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Nano-Biofertilizers: The Next Generation of Sustainable Crop Nutrition

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INTRODUCTION

Agriculture plays a vital role in ensuring global food security, but rapid population growth, shrinking cultivable land, climate change, and declining soil fertility have increased the need for sustainable crop production. Although chemical fertilizers have greatly improved agricultural productivity, their excessive use has led to nutrient imbalance, soil degradation, environmental pollution, and reduced fertilizer use efficiency. To address these challenges, Nano-Biofertilizers have emerged as an innovative and eco-friendly solution. They combine the benefits of nanotechnology with beneficial microorganisms to enhance nutrient availability, improve nutrient use efficiency, promote healthy plant growth, reduce dependence on chemical fertilizers, and support sustainable agriculture while protecting the environment.

2. Definition of Nano-Biofertilizers

Nano-biofertilizers are advanced fertilizer formulations that combine beneficial microorganisms with nanomaterials to improve nutrient availability and plant growth. In these formulations, microbes are encapsulated, coated, or associated with nanoparticles, which protect them from environmental stress, increase their shelf life, and enhance their efficiency in the soil. The nanoparticles act as carriers for the controlled and targeted release of nutrients, resulting in higher nutrient use efficiency and reduced losses. Nano-biofertilizers promote sustainable agriculture by improving soil fertility, stimulating beneficial microbial activity, reducing dependence on chemical fertilizers, increasing crop productivity, and minimizing environmental pollution.

Simple Definition

Nano-biofertilizers are eco-friendly fertilizers that combine beneficial microorganisms with nanoparticles to provide efficient nutrient supply, improve soil health, and enhance crop growth and productivity.

3. Concept of Nano-Biofertilizers

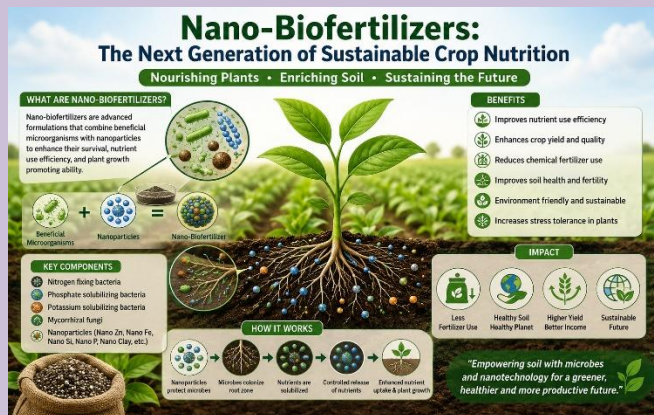
Nano-biofertilizers integrate two modern agricultural technologies:

A. Nanotechnology

Nanotechnology involves the manipulation and application of materials with dimensions ranging from 1–100 nanometers (nm). Nanoparticles possess a high surface area, enhanced reactivity, and unique physicochemical properties that enable controlled nutrient release, improved penetration into plant tissues, greater nutrient absorption, and increased nutrient use efficiency, thereby supporting sustainable crop production and environmental protection.

B. Biofertilizers

Biofertilizers are formulations containing living beneficial microorganisms that improve soil fertility and plant nutrition. These microbes help in fixing atmospheric nitrogen, solubilizing phosphorus and potassium, and producing plant growth-promoting substances such as hormones and vitamins. They enhance nutrient availability and uptake in crops while maintaining soil health. Common examples include Rhizobium, Azotobacter, Azospirillum, phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), cyanobacteria, and mycorrhizal fungi. Biofertilizers are eco-friendly inputs that reduce dependence on chemical fertilizers and support sustainable agriculture.



4. Components of Nano-Biofertilizers

A. Beneficial Microorganisms

Nitrogen Fixing Bacteria

Nitrogen-fixing bacteria are beneficial microorganisms that convert atmospheric nitrogen into plant-available forms such as ammonia. Important examples include Rhizobium, Azotobacter, and Azospirillum. These bacteria enhance soil fertility, promote plant growth, and significantly reduce the requirement of chemical nitrogen fertilizers, thereby supporting sustainable and eco-friendly agricultural production systems.

Phosphate Solubilizing Bacteria (PSB)

Phosphate Solubilizing Bacteria (PSB) are beneficial microorganisms that convert insoluble forms of phosphorus into plant-available forms, thereby improving soil fertility and nutrient uptake. Important examples include Bacillus spp. and Pseudomonas spp.. They enhance root growth, increase phosphorus use efficiency, and support sustainable crop production with reduced chemical fertilizer dependence.

Potassium Solubilizing Bacteria (KSB)

Potassium Solubilizing Bacteria (KSB) are beneficial microorganisms that release potassium from insoluble soil minerals and make it available to plants. They improve potassium nutrition, enhance enzyme activity, and support plant growth. KSB also increase nutrient use efficiency and reduce dependence on chemical fertilizers, promoting sustainable and eco-friendly agricultural systems.

Zinc Solubilizing Bacteria

Zinc Solubilizing Bacteria (ZSB) are beneficial microorganisms that convert insoluble zinc compounds in soil into plant-available forms. They increase zinc availability in the rhizosphere, improve micronutrient nutrition, and enhance plant growth and productivity. ZSB also help correct zinc deficiency in crops, supporting sustainable and balanced soil fertility management systems.

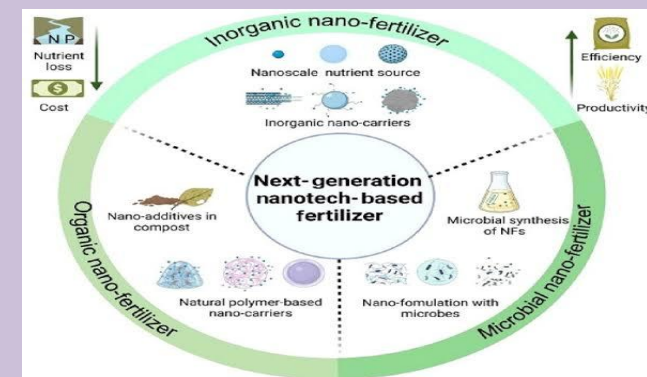
Mycorrhizal Fungi

Mycorrhizal fungi are beneficial symbiotic microorganisms that associate with plant roots. They increase the effective root surface area, enhance uptake of phosphorus and other nutrients, and improve plant water absorption. These fungi also help plants tolerate drought and stress conditions, thereby promoting better growth, soil health, and sustainable crop production.

B. Nanoparticles

Nanoparticles are ultra-small materials (1–100 nm) used in agriculture to enhance nutrient delivery and efficiency. Common examples include nano urea, nano zinc oxide, nano iron oxide, nano silica, nano hydroxyapatite, nano clay, and chitosan nanoparticles. They improve nutrient availability, reduce losses, and

promote sustainable and precision crop nutrition systems.



Source: <https://link.springer.com/>

5. Types of Nano-Biofertilizers

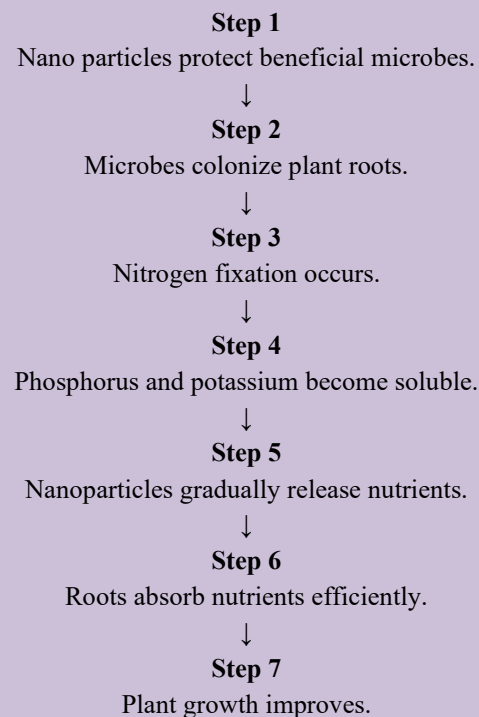
1. Nitrogen Nano-Biofertilizers

Nitrogen nano-biofertilizers contain nitrogen-fixing bacteria along with nano nitrogen carriers that enhance nitrogen availability to plants. They improve biological nitrogen fixation, ensure slow and efficient nitrogen release, and reduce nitrogen losses through leaching and volatilization. These fertilizers increase nitrogen use efficiency and support sustainable crop production with lower chemical fertilizer dependency.

2. Phosphorus Nano-Biofertilizers

Phosphorus nano-biofertilizers contain phosphate-solubilizing bacteria along with nano phosphorus formulations. They enhance the conversion of insoluble phosphorus into plant-available forms and reduce phosphorus fixation in soil. These systems improve phosphorus use efficiency, promote root development, and support better crop growth and productivity while ensuring sustainable soil fertility management.

7. Mechanism of Action



8. Role of Nanoparticles in Biofertilizers

Nanoparticles play a vital role in biofertilizers by protecting microorganisms from environmental stress and improving their survival. They ensure controlled nutrient release, enhance root penetration, and increase nutrient mobility in soil. Nanoparticles also reduce nutrient losses and significantly improve fertilizer efficiency, leading to better crop growth and sustainable agricultural productivity.

9. Benefits of Nano-Biofertilizers

Nano-biofertilizers improve nutrient use efficiency by releasing nutrients slowly according to crop demand, thereby reducing fertilizer requirements by 25–50%. They enhance crop yield through better nutrient

availability and stimulate root growth via microbial hormones. These fertilizers improve soil fertility by increasing organic matter decomposition, microbial activity, and nutrient cycling. They also protect the environment by reducing nitrate leaching, water pollution, and greenhouse gas emissions. Nano-biofertilizers enhance plant stress tolerance against drought, salinity, heat, and heavy metals. They improve nutrient uptake of N, P, K, Zn, and Fe, and ultimately enhance crop quality, including protein, vitamin, grain, and fruit quality.

10. Advantages of Nano-Biofertilizers

Nano-biofertilizers are eco-friendly, biodegradable, and sustainable agricultural inputs that enhance nutrient use efficiency and reduce dependence on chemical fertilizers. They improve soil health, microbial survival, and ensure controlled and targeted nutrient release with a longer shelf life. These fertilizers are cost-effective and minimize environmental pollution such as nitrate leaching and greenhouse gas emissions. They are highly suitable for precision agriculture and organic farming systems. Overall, nano-biofertilizers promote higher crop productivity, better nutrient management, and long-term sustainable agricultural development.

11. Limitations

Nano-biofertilizers have several limitations despite their advantages. High production cost and lack of large-scale manufacturing facilities restrict their wide adoption. Farmer awareness and trained manpower are limited, along with regulatory challenges and the need for standardized formulations. Storage under extreme environmental conditions can reduce effectiveness. Long-term field studies are still limited,

and performance may vary across different soil types. Improper use may also lead to potential nanoparticle toxicity. Therefore, careful management and further research are required for safe and effective application.

12. Applications in Different Crops

Nano-biofertilizers are widely applied in different crop groups for improving productivity and nutrient efficiency. In cereals such as rice, wheat, and maize, they enhance grain yield and nitrogen use efficiency. In pulses like chickpea, lentil, and pigeon pea, they promote nodulation and biological nitrogen fixation. Oilseeds such as mustard, soybean, and groundnut show improved oil content and phosphorus uptake. Fruit crops including mango, banana, and citrus exhibit better fruit quality and shelf life. Vegetables like tomato, potato, onion, and brinjal gain higher productivity and nutrient content. Plantation crops such as tea, coffee, and sugarcane benefit from improved nutrient efficiency and increased biomass production.

13. Environmental Importance

Nano-biofertilizers play a key role in sustainable agriculture by reducing dependence on chemical fertilizers and lowering greenhouse gas emissions. They help conserve soil biodiversity and improve water quality by minimizing nutrient runoff and leaching. These fertilizers also enhance carbon sequestration in soil and support efficient nutrient cycling. By improving resource use efficiency and reducing environmental pollution, nano-biofertilizers strongly contribute to climate-smart and eco-friendly agricultural production systems for long-term sustainability.

14. Future Prospects

Future developments in nano-biofertilizers include smart systems with sensor-based nutrient release and nano-encapsulated microbial consortia for enhanced efficiency. AI-assisted nutrient management and precision farming integration will optimize fertilizer use. Drone-based application, IoT connectivity, and nano-based seed coatings will further improve delivery systems. Gene-edited microbial inoculants and climate-resilient formulations will enhance adaptability under stress conditions. Personalized nutrient management based on soil health analysis will ensure sustainable, efficient, and highly productive agriculture for future farming systems.

15. Challenges for Commercialization

The commercialization of nano-biofertilizers faces several challenges, including the need for standardized formulations and proper safety assessment of nanoparticles. Large-scale production technologies are still developing, and cost reduction is essential for wider adoption. Quality control, shelf-life improvement, and regulatory approvals remain major concerns. Farmer training and awareness are limited, while public acceptance is still evolving. Additionally, environmental risk assessment is necessary to ensure safe use. Overcoming these challenges is crucial for successful commercialization and sustainable agricultural integration of nano-biofertilizers

16. Comparison Between Chemical Fertilizers, Biofertilizers, and Nano-Biofertilizers

Feature	Chemical Fertilizers	Biofertilizers	Nano-Biofertilizers
Nutrient Source	Synthetic chemicals	Beneficial microorganisms	Nanoparticles + microorganisms
Nutrient Release	Rapid	Gradual	Controlled and targeted
Nutrient Use Efficiency	Moderate	High	Very High
Environmental Impact	High	Low	Very Low
Soil Health	May degrade soil	Improves soil	Greatly improves soil
Microbial Activity	Reduces microbial diversity	Enhances microbial activity	Protects and enhances microbes
Nutrient Loss	High	Moderate	Low
Cost	Moderate	Low	Initially higher
Sustainability	Low	High	Very High
Crop Productivity	High	Moderate	High with improved efficiency

CONCLUSION

Nano-biofertilizers represent a revolutionary advancement in sustainable crop nutrition by combining nanotechnology with beneficial

microorganisms. They improve nutrient use efficiency, enhance soil fertility, and increase crop productivity while reducing environmental pollution through controlled nutrient release. These inputs reduce dependence on chemical fertilizers, support soil biodiversity, and improve plant resilience to abiotic stresses, making them highly suitable for climate-smart and precision agriculture. Despite challenges such as high production cost, regulatory issues, and limited adoption, continued research and innovation will promote their commercialization and ensure sustainable agricultural development and food security for future generations.