et al.*, 2024). This low nutrient use efficiency not only compromises agricultural sustainability but also promotes

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long-term declines in soil health and biodiversity, creating a feedback loop that increasingly undermines productivity and resilience (Das & Kim, 2023; Turner *et al.*, 2024). In response to these mounting challenges, the integration of nanotechnology with biofertilizer science has emerged as a novel and promising approach to nutrient management in cropping systems. Nano-biofertilizers are engineered materials that combine beneficial microorganisms (e.g., nitrogen-fixing bacteria, phosphate-solubilizing microbes, and plant growth-promoting rhizobacteria) with nanoparticles and nanocarrier systems capable of delivering nutrients in a targeted, controlled, and efficient manner (Das & Kim, 2023; Thirumurugan *et al.*, 2024). By harnessing the unique physicochemical properties of nanoscale materials such as high surface area-to-volume ratios, enhanced reactivity, and tunable release kinetics these formulations enable precision nutrient delivery that aligns with plant demand and minimizes nutrient losses, thereby significantly improving nutrient use efficiency (NUE) relative to bulk fertilizer applications (Turner *et al.*, 2024; Singh & Sharma, 2025).

Beyond agronomic performance, nano-biofertilizers embody the principles of sustainable agriculture, which emphasize environmental stewardship, resource efficiency, and long-term soil health. By reducing dependence on synthetic fertilizers, lowering nutrient volatilization and leaching, and fostering beneficial plant–microbe interactions, these formulations contribute to diminished greenhouse gas emissions, improved water quality, and enhanced soil fertility (Das & Kim, 2023; Turner *et al.*, 2024; Springer, 2024). Importantly, recent research highlights that nanomaterial-assisted nutrient management can reduce fertilizer input requirements by a significant margin while maintaining or improving productivity, aligning closely with global efforts to mitigate climate change impacts and promote eco-agricultural sustainability (Turner *et al.*, 2024; Thirumurugan *et al.*, 2024). Despite rapid advancements, challenges remain before wide-scale adoption of nano-biofertilizers becomes a reality. Key obstacles include production scalability, cost barriers, comprehensive safety and environmental risk assessments, and the development of appropriate regulatory frameworks to guide responsible use (Das & Kim, 2023; Thirumurugan *et al.*, 2024).

Nano-Biofertilizer Formulations

Nano-biofertilizer formulations represent a significant advancement in nutrient management by integrating nanotechnology with biological fertilizers to enhance nutrient stability, delivery efficiency, and microbial viability in agricultural systems. Conventional biofertilizers often suffer from short shelf life, low survival rates of microbial inoculants, and poor nutrient retention under field conditions, which limit their agronomic effectiveness. The incorporation of nanocarriers and biodegradable coating matrices into biofertilizer formulations addresses these challenges by providing physical protection to beneficial microorganisms and enabling the controlled and targeted release of nutrients in the rhizosphere (Thirumurugan *et al.*, 2024; Turner *et al.*, 2024). These nano-enabled systems improve nutrient use efficiency (NUE) by minimizing losses due to leaching, volatilization, and immobilization in soil, while also supporting sustained microbial activity and root–microbe interactions (Khan *et al.*, 2024; Singh & Sharma, 2025). As a result, nano-biofertilizers are increasingly being recognized as a key component of precision and sustainable agriculture, offering both agronomic and environmental benefits over traditional fertilizer technologies.

Nanocarrier materials and coating matrices play a central role in determining the functionality and performance of nano-biofertilizer formulations. Biodegradable and biocompatible polymers such as chitosan, cellulose, alginate, gelatin, and polyvinyl alcohol (PVA) are widely used to encapsulate nutrients and microbial inoculants because of their non-toxic nature, high water retention capacity, and ability to respond to soil environmental conditions (Thirumurugan *et al.*, 2024; Kumar & Meesala, 2025). These materials form nanoscale or microscale matrices that entrap nutrients and beneficial microbes, shielding them from adverse factors such as ultraviolet radiation, desiccation, extreme pH, and competition with native soil microflora. In particular, chitosan and alginate have attracted considerable attention due to their film-forming ability, biodegradability, and positive interaction with plant roots, which enhances nutrient uptake and microbial colonization (Khan *et al.*, 2024). Moreover, these nanopolymers can be engineered to exhibit pH-sensitive or moisture-responsive behavior, allowing nutrients to be released gradually in response to soil moisture levels, root exudates, or changes in soil acidity, thereby synchronizing nutrient availability with plant demand (Turner *et al.*, 2024; Singh & Sharma, 2025). Such controlled-release mechanisms are especially important for minimizing nutrient losses in rainfed and irrigated agroecosystems, where leaching and runoff are major causes of fertilizer inefficiency.

The encapsulation of beneficial microorganisms within nanocarrier matrices further enhances the functionality of nano-biofertilizers by stabilizing microbial inoculants and improving their performance in soil environments. Key microbial groups incorporated into nano-biofertilizer formulations include nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*), phosphate-solubilizing bacteria, potassium-mobilizing microbes, and plant growth-promoting rhizobacteria (PGPR), all of which play crucial roles in nutrient cycling and plant health (Thirumurugan *et al.*, 2024; Turner *et al.*, 2024). Encapsulation within nanoparticle coatings improves the shelf life and field survival of these microorganisms by protecting them from temperature fluctuations, oxidative stress, and desiccation during storage and application (Khan *et al.*, 2024). Once applied to soil, the gradual degradation of the nanopolymer matrix releases viable microbial cells in close proximity to plant roots, facilitating rapid colonization of the rhizosphere and efficient establishment of beneficial plant–microbe associations (Kumar and Meesala, 2025).

Furthermore, nano-encapsulation enhances the metabolic activity and functional efficiency of beneficial microbes by providing a favorable microenvironment rich in moisture and nutrients, which promotes microbial growth and enzymatic activity (Singh & Sharma, 2025). For instance, phosphate-solubilizing bacteria encapsulated in chitosan or alginate matrices have been shown to exhibit higher phosphorus-solubilization capacity than their free-living counterparts, resulting in increased phosphorus availability and improved crop uptake (Thirumurugan *et al*., 2024). Similarly, nano-encapsulated nitrogen-fixing bacteria demonstrate greater nitrogen fixation efficiency due to improved survival and prolonged activity in the rhizosphere (Turner *et al*., 2024). In addition, the presence of nanoparticles can enhance root permeability and stimulate root exudation, further strengthening plant–microbe interactions and nutrient acquisition (Khan *et al*., 2024).

Mechanisms of Efficient Nutrient Delivery

Nano-biofertilizers enhance nutrient delivery through a set of interconnected physicochemical and biological processes that overcome the limitations of conventional fertilization. A key mechanism is targeted and controlled nutrient release**,** in which nutrients are encapsulated within nanostructured carriers designed to release them gradually in the rhizosphere in response to environmental signals such as soil moisture, pH, or root exudates. According to Selvarani, Theivasanthi, Ajitha, and Siva (2025), nano-fertilizers are engineered to release macro- and micronutrients in a regulated manner that aligns with plant growth phases, significantly reducing nutrient losses due to leaching, volatilization, and fixation compared to traditional fertilizers. Controlled release not only improves the synchronization between nutrient availability and crop demand but also reduces the frequency and total quantity of fertilizer applications, enhancing nutrient use efficiency (NUE) and overall agronomic performance. Similarly, Meng *et al*. (2025) showed that nano-micronutrient fertilizers containing zinc, manganese, and molybdenum increased leaf and grain nutrient concentrations in maize, reinforcing the view that nanoscale delivery enhances internal nutrient assimilation more efficiently than conventional sources.

Another prominent mechanism is the interaction between nanomaterials and the soil microbiome**,** which can influence nutrient cycling, microbial activity, and soil health. Nanoparticles and protective carrier matrices in nano-biofertilizers support beneficial microorganisms such as nitrogen-fixing bacteria and phosphate-solubilizing microbes by creating a more stable microenvironment that enhances their survival and functional activity in soil. For example, research indicates that nanoparticles can stimulate microbial processes involved in nutrient mineralization and organic matter decomposition, thereby improving nutrient bioavailability and uptake by plants. This synergistic action between nanomaterials and microbes expands biological nutrient transformation beyond plant roots, promoting a healthier and more dynamic soil ecosystem (Springer, 2025). While some nanomaterials at high concentrations may affect microbial diversity, controlled nano-biofertilizer formulations focused on biodegradable polymers such as chitosan appear to support beneficial microbial populations without adverse ecological effects.

Together, targeted release, improved absorption, and enhanced microbial activity contribute to significantly higher nutrient use efficiency (NUE) in crops treated with nano-biofertilizers. Evidence suggests that nano-based nutrient delivery systems can reduce nutrient losses and increase harvestable yield even at reduced application rates, making them more efficient, economically viable, and environmentally sustainable compared to traditional fertilization methods (Selvarani *et al*., 2025; Springer, 2025).

Sustainability Impacts in Agriculture

Environmental Benefits

The sustainability advantages of nano-biofertilizers arise primarily from their ability to minimize nutrient waste and environmental contamination**.** Conventional fertilizer overuse is a major source of nutrient runoff and leaching into waterways, contributing to eutrophication, hypoxic zones in aquatic ecosystems, and greenhouse gas emissions such as nitrous oxide. Springer (2025) explains that nano-fertilizers reduce nutrient runoff and leaching by delivering nutrients more efficiently to plant roots, thereby lowering the environmental footprint of agricultural fertilization. Controlled release and minimized losses also reduce the energy and resources needed for fertilizer production, transportation, and repeated applications, supporting sustainable production systems.

CONCLUSION

Nano-biofertilizers represent a significant breakthrough in the evolution of plant nutrition and sustainable agricultural practices by integrating the precision of nanotechnology with the biological efficiency of microbial inoculants. This review highlights that nano-biofertilizer formulations, through advanced nanocarriers and biodegradable coating matrices, enable controlled and targeted nutrient delivery while preserving the viability and functional activity of beneficial microorganisms. These features directly address the fundamental limitations of conventional fertilizers, including low nutrient use efficiency, high nutrient losses, and adverse environmental impacts. The ability of nanocarriers to release nutrients in response to soil and plant signals ensures that macro- and micronutrients are supplied in synchrony with crop demand, resulting in enhanced nutrient uptake, improved physiological performance, and higher yield stability even under stress conditions such as drought, salinity, and nutrient deficiency. Overall, nano-biofertilizers hold substantial promise as next-generation nutrient delivery systems that can support high agricultural productivity while preserving natural resources. Their integration into precision agriculture and sustainable farming frameworks offers a viable pathway toward resilient, efficient, and environmentally responsible food production systems capable of meeting the demands of a growing global population under changing climatic conditions.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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