

Transforming Sustainable Agriculture through Nano-Coated Biofertilizers for Enhanced Soil Health and Crop Productivity

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ABSTRACT

Sustainable agriculture requires innovative nutrient management strategies capable of improving crop productivity while maintaining soil health and reducing environmental impacts. Nano-coated biofertilizers have emerged as a promising technology that integrates nanomaterials with beneficial microbial inoculants to enhance nutrient delivery, microbial stability, and plant growth performance. This review synthesizes current scientific evidence on the potential of nano-coated biofertilizers to improve soil biological functions and crop productivity within sustainable agricultural systems. A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and complemented with bibliometric analysis. Relevant publications were retrieved from ScienceDirect and screened using predefined inclusion and exclusion criteria based on publication year, topic relevance, article type, and language. Following the PRISMA screening stages, a total of 16 peer-reviewed research articles were included in the final qualitative analysis. The reviewed studies indicate that nano-coated biofertilizers formulated with various nanomaterials, including metal-based nanoparticles, polymeric nanocarriers, and nano-structured nutrient carriers, can improve microbial stability, regulate nutrient release, and increase nutrient use efficiency in the soil-plant system. These mechanisms enhance soil microbial activity, promote nutrient cycling, and reduce nutrient losses, thereby supporting healthier and more resilient soil ecosystems. At the plant level, nano-enabled biofertilizers stimulate root development, increase nutrient uptake, improve tolerance to abiotic stress, and enhance crop productivity while reducing dependence on chemical fertilizers. However, challenges related to formulation stability, large-scale production, and environmental safety remain important considerations for future research and agricultural implementation.

KEYWORDS: Crop productivity, Nanotechnology in agriculture, Nano-coated biofertilizers, Nutrient use efficiency, Soil health, Sustainable agriculture

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INTRODUCTION

Sustainable agriculture faces increasingly complex challenges due to the rising global food demand, soil degradation, and climate change (Chowdhuri & Pal, 2025). Declining soil fertility caused by intensive farming practices, excessive use of chemical fertilizers, and nutrient erosion threatens crop productivity and soil ecosystem health. In this context, the adoption of innovative technologies is crucial to ensure food production sustainability while maintaining environmental balance (Futa et al., 2024).

One promising innovation is the use of nano-coated biofertilizers, which represent a hybrid of biofertilizers encapsulated within nanoparticles designed to enhance nutrient delivery and crop productivity (Garg et al., 2023). These fertilizers integrate principles

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of biotechnology and nanotechnology, encapsulating beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, or arbuscular mycorrhizal fungi within nanomaterial matrices that improve their stability, protection, and controlled nutrient release (Karunakaran et al., 2024). This nano-encapsulation approach not only enhances microbial efficiency but also helps improve soil nutrient availability and support sustainable plant growth (Garg et al., 2023).

Recent studies have shown that nano-biofertilizers can improve crop productivity more efficiently than traditional fertilizers, as they enhance nutrient availability and plant uptake through synergistic effects of beneficial microbes and nanoscale carriers (Garg et al., 2023). Additionally, this technology has the potential to reduce dependence on synthetic chemical fertilizers and minimize environmental pollution by lowering nutrient losses via leaching and volatilization (Oyediran et al., 2025). However, despite its significant potential, the understanding of the interaction mechanisms between nanoparticles, microorganisms, soil, and plants remains limited, and more systematic research is needed to assess its long-term impacts on agricultural ecosystems (Patel et al., 2023).

Against this background, this review aims to summarize the latest developments in the application of nano-coated biofertilizers, evaluate their contribution to soil health and crop productivity, and highlight the challenges and opportunities for their implementation in sustainable agriculture. This approach is expected to provide a comprehensive perspective for researchers, agricultural practitioners, and policymakers in adopting innovative technologies to support global food security.

METHODS

This systematic literature review was conducted to evaluate the impact of nano-coated biofertilizers on soil health and crop productivity. The methodology followed a structured approach to ensure reproducibility and comprehensiveness of the retrieved studies.

Search Strategy

A keyword combination-based search strategy was developed to identify relevant articles. The primary database used was ScienceDirect, selected for its extensive collection of peer-reviewed journals in agricultural and environmental sciences. Six keyword combinations were applied, covering the concepts of nano-coated biofertilizers, soil health, nutrient management, microbial activity, and crop productivity. The combinations and the number of articles retrieved are summarized in Table 1. In total, 238 articles were initially identified.

Table 1. Keyword combination-based search strategy for retrieving relevant articles

Search Strategy	Sciencedirect
nano coated biofertilizer AND soil health AND sustainable agriculture	20
nano biofertilizer AND soil fertility AND crop yield	50
nano coated biofertilizer AND soil microbial activity AND plant growth	28
nano biofertilizer AND nutrient use efficiency AND crop productivity	72
nano coated biofertilizer AND soil microbiome AND nutrient availability	9
nano biofertilizer AND beneficial microorganisms AND agricultural productivity	59
Total	238

Inclusion and Exclusion Criteria

Predefined inclusion and exclusion criteria were applied to ensure the relevance and quality of the selected studies. The detailed criteria used in the screening process are presented in Table 2.

Table 2. Criteria for inclusion and exclusion were applied in this study

Criteria	Inclusion	Exclusion
Relevance Topic	Journal with a focus on nano-coated biofertilizers, soil health, and crop productivity	Journal without a core focus on agriculture, biofertilizers, or nanotechnology
Year of Publication	2016-2026	Years before 2016

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Type of Publication	Research article	Review article, book chapters, encyclopaedia, news, conference abstracts
Language of Publication	English	All other languages
Access	Open Access	No open access
Databases	Scencedirect	Other databases

PRISMA Screening and Study Selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for study selection. The process included four stages: identification of relevant articles, screening of titles and abstracts, eligibility assessment of full texts, and inclusion of studies meeting all criteria. A PRISMA flow diagram (Figure 1) was constructed to visualize the article selection process, illustrating the number of studies identified, screened, and included in the qualitative synthesis. This methodology ensures a rigorous, unbiased, and reproducible review process.

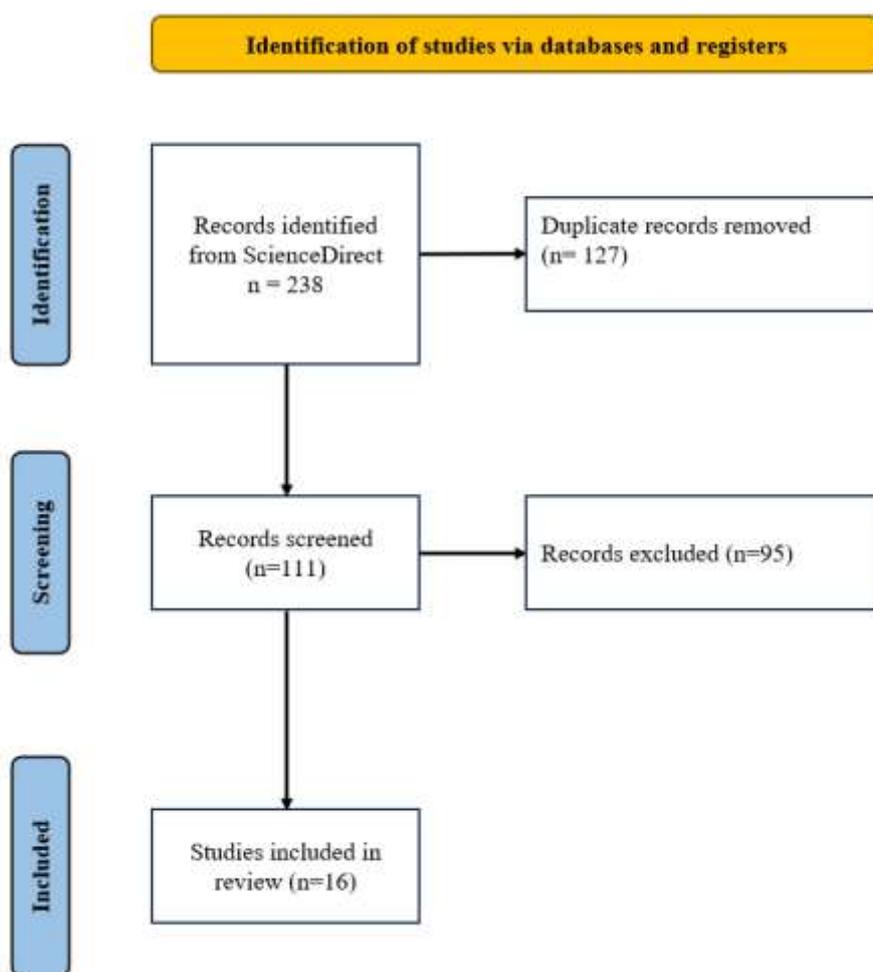


Figure 1. PRISMA Flow Diagram Showing the Selection of Articles for This Review

Data Retrieval for Bibliometric Analysis

Bibliographic records obtained from the database search were downloaded in RIS format. Duplicate entries were identified and removed using Mendeley Reference Manager (version 2.118.0). The cleaned dataset was then processed and visualized using VOSviewer version 1.6.20 to perform the bibliometric mapping and network analysis (Van Eck & Waltman, 2010)

RESULTS AND DISCUSSION

Bibliometric analysis by VOSviewer

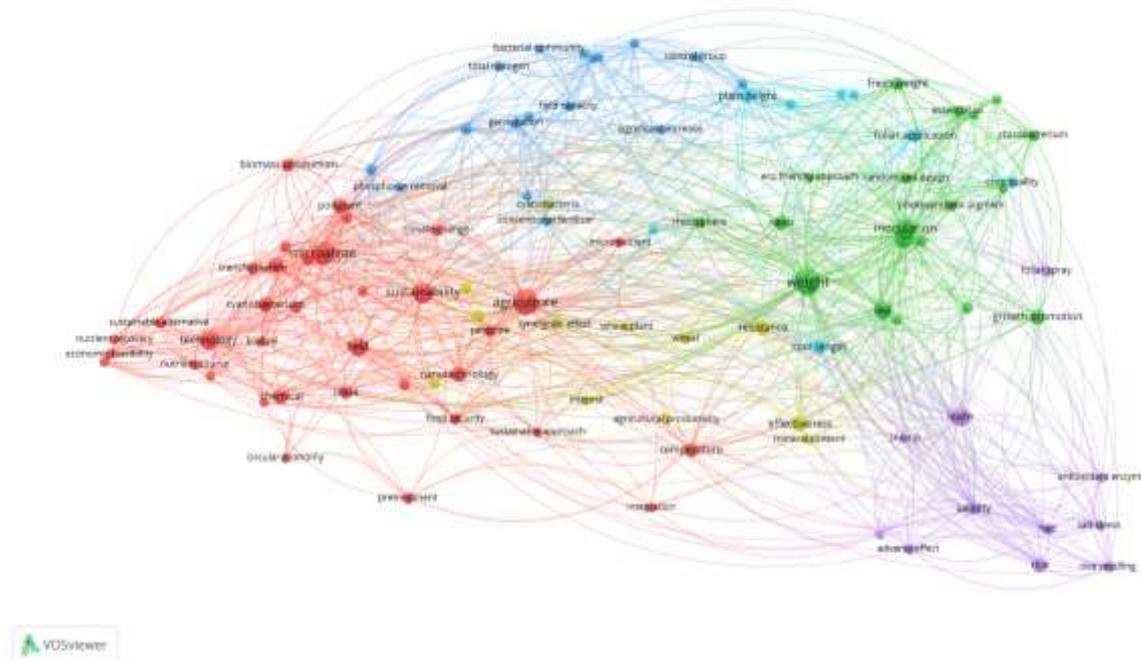


Figure 2. Network visualization of keyword co-occurrence related to nano-enabled biofertilizers and sustainable agriculture generated using VOSviewer.

Based on the bibliometric network visualization (Figure 2), five key clusters have been identified. The first cluster (red) represents research themes related to biological resources and sustainability concepts in agricultural systems. Keywords such as microalgae, cyanobacterium, biomass production, nutrient recovery, sustainability, technology, and circular economy illustrate efforts to utilize biological organisms as environmentally friendly alternative nutrient sources. Microalgae and cyanobacteria are known for their ability to improve nutrient cycling and enhance nutrient availability in soil systems. In the context of developing nano-coated biofertilizers, these organisms can serve as biological components integrated with nanotechnology to improve nutrient stability and release efficiency. Therefore, this cluster reflects an innovative approach that combines biological resources with advanced technologies to support more sustainable agricultural practices.

The second cluster (blue) is associated with soil microbial interactions and nutrient cycling dynamics that influence plant growth. Keywords such as bacterial community, total nitrogen, germination, field capacity, and plant height indicate that many studies focus on how soil microbial communities contribute to nutrient availability and plant development. Microbial activity plays a crucial role in improving soil fertility through biological processes such as nutrient mineralization and transformation. In the development of nano-coated biofertilizers, nano-coating technology can help protect functional microorganisms, ensuring that their biological activities remain stable in soil environments. Thus, this cluster highlights the importance of microbial communities in maintaining soil health and improving nutrient use efficiency in sustainable agricultural systems.

The third cluster (green) focuses on plant growth promotion mechanisms associated with root-related microorganisms. Keywords such as inoculation, rhizobacterium, IAA, root length, fresh weight, photosynthetic pigment, and crop quality indicate that research in this cluster evaluates the effects of biofertilizers on physiological and agronomic plant parameters. Rhizobacteria are known to produce plant growth hormones such as indole-3-acetic acid (IAA), which can stimulate root development and enhance nutrient uptake efficiency. The application of nano-coated biofertilizers has the potential to improve the effectiveness of microbial inoculants because nanotechnology can enhance microbial stability and distribution within the rhizosphere. Consequently, this cluster demonstrates the direct relationship between nano-based biofertilizers and improvements in plant growth and crop quality.

The fourth cluster (purple) represents research themes related to plant tolerance to environmental stress, particularly salinity stress. Keywords such as salinity, NaCl, salt stress, antioxidant enzyme, rice seedling, and adverse effect suggest that many studies investigate the role of biofertilizers and nanotechnology in enhancing plant resilience under unfavorable environmental conditions. Salinity stress can inhibit plant growth by disrupting ionic balance and increasing oxidative stress within plant tissues. The application of biofertilizers combined with nanotechnology may help plants increase antioxidant enzyme activity and maintain physiological balance. Therefore, this cluster highlights the potential of nano-coated biofertilizers in improving plant tolerance to various abiotic stresses.

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The fifth cluster (yellow) emphasizes the integration of nanotechnology into modern agricultural systems. Keywords such as nanotechnology, agriculture, effectiveness, mineral content, wheat plant, and agricultural productivity indicate that research in this cluster focuses on developing nano-based technologies to enhance agricultural input efficiency and crop productivity. Nanotechnology enables the development of biofertilizers with controlled nutrient release characteristics and improved stability of beneficial microorganisms used as biofertilizer agents. The integration of nanotechnology with biofertilizers provides significant opportunities to improve soil health while simultaneously supporting sustainable increases in crop productivity. Therefore, this cluster serves as a bridge between technological innovation and practical agricultural applications.

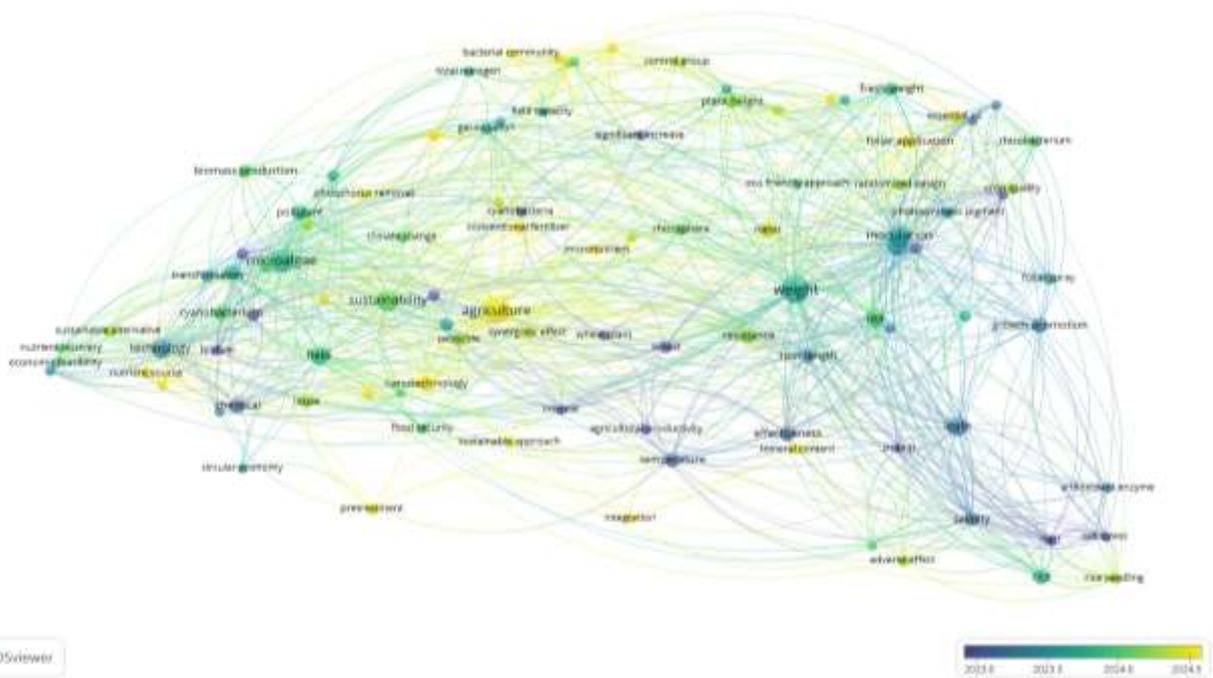


Figure 3. Density visualization of keyword co-occurrence in research on biofertilizers and nanotechnology in agriculture.

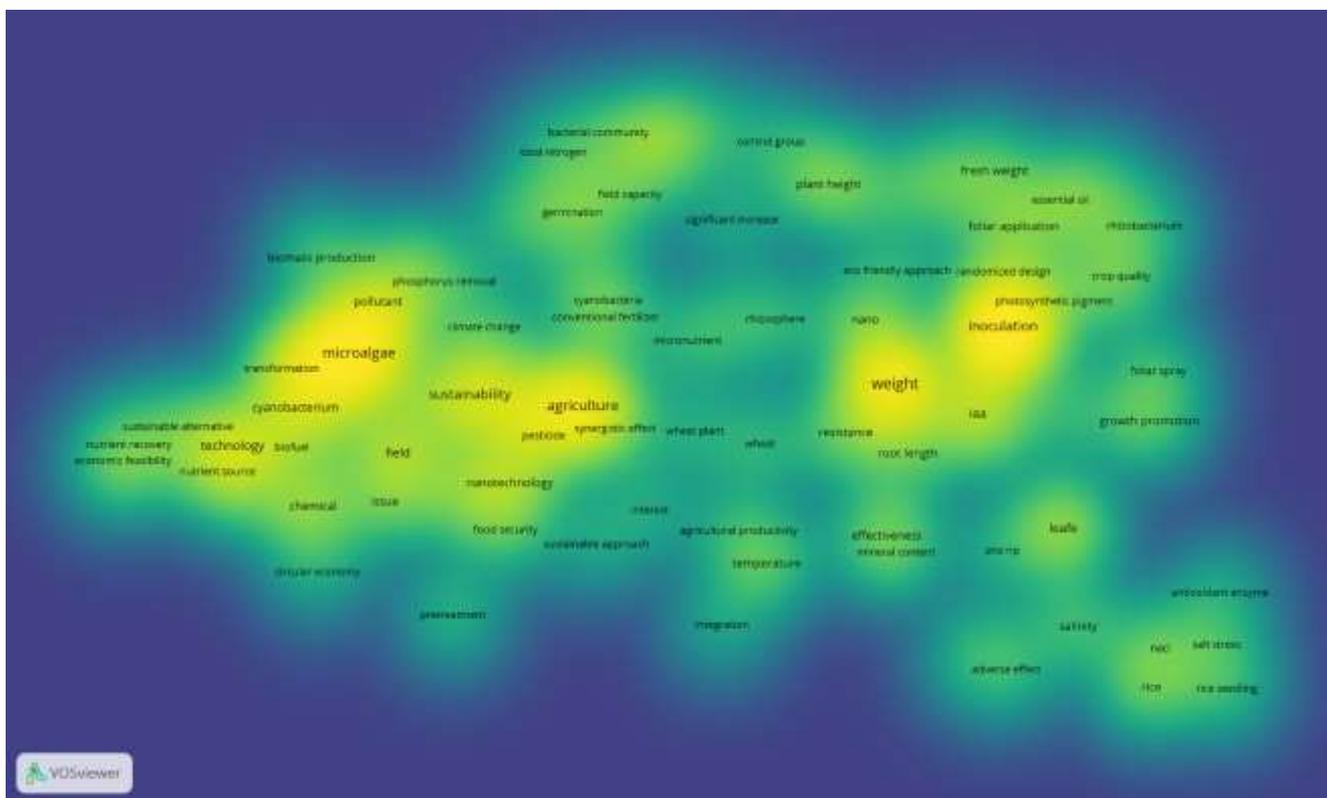


Figure 4. Overlay visualization showing the temporal evolution of research topics in nano-coated biofertilizers for sustainable agriculture.

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The density visualization (Figure 3) highlights the major research hotspots within the field of biofertilizers and nanotechnology in agriculture. Areas represented in bright yellow indicate a high frequency of keyword occurrences, suggesting strong research attention. Prominent keywords such as microalgae, sustainability, agriculture, weight, and inoculation appear as the most intensive nodes within the map. This pattern indicates that current research strongly emphasizes the utilization of biological resources, particularly microalgae and cyanobacteria, as sustainable biofertilizer sources. These microorganisms are widely recognized for their ability to enhance nutrient cycling and contribute to environmentally friendly agricultural systems. Within the framework of nano-coated biofertilizers, nanomaterial coatings can improve microbial stability and nutrient delivery efficiency, thereby enhancing the effectiveness of biological inputs in sustainable crop production systems.

The density map also reveals strong connections between plant growth parameters and microbial-based fertilization strategies. Keywords such as IAA, root length, fresh weight, photosynthetic pigment, and growth promotion appear in high-density areas, indicating that a substantial portion of the literature evaluates the physiological and agronomic responses of plants to biofertilizer applications. Plant growth-promoting rhizobacteria are known to synthesize phytohormones such as indole-3-acetic acid, which stimulate root development and improve nutrient uptake efficiency. The integration of nanotechnology with microbial inoculants has the potential to enhance the survival and functional activity of these microorganisms within the rhizosphere. Consequently, nano-coated biofertilizers represent an emerging strategy to improve plant biomass accumulation, physiological performance, and overall crop productivity.

In addition to plant growth responses, the visualization highlights the importance of soil biological processes in sustaining agricultural productivity. Keywords such as bacterial community, total nitrogen, rhizosphere, and micronutrient demonstrate the close relationship between soil microbial dynamics and nutrient cycling. Soil microorganisms play a crucial role in processes such as nitrogen fixation, phosphorus solubilization, and organic matter decomposition, all of which contribute to improved soil fertility and nutrient availability. The development of nano-coated biofertilizers offers an innovative approach to enhance these processes by protecting beneficial microorganisms and enabling controlled nutrient release. Such technological advancements contribute to improved soil health while simultaneously supporting efficient nutrient utilization in cropping systems.

The overlay visualization (Figure 4) provides further insight into the temporal evolution of research topics within this field. In this map, colors represent the average publication year of keywords, with darker colors indicating earlier studies and brighter yellow tones representing more recent research trends. Keywords such as technology, chemical, and microalgae appear in darker shades, suggesting that these topics have been studied for a relatively longer period. In contrast, terms including nanotechnology, inoculation, fresh weight, and foliar application appear in brighter colors, indicating their emergence as more recent research focuses. This trend suggests that the integration of nanotechnology into biofertilizer development represents a rapidly expanding research frontier aimed at improving the efficiency and functionality of biological fertilizers in modern agriculture.

Another emerging research direction identified in the overlay visualization involves the role of biofertilizers in improving plant tolerance to environmental stress. Keywords such as salinity, NaCl, salt stress, antioxidant enzyme, and rice seedling indicate growing interest in understanding how biofertilizers can enhance plant resilience under adverse environmental conditions. Salinity stress can disrupt plant physiological processes by inducing oxidative stress and ionic imbalance. Biofertilizers, particularly when combined with nanotechnology, may improve plant tolerance by stimulating antioxidant defense systems and maintaining cellular homeostasis. These findings highlight the potential of nano-coated biofertilizers not only to enhance plant growth but also to strengthen plant resilience under challenging environmental conditions.

Overall, the bibliometric visualization demonstrates a clear progression in research from conventional biological fertilization strategies toward the integration of advanced nanotechnological approaches. The strong interconnections among keywords related to sustainability, microbial activity, plant growth, and nanotechnology suggest that nano-coated biofertilizers are emerging as a transformative innovation in sustainable agriculture. By improving nutrient use efficiency, enhancing soil microbial functions, and promoting plant growth under both optimal and stressful conditions, nano-coated biofertilizers provide a promising pathway for improving soil health and crop productivity. These findings strongly support the central theme of the review article, which emphasizes the role of nano-enabled biofertilizers in transforming sustainable agricultural systems.

Types of Nano-Coated Biofertilizers

Nano-coated biofertilizers integrate microorganisms with nanoscale carriers to enhance stability and functional delivery. Common nano-materials include biodegradable polymers (e.g., chitosan), silica nanoparticles, and metal oxides (e.g., ZnO, iron oxides). Nano-coatings provide controlled nutrient release and protect microbes from abiotic stressors. As summarized in Table 3, numerous studies have reported that the combination of nanomaterials and microbial inoculants can positively influence soil properties and plant responses, demonstrating their potential to improve soil health and crop productivity.

Table 3. Reported Effects of Nanomaterials and Microbial Inoculants on Soil and Plant Systems

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Type of Nanoparticles / Nano Materials	Microorganisms	Tested Plants	Impact on Soil	Impact on Plants	Citation
Cerium oxide nanoparticles (CeO ₂) nanocomposite	<i>Pseudomonas gessardi</i> , <i>P. azotoformans</i>	Fenugreek (<i>Trigonella foenum-graecum</i>)	Improves micronutrient availability	Increases shoot and root growth	Sonali et al., 2022
Nano-iron phycofertilizer (~25 nm)	<i>Spirulina</i> sp.	Rice (<i>Oryza sativa</i>)	Increases Fe availability	Improves yield and grain weight	Mondal et al., 2024
ZnO, Fe ₂ O ₃ , Se nanoparticles; chitosan NP; carbon NP; nanosensors	<i>Pseudomonas</i> sp. (biofertilizer synergy)	Sprouts and microgreens	Potential interaction with soil microbiota	Improves germination, nutrient uptake, growth, and stress tolerance	Zhu et al., 2025
ZnO nanoparticles	Zinc-solubilizing bacteria	Wheat (<i>Triticum aestivum</i>)	Increases beneficial microbes (N-fixers, P and Zn solubilizers)	Improves growth, yield, protein, and grain Zn content	Saleem et al., 2023
ZnO nanoparticles	Biofertilizer PhytoGuard	Safflower (<i>Carthamus tinctorius</i>)	Reduces Na ⁺ uptake under salinity	Improves growth and salinity tolerance	Yasmin et al., 2021
FeOx and MnOx nanoparticles	Bacterial supernatant with IAA	Maize (<i>Zea mays</i>)	Increases micronutrient availability	Improves germination and growth	de França Bettencourt et al., 2020
Biogenic nanoparticles from rhizobacteria	<i>Pseudomonas</i> sp.	-	Increases soil microbial activity	Enhances plant growth and stress tolerance	Thakur & Yadav, 2024
Bio Zn, Bio NPK, Rhizobium, MDSR14, Burkholderia arboris	<i>Rhizobium</i> + <i>Burkholderia arboris</i>	Soybean (<i>Glycine max</i> L. Merrill)	Increases soil biological activity	Improves yield and plant growth	Dass et al., 2025
LiFePO ₄	Fe-solubilizing & P-mobilizing bacteria	Peanut & maize	Changes soil pH and increases microbiome	Improves root biomass, yield, and nutrients	Jiang et al., 2025
Iron oxide nanoparticles (Fe ₂ O ₃ NPs)	<i>Curtobacterium plantarum</i> , <i>Pseudomonas brassicacearum</i>	<i>Satureja khuzistanica</i>	Improved Fe availability and uptake	Increased chlorophyll, antioxidant activity, essential oil yield, and plant growth	Mumivand et al., 2025
Ag, ZnO, Cu NPs; lipid nanoparticles; nanoemulsions; lignin nanocarriers	<i>Bacillus</i> , <i>Trichoderma</i> , <i>Nostoc</i>	Soybean and other crops	May alter soil microbial activity	Improves nematode control and plant growth	Silva et al., 2025
Nano-hydroxyapatite (nano-bio P)	<i>Pseudomonas putida</i>	Tomato (<i>Solanum lycopersicum</i>)	Improved phosphorus availability and uptake efficiency in the rhizosphere	Improved root biomass, shoot growth, fruit firmness, vitamin C, pigments, and leaf P content	Kooshki et al., 2024

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Type of Nanoparticles / Nano Materials	Microorganisms	Tested Plants	Impact on Soil	Impact on Plants	Citation
CuO, ZnO, and γ -Fe ₂ O ₃ nanoparticles	<i>Humicola</i> , <i>Sphingomonas</i> , <i>Arenimonas</i>	<i>Salvia miltiorrhiza</i>	Altered rhizosphere microbial community and metal availability	Increased root biomass and diameter; enhanced salvanolic acid B content	Wei et al., 2021
Cerium oxide nanoparticles (CeO ₂ NPs) + wheat husk biochar	<i>Ustilago tritici</i>	Wheat (<i>Triticum aestivum</i>)	Reduced cadmium toxicity, improved soil health	Increased plant growth, yield, photosynthesis, stress resistance, and antifungal activity	Irshad et al., 2026
Selenium nanoparticles (SeNPs), L-cysteine-functionalized SeNPs (Cys-SeNPs)	<i>Bacillus licheniformis</i> T6	Tobacco (<i>Nicotiana tabacum</i> var. <i>Xanthi nc</i>)	-	Enhanced antiviral resistance; upregulated defense genes; improved efficacy; no phytotoxicity	Wang et al., 2026
Chitosan nanoparticles (CS) combined with biofertilizer and reduced chemical fertilizer	<i>P. agglomerans</i> , <i>P. putida</i> , <i>P. koreensis</i> , <i>P. vancouverensis</i> , <i>Thiobacillus</i> spp.	Camelina (<i>Camelina sativa</i> L. Crantz)	Improved nutrient availability and microbial-mediated nutrient cycling (N, P, K, S)	Increased nutrient uptake, antioxidant activity, drought tolerance, seed yield, oil yield, and unsaturated fatty acids	Haghaninia et al., 2024

Nano-Coated Biofertilizers in Sustainable Agriculture

Concept and Development of Nano-Coated Biofertilizers

The concept of nano-coated biofertilizers is based on the integration of beneficial microorganisms with nanostructured materials that function as protective carriers or coating agents (Reddy et al., 2024). In this system, nanomaterials encapsulate microbial cells or nutrient compounds, forming a protective matrix that creates a controlled microenvironment around the biological component. This microenvironment helps maintain microbial viability and metabolic activity while protecting the cells from unfavorable soil conditions. Through nano-coating or nano-encapsulation techniques, both nutrients and microorganisms can be released gradually into the soil, ensuring a more synchronized supply of nutrients with plant demand (Manjunatha et al., 2016). As a result, plants are able to access essential nutrients more efficiently throughout their growth stages, improving nutrient use efficiency and reducing nutrient losses.

The development of nano-coated biofertilizers has accelerated with rapid progress in nanotechnology, biotechnology, and materials science (Singh & Sayyeda, 2025). Various nano-formulation strategies have been explored to improve the performance of microbial inoculants, including nano-encapsulation, nano-emulsions, polymer-based nano-carriers, and nanocomposite matrices. These technologies are designed to enhance the physical stability, storage life, and field effectiveness of biofertilizer products. By protecting microbial cells from environmental stresses such as ultraviolet radiation, desiccation, temperature fluctuations, and soil toxicity, nano-coating systems significantly improve microbial survival during storage and after application in the field (Guha et al., 2025). Consequently, the biological activity of beneficial microbes can be sustained for longer periods in the rhizosphere.

Another important aspect in the development of nano-coated biofertilizers is the improvement of nutrient delivery systems (Yadav et al., 2023). Nanomaterials possess a high surface area and unique physicochemical properties that allow them to adsorb, retain, and gradually release nutrients. This controlled release mechanism not only improves nutrient availability but also reduces losses through leaching, volatilization, or fixation in the soil. In addition, nanomaterials can facilitate closer interactions between microorganisms, soil particles, and plant roots, enhancing microbial colonization in the rhizosphere (Wang et al., 2023). Such interactions play a critical role in stimulating nutrient transformation processes and promoting plant growth.

Recent research has increasingly emphasized the role of nano-enabled biofertilizers as a key innovation for sustainable agriculture. Nano-coated formulations have been shown to improve microbial performance, enhance nutrient use efficiency, and support plant growth under diverse environmental conditions (Singh et al., 2024). Furthermore, the integration of nanotechnology

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with microbial fertilizers offers opportunities to design advanced delivery systems capable of responding to plant nutrient requirements in a more precise manner. Therefore, nano-coated biofertilizers represent a promising strategy to bridge the gap between biological fertilization and modern precision agriculture, contributing to improved soil health, increased crop productivity, and long-term environmental sustainability (Dabare et al., 2025).

Types of Nanomaterials Used in Biofertilizer Coating

Various nanomaterials have been explored for the development of nano-coated biofertilizers due to their unique physicochemical characteristics that enable controlled nutrient delivery and improved stability of microbial inoculants (Yadav et al., 2023). Among these, metal oxide nanoparticles such as zinc oxide (ZnO), iron oxide (Fe₂O₃/Fe₃O₄), and titanium dioxide (TiO₂) are widely reported in agricultural nanotechnology. These nanoparticles not only function as protective coatings that enhance the survival of beneficial microorganisms during storage and field application, but also act as micronutrient sources that can improve plant metabolic processes (Mgadi et al., 2024). For instance, zinc and iron are essential elements involved in enzymatic activation, chlorophyll synthesis, and photosynthetic efficiency, thereby contributing to improved plant growth and productivity. In nano-coated formulations, these metal oxides may also facilitate gradual nutrient dissolution, enhancing nutrient use efficiency compared with conventional fertilizer systems.

Polymeric nanomaterials represent another important category in biofertilizer coating technologies (Garg et al., 2023). Biopolymers such as chitosan, alginate, and starch-based nanomaterials have gained considerable attention due to their biodegradability, biocompatibility, and ability to form stable nano-encapsulation matrices. These materials can encapsulate microbial cells or bioactive compounds, protecting them from environmental stresses such as ultraviolet radiation, desiccation, and temperature fluctuations during storage and field application. In addition, polymeric nanocarriers enable controlled and sustained release of nutrients and microbial metabolites into the rhizosphere, which may enhance microbial colonization and plant–microbe interactions (Shanmugam et al., 2026). Their biodegradable nature ensures minimal environmental accumulation, making them particularly suitable for sustainable agricultural systems and long-term soil health management.

Carbon-based nanomaterials, including carbon nanotubes and graphene derivatives, have also been investigated as potential carriers in biofertilizer delivery systems (Ayanda et al., 2024). These materials possess exceptionally high surface area, strong adsorption capacity, and remarkable mechanical strength, which can facilitate the immobilization of nutrients and microbial cells within nano-structured matrices. Furthermore, carbon-based nanomaterials may enhance root–microbe interactions by improving nutrient retention in the rhizosphere and promoting more efficient nutrient transfer to plants. However, despite their promising functional properties, the environmental behavior and potential ecotoxicological risks of some carbon nanomaterials remain a subject of ongoing investigation. Therefore, careful consideration of material selection, dosage, and environmental compatibility is essential when designing nano-coated biofertilizer systems.

Overall, the effectiveness of nano-coated biofertilizers largely depends on the physicochemical properties of the selected nanomaterials, including particle size, surface charge, biodegradability, and interaction with soil components. A balanced design that combines nutrient delivery efficiency, microbial protection, and environmental safety is critical to ensure that nano-enabled biofertilizers can contribute to sustainable soil management and enhanced crop productivity.

Microbial Agents in Nano-Coated Biofertilizers

Beneficial microorganisms constitute the fundamental biological component of nano-coated biofertilizers, as they mediate essential biochemical processes that enhance soil fertility and plant productivity (Hasan et al., 2024). These microbial agents primarily include nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and plant growth-promoting rhizobacteria (PGPR), all of which play critical roles in nutrient transformation and rhizosphere functioning. By integrating these microorganisms with nanomaterial-based coatings, biofertilizer formulations can achieve improved microbial stability, enhanced nutrient delivery, and greater functional efficiency under field conditions (Ray et al., 2025).

Nitrogen-fixing bacteria such as *Azotobacter*, *Azospirillum*, and *Rhizobium* are among the most widely utilized microbial inoculants in biofertilizer technologies due to their capacity to convert atmospheric nitrogen (N₂) into plant-available forms such as ammonium through biological nitrogen fixation (Aasfar et al 2021). This process significantly reduces dependency on synthetic nitrogen fertilizers while improving soil nitrogen dynamics. In nano-coated biofertilizer systems, nanomaterials can serve as protective matrices that enhance the survival and viability of nitrogen-fixing bacteria during storage and soil application (Yadav et al., 2023). The nano-encapsulation process may also facilitate gradual release and targeted delivery of microbial cells to the rhizosphere, thereby improving colonization efficiency and nitrogen fixation activity.

Phosphate-solubilizing bacteria (PSB) represent another important group of microorganisms commonly incorporated into biofertilizer formulations (Soumare et al., 2020). These microbes are capable of converting insoluble phosphorus compounds, such as calcium phosphate and iron phosphate, into plant-available forms through the secretion of organic acids and phosphatase enzymes. In nano-coated systems, nanomaterials may enhance the functional performance of PSB by stabilizing microbial cells and increasing their persistence in soil environments that are often characterized by fluctuating moisture, temperature, and pH

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conditions. Moreover, nano-carriers can improve the spatial distribution of microbial inoculants in the rhizosphere, which may enhance phosphorus mobilization and nutrient uptake by plant roots (Kant et al., 2025).

Plant growth-promoting rhizobacteria (PGPR) further contribute to plant development through multiple direct and indirect mechanisms, including the production of phytohormones (such as indole-3-acetic acid), siderophores, and various hydrolytic enzymes that stimulate root growth and enhance nutrient acquisition (Vocciante et al., 2022). PGPR can also improve plant tolerance to abiotic stresses by modulating plant physiological responses and promoting beneficial microbial interactions in the rhizosphere (Khan et al., 2021). When integrated with nanomaterial-based coatings, the functional activity of PGPR can be enhanced due to improved microbial protection, prolonged viability, and more efficient colonization of plant root systems.

Overall, the synergistic integration of beneficial microorganisms with nanomaterials represents a promising strategy to improve the performance of biofertilizers in sustainable agricultural systems. Nano-coated biofertilizers can enhance microbial survival, optimize nutrient transformation processes, and strengthen plant–microbe interactions in the rhizosphere. Consequently, this integrated approach has significant potential to improve soil health, increase nutrient use efficiency, and enhance crop productivity while reducing reliance on synthetic agrochemical inputs.

Mechanisms of Nano-Coated Biofertilizers in Soil and Plant Systems

Controlled Nutrient Release and Nutrient Use Efficiency

One of the most significant advantages of nano-coated biofertilizers lies in their ability to regulate nutrient release in a controlled and sustained manner. Conventional fertilizers typically release nutrients rapidly after application, often exceeding the immediate uptake capacity of plants (Ashitha & Rakhimol, 2021). This rapid release frequently leads to substantial nutrient losses through leaching, volatilization, runoff, or fixation within the soil matrix. In contrast, nano-coating technologies utilize nanostructured carriers or encapsulation materials that enable gradual nutrient diffusion into the surrounding soil environment. The nanoscale structure provides a large surface area and controlled permeability, allowing nutrients to be released slowly and consistently (Guo et al., 2018). As a result, nano-coated biofertilizers ensure a prolonged nutrient supply that aligns more closely with the physiological requirements of crops during different growth stages.

Controlled nutrient release plays a critical role in improving nutrient use efficiency (NUE) in agricultural systems (Guo et al., 2018). By synchronizing nutrient availability with plant demand, nano-coated formulations reduce nutrient wastage and enhance the ability of plant roots to absorb essential elements. This synchronization ensures that nutrients remain available in the rhizosphere during critical periods of plant growth, such as root establishment, vegetative development, and reproductive stages. Additionally, the gradual release mechanism helps maintain stable nutrient concentrations in the soil solution, preventing sudden nutrient surges that could disrupt plant metabolic processes. Improved nutrient use efficiency not only enhances plant growth and biomass accumulation but also contributes to higher crop yields and better overall crop performance (Govindasamy et al., 2023).

Nanomaterials used in biofertilizer coatings can also improve nutrient retention and mobility in soil systems (Garg et al., 2023). Due to their high adsorption capacity and reactive surface properties, nanocarriers can bind nutrients and release them progressively under specific environmental conditions, such as changes in soil moisture, pH, or microbial activity. In some cases, nanomaterials may also facilitate improved interactions between nutrients and plant roots by enhancing nutrient transport across the rhizosphere interface (Wang et al., 2023). These mechanisms contribute to improved nutrient availability and reduced nutrient fixation in soils that typically limit nutrient accessibility, particularly phosphorus in highly weathered or calcareous soils.

Nano-based nutrient delivery systems provide important environmental benefits by reducing the negative impacts associated with excessive fertilizer use. Conventional fertilization practices often contribute to groundwater contamination, eutrophication of water bodies, and greenhouse gas emissions due to inefficient nutrient management (Ashitha & Rakhimol, 2021). By minimizing nutrient losses through controlled release and improved uptake efficiency, nano-coated biofertilizers help mitigate these environmental risks. Reduced nutrient runoff and lower fertilizer application rates contribute to more sustainable nutrient management practices, supporting both agricultural productivity and environmental protection (Shah & Wu, 2019). Consequently, nano-coated biofertilizers represent a promising approach for enhancing nutrient efficiency while promoting environmentally responsible farming systems.

Enhancement of Soil Microbial Activity and Soil Health

Nano-coated biofertilizers can significantly enhance soil microbial activity by creating a favorable microenvironment for beneficial microorganisms within the soil matrix (Das et al., 2025). The nano-coating acts as a protective barrier that shields microbial cells from environmental stresses such as desiccation, temperature fluctuations, ultraviolet radiation, and toxic soil compounds. This protection helps maintain microbial viability and metabolic activity during storage and after field application. As a result, beneficial microbes are better able to establish themselves in the rhizosphere, where they perform critical ecological functions. The sustained activity of these microorganisms promotes essential biological processes such as nitrogen fixation, phosphorus solubilization, and organic matter mineralization, all of which contribute to improved nutrient availability for plants (Timofeeva et al., 2023).

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Enhanced microbial activity also has important implications for soil structure and overall soil fertility. Many soil microorganisms produce extracellular polymeric substances and organic binding agents that facilitate the aggregation of soil particles (Ali et al., 2024). These aggregates improve soil structure by increasing porosity, water infiltration, and water-holding capacity. Improved aggregation also enhances soil aeration, which is essential for root respiration and microbial metabolism. In addition, active microbial populations accelerate the decomposition of organic residues, releasing nutrients that can be readily absorbed by plants (Shahbaz et al., 2024). Through these mechanisms, nano-coated biofertilizers indirectly improve soil physical and chemical properties, thereby supporting healthier and more productive soil systems.

Another key advantage of nano-coated biofertilizers is their ability to promote microbial colonization and interactions within the rhizosphere (Singh & Sayyeda, 2025). Nanomaterials often possess high surface area and reactive properties that facilitate the attachment of microbial cells to soil particles and plant roots. This enhanced microbial colonization strengthens plant–microbe interactions, leading to improved nutrient uptake and plant growth promotion. Moreover, stable microbial communities can suppress soil-borne pathogens through competitive exclusion, production of antimicrobial compounds, and induction of plant defense responses (Liu et al., 2021). These biological interactions contribute to a more resilient soil ecosystem capable of supporting sustainable agricultural production.

Furthermore, active and diverse microbial communities play a central role in maintaining soil ecosystem stability and long-term soil health. Soil microorganisms regulate biogeochemical cycles and contribute to the maintenance of soil fertility over time (Basu et al., 2021). By promoting microbial diversity and sustained biological activity, nano-coated biofertilizers help maintain the functional balance of soil ecosystems. This balance is crucial for preventing soil degradation, enhancing soil resilience to environmental stresses, and ensuring sustainable crop production (Shah & Wu, 2019). Consequently, the use of nano-coated biofertilizers represents an important strategy for strengthening soil biological processes and supporting the long-term sustainability of agricultural systems.

Plant Growth Promotion and Physiological Responses

Nano-coated biofertilizers can enhance plant growth through multiple physiological and biochemical mechanisms that operate at the root–soil interface. Beneficial microorganisms incorporated within these formulations, such as plant growth–promoting rhizobacteria (PGPR), are capable of producing a range of phytohormones including indole-3-acetic acid (IAA), gibberellins, and cytokinins (Basu et al., 2021). These plant hormones play crucial roles in regulating plant development by stimulating cell division, cell elongation, and differentiation. The production of such growth regulators promotes the formation of a more extensive root system, characterized by increased root length, root surface area, and root hair density. A well-developed root architecture enhances the plant’s ability to explore a larger soil volume, thereby improving water and nutrient acquisition and ultimately increasing plant vigor (Tao et al., 2024).

In addition to hormonal stimulation, nano-coated biofertilizers improve plant growth by enhancing nutrient uptake efficiency in the rhizosphere. Nanomaterials used as carriers or coatings often possess high surface area and reactive properties that facilitate nutrient adsorption and controlled release (Guo et al., 2018). This process maintains a steady supply of essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients in the root zone. Improved nutrient availability directly influences key physiological processes within plants, including chlorophyll synthesis, photosynthetic efficiency, and enzymatic activity. Enhanced photosynthetic performance leads to greater carbohydrate production and energy availability, which supports increased biomass accumulation and improved crop productivity (Croce et al., 2024).

The synergistic interaction between nanoparticles, beneficial microorganisms, and plant roots further stimulates various metabolic pathways involved in plant growth and development. Nanoparticles can enhance microbial colonization in the rhizosphere, allowing beneficial microbes to more effectively interact with plant roots (Kibbey & Strevett 2019). These interactions can trigger signaling pathways that regulate nutrient transport, hormone balance, and gene expression associated with plant growth. Additionally, microbial metabolites such as siderophores, organic acids, and enzymes can improve nutrient solubilization and uptake, particularly for nutrients that are otherwise poorly available in soil environments (Pattnaik et al., 2021).

Nano-coated biofertilizers can strengthen plant physiological performance by stimulating plant defense mechanisms and improving stress resilience. The presence of beneficial microbes and nanomaterials can activate plant antioxidant systems and induce systemic resistance responses that protect plants against environmental stress and pathogens (Yu et al., 2022). Increased activity of antioxidant enzymes helps mitigate oxidative damage caused by abiotic stresses such as drought, salinity, and temperature extremes (Mishra et al., 2023). Consequently, plants treated with nano-coated biofertilizers often exhibit improved physiological stability, enhanced growth performance, and higher yields under both optimal and challenging environmental conditions.

Improved Plant Tolerance to Abiotic Stress

Abiotic stresses such as salinity, drought, extreme temperatures, and nutrient deficiencies are among the most significant factors limiting global crop productivity. These environmental constraints disrupt plant physiological processes, reduce nutrient uptake, and induce oxidative stress that damages cellular structures (Xie et al., 2019). In recent years, nano-coated biofertilizers

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have emerged as a promising strategy to enhance plant tolerance to abiotic stress while maintaining sustainable agricultural productivity. The combination of beneficial microorganisms with nanostructured carriers enables improved plant-soil interactions and more efficient nutrient delivery. Beneficial microbes present in nano-coated biofertilizers, including plant growth-promoting rhizobacteria, can stimulate the production of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase (Akhtar et al., 2022). These enzymes play a crucial role in scavenging reactive oxygen species generated under stress conditions, thereby protecting plant cells from oxidative damage and maintaining physiological stability.

Nanomaterials used in biofertilizer coatings further contribute to plant stress tolerance by improving soil physical and chemical properties (Karunakaran et al., 2024). Due to their high surface area and adsorption capacity, nanomaterials can enhance soil moisture retention and regulate nutrient availability in the rhizosphere. Improved water-holding capacity is particularly important under drought or salinity stress, as it allows plants to maintain cellular hydration and metabolic activity. Additionally, controlled nutrient release from nano-coated formulations ensures a steady supply of essential elements such as nitrogen, phosphorus, and micronutrients during critical growth stages (Ashgar et al & Kazerooni, 2024). This stable nutrient availability helps plants sustain photosynthesis, chlorophyll production, and energy metabolism even under unfavorable environmental conditions.

Another important mechanism by which nano-coated biofertilizers improve stress tolerance is through the stimulation of root growth and rhizosphere activity. Beneficial microorganisms produce phytohormones such as indole-3-acetic acid that promote root elongation and branching, allowing plants to access water and nutrients from deeper soil layers (Egamberdieva et al., 2017). A more extensive root system enhances the plant's capacity to adapt to fluctuating environmental conditions and increases overall resource use efficiency. Furthermore, the synergistic interaction between nanomaterials, microorganisms, and plant roots strengthens plant defense systems and supports metabolic adjustments under stress (Sodhi et al., 2025). Through these integrated mechanisms, nano-coated biofertilizers represent an innovative and sustainable approach for improving crop resilience to abiotic stress, ultimately contributing to stable crop production in the face of climate change and environmental challenges.

Applications of Nano-Coated Biofertilizers in Crop Production

Applications in Major Agricultural Crops

Nano-coated biofertilizers have increasingly been applied in major cereal crops such as rice (*Oryza sativa*), wheat (*Triticum aestivum*), and maize (*Zea mays*), which represent the primary staple food sources in many regions of the world (Hasan et al., 2025). These crops typically require high nutrient inputs, particularly nitrogen and phosphorus, to sustain optimal growth and yield. However, conventional fertilization practices often suffer from low nutrient use efficiency due to losses through leaching, volatilization, and fixation in the soil. The application of nano-coated biofertilizers offers a promising alternative by improving nutrient delivery efficiency and enhancing the functional performance of beneficial microbial inoculants (Akhtar et al., 2022).

In cereal cropping systems, nano-coated microbial formulations can enhance biological nitrogen fixation and phosphorus solubilization processes in the rhizosphere. The nano-coating matrix provides a protective microenvironment that helps maintain microbial viability during storage and field application, while also enabling gradual release of microbial cells and nutrients into the root zone (Guha et al., 2025). This controlled release mechanism improves microbial colonization of plant roots and promotes sustained nutrient transformation processes in the soil. As a result, plants can access nutrients more efficiently throughout their growth stages, which contributes to improved vegetative development and grain formation (Shrivastav et al., 2020).

Several studies have reported that the use of nano-enabled biofertilizers in cereal crops can lead to enhanced root architecture, increased chlorophyll content, and improved nutrient uptake efficiency (Singh et al., 2025). These physiological improvements ultimately translate into higher biomass accumulation and increased grain yield. In addition, the integration of nanomaterials with microbial inoculants may help stabilize soil microbial activity and support beneficial plant-microbe interactions within the rhizosphere, thereby contributing to long-term soil fertility (Ahmad & Ahmad, 2024).

Overall, the integration of nano-coated biofertilizers into cereal production systems represents a promising strategy for improving crop productivity while simultaneously reducing the environmental impacts associated with excessive chemical fertilizer use. By enhancing nutrient use efficiency and promoting sustainable soil management, nano-enabled biofertilizers can play a significant role in supporting the transition toward more sustainable and resource-efficient agricultural systems.

Environmental Benefits and Sustainability Implications

Reduction of Chemical Fertilizer Dependency

The excessive application of chemical fertilizers in modern agriculture has contributed to a range of environmental challenges, including soil degradation, nutrient imbalance, and contamination of water bodies through leaching and runoff (Hossain et al., 2022). In many intensive cropping systems, only a fraction of applied nutrients is effectively absorbed by plants, while the remaining portion is lost to the environment. This inefficiency not only increases production costs but also accelerates ecological degradation (Huesemann, 2024). In this context, nano-coated biofertilizers have emerged as a promising strategy to reduce the dependency on synthetic fertilizers while maintaining agricultural productivity.

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Nano-coated biofertilizers improve nutrient use efficiency by integrating beneficial microorganisms with nanomaterial-based delivery systems that facilitate controlled nutrient release and enhanced microbial stability (Singh & Sayyeda 2025). The nano-coating matrix protects microbial inoculants from environmental stresses and allows gradual release of nutrients and microbial metabolites into the rhizosphere (Guha et al., 2025). As a result, biological processes such as nitrogen fixation, phosphorus solubilization, and organic nutrient mineralization can occur more effectively, increasing the availability of essential nutrients for plant uptake.

Furthermore, the improved interaction between plant roots, beneficial microorganisms, and nano-enabled carriers enhances nutrient acquisition efficiency throughout different plant growth stages. This synergistic interaction can reduce the need for high fertilizer application rates while maintaining optimal crop growth and productivity (Shah & Wu, 2019). By improving the efficiency of nutrient cycling in the soil–plant system, nano-coated biofertilizers help minimize nutrient losses and reduce the environmental footprint associated with intensive fertilization practices (Avilla et al., 2022).

Overall, the integration of nano-coated biofertilizers into agricultural management systems represents an important step toward sustainable nutrient management. By lowering reliance on chemical fertilizers and improving nutrient use efficiency, these technologies contribute to environmentally friendly farming practices while supporting long-term soil health and agricultural sustainability.

Contribution to Soil Health and Ecosystem Stability

Nano-coated biofertilizers play an important role in enhancing soil health and maintaining ecosystem stability within agricultural systems (Basavegowda & Baek, 2021). Soil health is closely linked to the biological, chemical, and physical properties of soil, all of which influence nutrient availability and plant productivity (Usharani et al., 2019). The introduction of beneficial microorganisms through nano-coated biofertilizer formulations can significantly stimulate soil biological activity, leading to improved nutrient cycling and enhanced soil fertility.

Beneficial microorganisms delivered through nano-coated systems, including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and plant growth-promoting rhizobacteria, contribute to the transformation of nutrients into plant-available forms (Singh et al., 2013). The nano-coating matrix not only protects microbial inoculants from environmental stresses but also enables a more controlled release and prolonged survival of these microorganisms in the soil environment (Guha et al., 2025). As a result, microbial activity in the rhizosphere can be sustained over longer periods, which enhances nutrient turnover and promotes more efficient plant–microbe interactions.

In addition to improving nutrient dynamics, increased microbial diversity and activity can strengthen soil ecosystem resilience. Diverse microbial communities contribute to the stabilization of soil organic matter, improved soil aggregation, and enhanced soil structure (Lin et al., 2019). These processes help increase the soil's capacity to retain water and nutrients while reducing the risk of nutrient losses through leaching or erosion (Bashagaluke et al., 2018). Consequently, soils with active and diverse microbial communities are better able to support stable and productive cropping systems under varying environmental conditions.

Furthermore, the integration of nano-enabled biofertilizers into soil management practices may support the restoration of degraded soils by promoting beneficial microbial colonization and improving biological soil functions. By strengthening nutrient cycling processes and enhancing the biological integrity of soil ecosystems, nano-coated biofertilizers contribute to long-term agricultural sustainability and ecosystem stability.

Challenges and Future Perspectives

Technical and Production Challenges

Despite the promising potential of nano-coated biofertilizers in sustainable agriculture, several technical and production challenges still hinder their large-scale implementation. One of the major limitations lies in the complexity of formulation processes required to integrate living microbial inoculants with nanomaterial-based carriers (Shabir et al., 2026). Maintaining microbial viability during nano-encapsulation, storage, and field application remains a critical challenge, as microorganisms are highly sensitive to environmental stresses such as temperature fluctuations, desiccation, ultraviolet radiation, and oxidative conditions. Ensuring that nanomaterials provide adequate protection without negatively affecting microbial metabolic activity is therefore a key consideration in the design of effective nano-coated biofertilizer formulations.

Another technical challenge involves achieving stable nano-formulations with consistent physicochemical properties, including particle size distribution, surface charge, and coating stability. Variations in these parameters can influence the release behavior of nutrients and microbial cells, which ultimately affects the performance of the biofertilizer in the soil environment (Schütz et al., 2018). Additionally, interactions between nanomaterials, soil components, and microbial cells can be complex and may alter the stability or effectiveness of the formulation under field conditions.

From a production perspective, the large-scale manufacturing of nanomaterials and nano-encapsulation systems can be costly and technologically demanding. The synthesis of high-quality nanomaterials often requires specialized equipment, controlled

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reaction conditions, and additional purification steps, which can increase production costs and limit accessibility for agricultural applications (Osman et al., 2024). Consequently, the economic feasibility of nano-coated biofertilizers remains a significant barrier to widespread adoption, particularly for smallholder farming systems.

Current research efforts are therefore focused on developing more cost-effective and scalable production methods, including the use of biodegradable biopolymers, green synthesis approaches for nanomaterials, and simplified nano-encapsulation techniques. Improving formulation stability while reducing production costs will be essential to facilitate the commercialization and practical implementation of nano-coated biofertilizers in sustainable agricultural systems.

Future Research Directions

Future research on nano-coated biofertilizers should prioritize the development of environmentally friendly and biodegradable nanomaterials that are compatible with soil ecosystems. Although various nanomaterials have demonstrated promising functionality in enhancing nutrient delivery and microbial stability, concerns regarding long-term environmental persistence and potential ecological impacts remain. Therefore, the design of green nanomaterials derived from natural polymers or bio-based sources represents an important direction for improving the environmental safety of nano-enabled biofertilizer technologies.

Another key research priority involves optimizing microbial formulations to maximize the functional efficiency of beneficial microorganisms within nano-coated systems. Advances in nanotechnology may enable the development of intelligent or responsive delivery systems capable of releasing nutrients and microbial inoculants in response to plant physiological signals or soil environmental conditions. Such smart delivery systems could significantly improve nutrient use efficiency by synchronizing nutrient availability with plant growth stages and metabolic demands.

Further investigation is also required to better understand the complex interactions among nanomaterials, microbial communities, plant root systems, and soil components. These interactions occur primarily within the rhizosphere, where biochemical and microbiological processes regulate nutrient cycling and plant growth. Comprehensive studies integrating molecular biology, soil microbiology, and nanomaterial characterization are therefore necessary to elucidate the mechanisms governing nano-biofertilizer performance under different environmental conditions, including variations in soil type, climate, and crop species.

In addition, more long-term field trials are needed to evaluate the agronomic effectiveness, environmental safety, and economic feasibility of nano-coated biofertilizers under real agricultural conditions. Most existing studies remain limited to laboratory or greenhouse experiments, which may not fully represent field-scale variability. Expanding field-based research will be crucial to validate the practical applicability of these technologies and to support their large-scale adoption by farmers.

Ultimately, the integration of nanotechnology with microbial-based fertilization strategies holds significant potential to transform sustainable agricultural practices. By enhancing nutrient efficiency, improving soil biological functions, and reducing reliance on synthetic fertilizers, nano-coated biofertilizers may contribute to more resilient agricultural systems and support global food security in the face of increasing environmental and population pressures.

CONCLUSION

Nano-coated biofertilizers represent a promising technological advancement in sustainable agriculture by integrating nanomaterials with beneficial microbial inoculants to improve nutrient delivery and soil biological functions. Evidence from the reviewed studies indicates that diverse nanomaterials-including metal-based nanoparticles, polymeric nanocarriers, and nano-structured nutrient carriers-can enhance microbial stability, regulate nutrient release, and improve nutrient use efficiency. These mechanisms contribute to improved soil microbial activity, enhanced nutrient cycling, and reduced nutrient losses, thereby supporting healthier and more resilient soil ecosystems.

At the plant level, nano-enabled biofertilizer systems have demonstrated significant potential to enhance root development, nutrient uptake, stress tolerance, and crop productivity across various agricultural crops. Moreover, their ability to reduce dependency on chemical fertilizers highlights their relevance for environmentally sustainable nutrient management. Despite these advantages, challenges related to formulation stability, production scalability, and environmental safety remain important considerations. Future research should therefore focus on environmentally friendly nanomaterials, deeper understanding of nano-microbe-plant interactions, and long-term field validation to ensure safe and effective implementation. Overall, nano-coated biofertilizers hold substantial potential to support climate-resilient agriculture, improve soil health, and contribute to global food security.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to check typographical errors and improve sentence structure. The authors subsequently reviewed and edited the generated suggestions and take full responsibility for the content of the published article.

Data availability

No datasets were generated or analysed during the current study

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