



Modern Nano-Fertilizer Delivery Systems and Nano-Biofertilizers: Advances, Mechanisms, and Sustainable Applications in Climate-Smart Agriculture: A Comprehensive Review

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ABSTRACT

The rapid intensification of agriculture has resulted in an increased reliance on chemical fertilizers, leading to poor nutrient use efficiency, environmental deterioration, and declining soil quality. In response to these challenges, Nanofertilizers act as an innovative solution at the intersection of nanotechnology and biological nutrient management, providing a sustainable and precision-based applied practices. These innovative formulations combine beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing microbes, potassium-mobilizing organisms, and plant growth-promoting rhizobacteria with engineered nanomaterials. This integration enhances nutrient stability, improves their availability, and enables more precise delivery to plants. Contemporary nano-fertilizer delivery systems utilize a wide range of nanocarriers, including polymeric nanoparticles, nano-emulsions, mesoporous silica particles, chitosan- and alginate-based nanocomposites, nano-hydrogels, layered double hydroxides, magnetic nanoparticles, and stimuli-responsive smart delivery systems. These platforms enable controlled, gradual, and site-specific nutrient release governed by soil pH, moisture levels, enzymatic activity, and root exudates, thereby aligning nutrient availability with the physiological needs of crops. Compared to traditional fertilizers, such systems effectively reduce nutrient losses caused by leaching, volatilization, and runoff, resulting in improved nutrient use efficiency.

Recent studies indicate that the encapsulation of nutrients and microbial inoculants within biodegradable nanocarriers enhances microbial survival under challenging soil conditions and supports sustained colonization in the rhizosphere. This review provides a comprehensive overview of recent advancements in nano-fertilizer delivery mechanisms, formulation strategies, interactions among plants, nanomaterials, and microorganisms, as well as agronomic performance and sustainability outcomes. It also addresses existing limitations, regulatory considerations, and future research priorities required for the successful large-scale adoption of nano-enabled nutrient delivery systems.

The significance of this review lies in its systematic integration of emerging knowledge on nano-biofertilizer technologies, offering valuable insights for researchers, policymakers, and agricultural practitioners. It highlights the potential of these advanced systems to enhance crop productivity, improve soil health, and reduce environmental impacts, thereby supporting the transition toward climate-resilient and sustainable agricultural practices.

Keywords: Nanobiofertilizers, Smart Nanocarriers, Sustainable Agrofarming.

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Introduction

Agriculture worldwide is under growing strain as it must both feed an expanding population and reduce the environmental damage caused by heavy reliance on agrochemicals. With the global population expected to reach around 9.7 billion by 2050, food production will need to rise by roughly 50–70% to satisfy future nutritional needs [1].

Achieving this target under current farming paradigms remains difficult due to diminishing natural resources, climate variability, declining soil fertility, and escalating environmental pollution.

Conventional agricultural systems rely heavily on synthetic chemical fertilizers to enhance crop productivity; however, their inefficient utilization represents a major constraint to sustainability.

It is estimated that more than 40–60% of applied nitrogen and phosphorus fertilizers are lost through leaching, surface runoff, denitrification, and volatilization before plant uptake occurs [5,6]. These nutrient losses contribute significantly to groundwater contamination, eutrophication of aquatic ecosystems, soil acidification, and increased emissions of greenhouse gases such as nitrous oxide, one of the most potent contributors to climate change [8,9]. Consequently, low nutrient use efficiency (NUE) has emerged as a critical bottleneck in modern agriculture, threatening long-term soil health, microbial diversity, and agroecosystem resilience [12].

In recent years, sustainable nutrient management strategies have increasingly emphasized biological and nanotechnological interventions as viable alternatives to conventional fertilization practices. Biofertilizers enriched with nitrogen-fixing bacteria, phosphate- and potassium-solubilizing microbes, and plant growth-promoting rhizobacteria (PGPR) have been shown to support nutrient cycling, enhance soil fertility, and promote plant development through natural biological processes [10]. However, their widespread field application is often constrained by poor shelf life, limited survival under harsh soil conditions, inconsistent field performance, and reduced colonization efficiency in the rhizosphere.

To address these limitations, the integration of nanotechnology with biofertilizer science has given rise to nano-biofertilizers as an advanced approach to nutrient delivery. These formulations combine beneficial microbial inoculants with nanoscale carriers that protect both microbial cells and nutrients while enabling their controlled and targeted release within soil–plant systems. The distinctive physicochemical characteristics of nanomaterials—such as high surface area, strong adsorption capacity, improved solubility, and adjustable surface properties—allow for more precise nutrient delivery, ensuring that nutrient availability is closely aligned with the physiological requirements of plants [7].

Smart Nanocarriers:

Smart nanocarriers have emerged as an advanced and efficient strategy for biofertilizer delivery, enabling precise regulation of nutrient release and microbial activity within soil–plant systems. These carriers are typically engineered from stimuli-responsive materials that respond to environmental cues such as pH, temperature, moisture, enzymatic activity, and root exudates, thereby ensuring site-specific and timely delivery of nutrients and beneficial microorganisms [2,34]. By encapsulating microbial inoculants within nanoscale matrices, smart nanocarriers protect them from environmental stresses and enhance their survival, activity, and functional efficiency in the rhizosphere [17,20].

Furthermore, these systems significantly improve nutrient use efficiency by synchronizing nutrient release with plant demand, reducing losses caused by leaching, volatilization, and runoff [9,15]. Materials such as chitosan nanoparticles, mesoporous silica, nano-hydrogels, and layered double hydroxides have demonstrated strong potential in developing controlled and responsive delivery platforms [17,25]. In addition, smart nanocarriers enhance plant growth by improving root colonization, stimulating beneficial plant–microbe interactions, and increasing tolerance to abiotic stresses [4,17]. Although these technologies show strong potential, issues such as elevated production costs, difficulties in large-scale implementation, possible environmental impacts, and regulatory hurdles need to be resolved before they can be widely adopted.

Overall, smart biofertilizer systems based on nanocarriers offer a promising step forward in advancing precision farming and promoting sustainable crop production.

Modern nano-fertilizer delivery systems employ a diverse range of nanocarriers such as polymeric nanoparticles, nano-hydrogels, nano-emulsions, mesoporous silica nanoparticles, layered double hydroxides, magnetic nanoparticles, and biodegradable chitosan–alginate nanocomposites [3,4]. These delivery platforms facilitate slow, sustained, and stimuli-responsive nutrient release regulated by environmental triggers including soil pH, moisture, enzymatic activity, and root exudates. Such precision-based nutrient management significantly enhances NUE, reduces fertilizer input requirements, and minimizes nutrient losses to the environment. Addressing these knowledge gaps is essential to enable the safe and scalable adoption of nano-biofertilizers within climate-smart and precision agriculture frameworks [2]. Therefore, a comprehensive understanding of modern nano-fertilizer delivery mechanisms, plant–microbe–nanomaterial interactions, and sustainability implications is critical for translating laboratory-scale innovations into practical field-level solutions.

Beyond their direct effects on crop performance, nano-biofertilizers align closely with the core goals of sustainable agriculture, including environmental protection, efficient resource use, and the preservation of long-term soil health. By decreasing reliance on chemical fertilizers, minimizing nutrient losses through volatilization and leaching, and encouraging beneficial interactions between plants and microorganisms, these systems help lower greenhouse gas emissions, enhance water quality, and improve soil fertility. Recent studies further indicate that nanotechnology-supported nutrient management can substantially reduce the amount of fertilizer required while maintaining or even increasing yields, supporting global efforts toward climate resilience and environmentally sustainable farming practices.

Nano-Biofertilizer Formulations

Nano-biofertilizer formulations mark an important progression in modern nutrient management by combining the principles of nanotechnology with biological fertilization to improve nutrient stability, delivery, and microbial survival in agricultural environments. Traditional biofertilizers often face limitations such as limited shelf life, reduced viability of microbial inoculants, and inadequate nutrient retention in field conditions, which restrict their overall effectiveness. The use of nanocarriers along with biodegradable coating materials helps overcome these drawbacks by protecting beneficial microorganisms and ensuring a controlled and site-specific release of nutrients within the rhizosphere [17]. These advanced formulations enhance nutrient use efficiency by reducing losses through leaching, volatilization, and soil immobilization, while also promoting consistent microbial activity and stronger root–microbe interactions [18]. Consequently, nano-biofertilizers are emerging as a vital component of precision and sustainable agriculture, providing improved crop performance along with reduced environmental impact compared to conventional fertilizer systems.

Nanocarrier systems and coating materials are crucial in defining the efficiency and behavior of nano-biofertilizer formulations. Biodegradable and biocompatible polymers such as chitosan, cellulose, alginate, gelatin, and polyvinyl alcohol (PVA) are commonly employed to encapsulate nutrients and beneficial microorganisms due to their non-toxic properties,

strong water-holding capacity, and responsiveness to soil conditions [21]. These substances create nano- or micro-scale protective matrices that enclose nutrients and microbial inoculants, safeguarding them from environmental stresses like ultraviolet radiation, drying, extreme pH levels, and competition from native soil microorganisms. Among these materials, chitosan and alginate are particularly valued for their excellent film-forming characteristics, biodegradability, and favorable interactions with plant roots, which support improved nutrient absorption and microbial establishment. Additionally, such polymer-based systems can be designed to respond to variations in pH or moisture, enabling the gradual and controlled release of nutrients based on soil conditions, root activity, and environmental changes [22]. This targeted release aligns nutrient availability with plant requirements and plays a vital role in reducing nutrient losses, especially in both rainfed and irrigated farming systems where leaching and runoff significantly impact fertilizer efficiency.

Encapsulating microbial inoculants within nanoparticle-based coatings significantly enhances their storage stability and survival under field conditions by shielding them from temperature variations, oxidative damage, and moisture loss. After application to the soil, the slow breakdown of the nano polymer matrix enables the controlled release of active microbial cells near the plant root zone. This targeted delivery promotes quick colonization of the rhizosphere and supports the effective establishment of beneficial plant-microbe interactions [3,4]. Furthermore, nano-encapsulation improves the metabolic performance and overall functional efficiency of beneficial microorganisms by creating a protective microenvironment enriched with moisture and essential nutrients. This supportive environment not only stimulates microbial growth but also enhances enzymatic activity, leading to more effective nutrient transformation and availability in the soil. In addition, the encapsulation matrix helps maintain cell viability over extended periods, reduces environmental stress, and ensures a gradual release of active microbes in the rhizosphere. It also promotes better root colonization and strengthens plant-microbe interactions, ultimately contributing to improved soil fertility and plant health [16,17]. For example, phosphate-solubilizing bacteria encapsulated within chitosan or alginate matrices have demonstrated a significantly greater capacity to solubilize phosphorus compared to their free-living forms, leading to enhanced phosphorus availability and improved uptake by crops. Likewise, nano-encapsulated nitrogen-fixing bacteria exhibit higher nitrogen fixation efficiency as a result of improved survival, sustained activity, and better establishment in the rhizosphere. Additionally, the incorporation of nanoparticles can increase root permeability and stimulate the release of root exudates, thereby strengthening plant-microbe interactions and facilitating more efficient nutrient acquisition.

The significance of nano-encapsulated biofertilizers lies in their ability to provide a controlled and sustained delivery of both nutrients and beneficial microorganisms, ensuring their availability in synchrony with plant demand. This approach not only enhances nutrient use efficiency and crop productivity but also reduces dependency on chemical fertilizers, minimizes environmental losses, and supports long-term soil health. Consequently, nano-encapsulated biofertilizers represent a promising and sustainable strategy for improving agricultural productivity while maintaining ecological balance [9].

Efficiency of Nutrient Delivery:

Nano-biofertilizers improve the efficiency of nutrient delivery through a combination of interconnected physicochemical and biological processes that address the shortcomings of conventional fertilizers. One of the central mechanisms is the controlled and site-specific release of nutrients. In this approach, nutrients are encapsulated within nanoscale carriers that gradually release them in the rhizosphere in response to environmental cues such as soil moisture, pH, and root exudates. This regulated release ensures better synchronization between nutrient availability and plant demand, thereby reducing excessive fertilizer application and improving nutrient use efficiency (NUE) as well as overall crop performance. Studies have also demonstrated that nano-formulated micronutrients, including zinc, manganese, and molybdenum, enhance nutrient accumulation in plant tissues such as leaves and grains, indicating superior uptake and internal utilization compared to traditional fertilizers.

In addition to improved delivery, nano-biofertilizers interact actively with the soil microbiome, playing a significant role in nutrient cycling and soil health. Nanoparticles and carrier materials provide a protective and supportive microenvironment for beneficial microorganisms, including nitrogen-fixing and phosphate-solubilizing bacteria, which enhances their survival and metabolic activity in soil. These interactions stimulate key biological processes such as nutrient mineralization and organic matter decomposition, ultimately increasing nutrient availability for plant uptake. The combined action of nanomaterials and microbes extends nutrient transformation processes beyond the immediate root zone, contributing to a more active and balanced soil ecosystem.

Although excessive concentrations of certain nanomaterials may influence microbial diversity, carefully designed nano-biofertilizer systems—particularly those based on biodegradable polymers like chitosan—have been shown to support beneficial microbial communities without causing harmful environmental effects. Overall, the integration of controlled nutrient release, enhanced plant uptake, and stimulated microbial activity leads to significantly improved nutrient use efficiency. These systems also reduce nutrient losses and can increase crop yields even at lower application rates, making them a more sustainable, cost-effective, and environmentally friendly alternative to conventional fertilization practices [20].

Sustainability of Nano-biofertilizer:

The sustainability benefits of nano-biofertilizers largely stem from their ability to limit nutrient losses and lessen the environmental damage linked to traditional fertilizer use. The overuse and inefficient application of synthetic fertilizers often lead to nutrient runoff and leaching into surface and groundwater, which in turn contributes to problems such as eutrophication, oxygen-depleted aquatic zones, soil deterioration, and increased emissions of greenhouse gases like nitrous oxide. In contrast, recent research indicates that nano-enabled fertilizer systems can significantly reduce these negative effects by improving nutrient retention within the root zone and increasing the efficiency of nutrient uptake by plants [14,23,27]

Nano-biofertilizers employ controlled- and slow-release mechanisms that regulate nutrient diffusion based on plant demand, soil moisture, and rhizosphere activity.

This targeted delivery significantly reduces nitrogen and phosphorus losses through volatilization, denitrification, and deep percolation compared with conventional fertilizers [10,18]. It has been reported that nano-fertilizer-based nutrient management can reduce nutrient runoff and leaching by up to 30–50%, thereby lowering contamination risks to freshwater and marine ecosystems [20]. Improved nutrient efficiency also contributes to reduced fertilizer application rates, which in turn decreases the accumulation of excess salts and heavy metals in agricultural soils.

In addition to reducing nutrient losses, nano-biofertilizers play a significant role in promoting environmental sustainability by decreasing the carbon footprint linked to fertilizer production and utilization. Their ability to deliver nutrients efficiently and reduce the need for frequent applications helps lower energy consumption associated with manufacturing, packaging, transportation, and repeated field use [11,16]. Furthermore, by aligning nutrient release more closely with crop uptake, nano-biofertilizers help reduce the emission of nitrous oxide one of the most powerful greenhouse gases associated with agriculture—thereby contributing to efforts aimed at mitigating global climate change [23,25].

Nano-biofertilizers also promote improved soil ecological balance by sustaining beneficial microbial populations and reducing chemical stress on soil biota. Enhanced microbial diversity and enzymatic activity improve soil structure, nutrient cycling efficiency, and long-term soil fertility, which are essential components of regenerative and climate-resilient agricultural systems [22,12]. Collectively, these environmental benefits position nano-biofertilizers as a promising technology for advancing sustainable intensification while safeguarding soil and water resources.

Conclusion

Nano-biofertilizers represent a transformative advancement in plant nutrition and sustainable agricultural management by effectively integrating the precision of nanotechnology with the functional efficiency of beneficial microbial inoculants. This review comprehensively demonstrates that nano-biofertilizer formulations, developed using advanced nanocarriers and biodegradable polymeric matrices, provide controlled, targeted, and stimuli-responsive nutrient delivery while simultaneously enhancing the survival, stability, and metabolic performance of beneficial microorganisms in soil–plant systems. Through these mechanisms, nano-biofertilizers directly overcome the inherent limitations of conventional chemical fertilizers, including low nutrient use efficiency, excessive nutrient losses, inconsistent nutrient availability, and negative environmental externalities. The reviewed evidence suggests that advanced nano-fertilizer delivery systems—such as polymer-based nanoparticles, nano-hydrogels, mesoporous carriers, and bio-derived nanocomposites facilitate the controlled and synchronized release of both macro- and micronutrients in response to dynamic soil factors, including moisture levels, pH variations, enzymatic activity, and root exudates. This targeted synchronization improves nutrient uptake efficiency, enhances root development, and stimulates key physiological and biochemical functions in plants. As a result, crops exhibit increased resilience to abiotic stresses such as drought, salinity, temperature fluctuations, and nutrient limitations.

Moreover, nano-encapsulation plays a crucial role in strengthening interactions between plants and beneficial soil microorganisms in the rhizosphere, thereby promoting processes like biological nitrogen fixation and phosphorus solubilization while contributing to the long-term restoration of soil fertility. Recent studies also highlight that these nano-enabled systems can improve soil structure, increase microbial diversity, and reduce uptake of nutritional requirement, ultimately leading to higher crop productivity with lower environmental impact. Consequently, nano-fertilizer technologies are increasingly recognized as a key component of climate-smart and sustainable agricultural practices. From a sustainability perspective, nano-biofertilizers contribute substantially to environmentally responsible agriculture by reducing fertilizer input requirements, minimizing nutrient runoff and leaching, lowering greenhouse gas emissions, and improving soil biological health. Their compatibility with precision agriculture, climate-smart farming, and regenerative agriculture frameworks positions nano-biofertilizers as a strategic tool for achieving sustainable intensification while safeguarding soil and water resources. Moreover, recent advancements in green synthesis methods and biodegradable nanomaterials further enhance their environmental safety and long-term applicability. Despite their considerable potential, the large-scale adoption of nano-biofertilizers requires continued research focused on formulation optimization, field-level validation across diverse agroclimatic conditions, comprehensive biosafety assessment, economic feasibility, and the development of harmonized regulatory guidelines. Addressing these challenges through interdisciplinary collaboration among agronomists, nanotechnologists, soil scientists, policymakers, and industry stakeholders will be critical for translating laboratory innovations into practical agricultural solutions.

In conclusion, nano-biofertilizers emerge as next-generation nutrient delivery systems capable of supporting high crop productivity, improving nutrient use efficiency, and advancing environmental sustainability. Their integration into modern agricultural practices offers a promising pathway toward resilient, resource-efficient, and climate-adaptive food production systems necessary to meet the nutritional demands of a growing global population under the pressures of climate change and declining soil health.

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