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Next-Generation Biofertilizers for Sustainable Nutrient Management

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INTRODUCTION

Agriculture is facing the dual challenge of increasing food production while conserving natural resources and minimizing environmental degradation. The intensive use of chemical fertilizers has undoubtedly improved crop yields, but excessive fertilizer application has reduced soil biodiversity, lowered nutrient use efficiency, increased production costs, and contributed to climate change.

According to the Food and Agriculture Organization (FAO), nearly half of the applied nitrogen fertilizer is lost through leaching, volatilization, denitrification, or runoff before plants can utilize it. These nutrient losses not only reduce fertilizer efficiency but also cause eutrophication of water bodies and greenhouse gas emissions.

Biofertilizers have emerged as an environmentally friendly alternative by utilizing beneficial microorganisms capable of fixing atmospheric nitrogen, solubilizing phosphorus and potassium, producing plant growth regulators, and enhancing nutrient uptake. Recent advances in molecular biology, microbial ecology, genomics, and nanotechnology have led to the development of next-generation biofertilizers, which offer improved efficiency, stability, and field performance.

2. Concept of Next-Generation Biofertilizers

Next-generation biofertilizers are advanced microbial formulations developed using modern biotechnology to enhance nutrient availability, promote plant growth, improve soil health, and support environmental sustainability. Unlike conventional biofertilizers, which typically contain a single microbial strain, these innovative products combine multiple beneficial microorganisms with advanced delivery technologies for greater efficiency and consistency.

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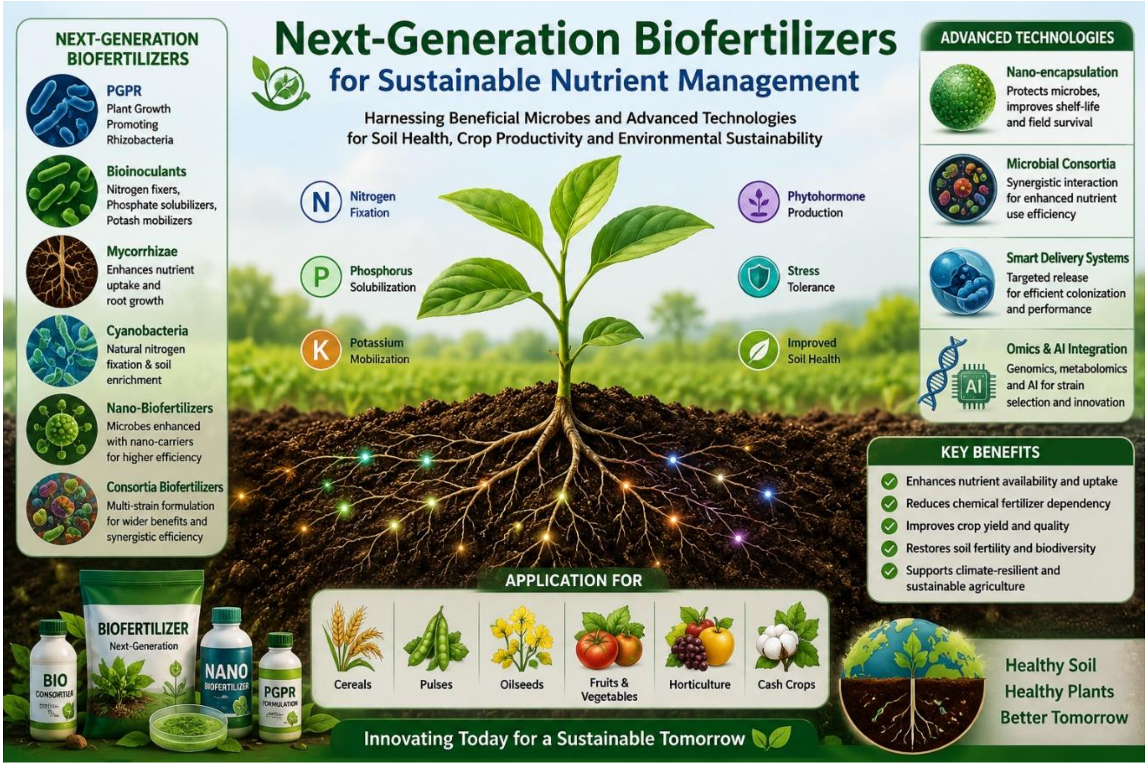
They often include multi-strain microbial consortia, engineered beneficial microorganisms, endophytic microbes, nanocarrier-based formulations, stress-tolerant microbial inoculants, and smart controlled-release microbial systems. These biofertilizers exhibit improved shelf life, enhanced survival under diverse environmental conditions, superior root colonization, and higher nutrient-use efficiency, making them an essential component of sustainable and climate-smart agricultural production systems.



3. Need for Next-Generation Biofertilizers

Several limitations of traditional biofertilizers have encouraged the development of advanced formulations.

Major needs include:

- Improving nutrient use efficiency
- Reducing dependence on chemical fertilizers
- Enhancing microbial survival under stress
- Increasing crop productivity
- Restoring degraded soils
- Improving soil microbial diversity
- Reducing greenhouse gas emissions
- Supporting climate-smart agriculture
- Promoting regenerative farming systems
- Achieving Sustainable Development Goals (SDGs)

4. Components of Next-Generation Biofertilizers

4.1 Plant Growth-Promoting Rhizobacteria (PGPR)

Plant Growth-Promoting Rhizobacteria (PGPR) are beneficial bacteria that colonize the rhizosphere and enhance plant growth through various biological processes. They improve nutrient availability, stimulate root development, and increase plant tolerance to biotic and abiotic stresses. PGPR promote sustainable agriculture by enhancing nutrient-use efficiency and reducing dependence on chemical fertilizers. Common examples include Azospirillum, Azotobacter, Bacillus, Pseudomonas, and Paenibacillus. These microorganisms are widely used in next-generation biofertilizers because of their multifunctional roles in improving crop productivity and maintaining soil health.

Functions:

- ❖ Nitrogen fixation
- ❖ Phosphate solubilization
- ❖ Potassium mobilization
- ❖ Hormone production
- ❖ Disease suppression

4.2 Endophytic Bacteria

Endophytic bacteria are beneficial microorganisms that live inside plant tissues without causing disease and form a symbiotic relationship with their host. They promote plant growth by improving nutrient absorption, producing phytohormones, and enhancing tolerance to environmental stresses such as drought and salinity. Endophytes also strengthen plant defense mechanisms against pathogens, leading to improved disease resistance and increased biomass production. Common examples include Herbaspirillum, Burkholderia, and Enterobacter, which are increasingly incorporated into next-generation biofertilizers for sustainable crop production and soil health improvement.

4.3 Mycorrhizal Fungi

Arbuscular Mycorrhizal Fungi (AMF) are beneficial fungi that form symbiotic associations with plant roots, improving nutrient and water uptake. They extend the root system through an extensive network of hyphae, enhancing the absorption of phosphorus, zinc, and other essential micronutrients. AMF also improve water absorption, increase drought tolerance, and enhance soil structure by promoting soil aggregation. Common examples include Glomus, Rhizophagus, and Funneliformis. These fungi are key components of next-generation biofertilizers for sustainable nutrient management and resilient crop production.

4.4 Phosphate Solubilizing Microorganisms (PSM)

Phosphate Solubilizing Microorganisms (PSM) are beneficial microbes that convert insoluble phosphorus compounds in the soil into plant-available forms, thereby improving phosphorus nutrition and crop growth. They enhance phosphorus availability through the production of organic acids, proton release, and the secretion of phosphatase enzymes, which dissolve mineral phosphates and mineralize organic phosphorus. Common examples include Bacillus megaterium, Pseudomonas fluorescens, and Aspergillus niger. PSM are important components of next-generation biofertilizers, increasing phosphorus-use efficiency while reducing dependence on chemical phosphorus fertilizers.

4.5 Potassium Solubilizing Bacteria (KSB)

Potassium Solubilizing Bacteria (KSB) are beneficial microorganisms that release potassium from insoluble silicate minerals and make it available for plant uptake. They produce organic acids and other metabolites that dissolve potassium-bearing minerals, thereby improving potassium availability in the soil. Enhanced potassium nutrition supports plant growth, enzyme activation, photosynthesis, water regulation, and stress tolerance. Common examples include Bacillus mucilaginosus and Frateuria aurantia. KSB are important components of next-generation biofertilizers, helping to improve potassium-use efficiency and reduce reliance on chemical potassium fertilizers.

4.6 Zinc Solubilizing Bacteria

Zinc Solubilizing Bacteria (ZSB) are beneficial microorganisms that enhance the availability of zinc by converting insoluble zinc compounds into soluble forms that can be readily absorbed by plants. They produce organic acids and chelating compounds that increase zinc solubility in the rhizosphere. Improved zinc nutrition promotes enzyme activity, chlorophyll synthesis, protein production, and overall plant growth. Common examples include Pseudomonas and Bacillus species. These bacteria are valuable components of next-generation biofertilizers, improving micronutrient-use efficiency and supporting sustainable crop production.

4.7 Cyanobacteria

Cyanobacteria, also known as blue-green algae, are photosynthetic microorganisms widely used as biofertilizers, particularly in rice cultivation. They improve soil fertility by fixing atmospheric nitrogen, thereby reducing the need for synthetic nitrogen fertilizers. In addition, they contribute to organic matter production, enhance soil aggregation, and improve soil structure and water-holding capacity. Cyanobacteria also stimulate beneficial microbial activity and support sustainable nutrient cycling. Common examples include Anabaena and Nostoc, which play a significant role in eco-friendly and sustainable agricultural systems.

5. Advanced Technologies in Next-Generation Biofertilizers

5.1 Microbial Consortia

Microbial consortia are advanced biofertilizer formulations that contain compatible groups of beneficial microorganisms instead of a single microbial strain. These microbial communities work synergistically to enhance plant growth and nutrient availability. They facilitate multiple nutrient mobilization, including nitrogen fixation and phosphorus and potassium solubilization, resulting in improved nutrient-use efficiency. Microbial consortia also ensure better root colonization, enhance plant tolerance to abiotic stresses such as drought and salinity, and provide more consistent field performance, making them a key component of next-generation biofertilizers.

5.2 Genomics and Metagenomics

Genomics and metagenomics are advanced molecular tools used to identify and characterize beneficial microorganisms with superior nutrient-mobilizing abilities. Genome sequencing helps discover genes responsible for nitrogen fixation, phosphorus solubilization, stress tolerance, and plant growth promotion. Metagenomics enables comprehensive analysis of the soil microbiome without the need for culturing microorganisms. These technologies support microbial selection, functional gene identification, soil microbiome analysis, and the development of efficient biofertilizer inoculants, thereby enhancing the effectiveness and reliability of next-generation biofertilizers for sustainable agriculture.

5.3 Synthetic Biology

Synthetic biology applies advanced genetic engineering techniques to modify microbial metabolic pathways for improved nutrient acquisition and plant growth promotion. It enables the development of beneficial microorganisms with enhanced functional traits, making biofertilizers more efficient and reliable. Potential applications include improved biological nitrogen fixation, enhanced phosphorus solubilization, increased production of phytohormones such as indole-3-acetic acid (IAA), and controlled microbial behavior for targeted nutrient delivery. These innovations contribute to higher nutrient-use efficiency, sustainable crop productivity, and climate-resilient agricultural systems.

5.4 Nanotechnology

Nanotechnology enhances the performance of next-generation biofertilizers by using nanocarriers to protect beneficial microorganisms from adverse environmental conditions such as heat, desiccation, and ultraviolet radiation. These nanocarriers improve microbial stability and ensure efficient delivery of nutrients to plants. Major advantages include controlled release of microorganisms and nutrients, longer shelf life, higher microbial survival during storage and field application, and enhanced nutrient delivery. Consequently, nanotechnology increases biofertilizer efficiency, nutrient-use efficiency, and crop productivity while supporting sustainable agriculture.

5.5 Encapsulation Technology

Encapsulation technology is an advanced technique in which beneficial microbial cells are enclosed within biodegradable polymer matrices to protect them from environmental stresses and improve their viability. Common encapsulating materials include alginate,

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chitosan, gelatin, and **starch**. This technology enhances microbial survival during storage and field application, provides controlled release of microorganisms, extends shelf life, and improves root colonization. As a result, encapsulated biofertilizers exhibit greater stability, higher effectiveness, and more consistent performance, making them valuable components of next-generation biofertilizer formulations.

5.6 Artificial Intelligence (AI)

Artificial Intelligence (AI) enhances the effectiveness of next-generation biofertilizers by analyzing large agricultural and microbial datasets. AI assists in selecting compatible microbial combinations, predicting soil–microbe interactions, optimizing nutrient recommendations based on crop and soil conditions, and enabling precision biofertilizer application. These capabilities improve nutrient-use efficiency, reduce input costs, support site-specific nutrient management, and promote sustainable, climate-smart agriculture through data-driven decision-making and efficient resource utilization.

6. Mechanisms of Nutrient Management

Next-generation biofertilizers improve nutrient management through multiple biological mechanisms.

6.1 Biological Nitrogen Fixation

Biological Nitrogen Fixation (BNF) is a natural process in which nitrogen-fixing microorganisms convert atmospheric nitrogen (N_2) into ammonia, a form that plants can readily utilize. This process enriches soil nitrogen, enhances crop growth, and reduces dependence on synthetic nitrogen fertilizers. It plays a crucial role in sustainable nutrient management and improving soil fertility. Common nitrogen-fixing microorganisms include Rhizobium, which forms symbiotic associations with legumes, and free-living bacteria such as Azotobacter and Azospirillum.

6.2 Phosphorus Solubilization

Phosphorus solubilization is the process by which beneficial microorganisms convert insoluble phosphorus compounds into plant-available forms. These microorganisms produce organic acids that lower soil pH and dissolve mineral phosphates, thereby increasing phosphorus availability for plant uptake. Common organic acids involved in this process include citric acid, gluconic acid, and oxalic acid. Enhanced phosphorus solubilization improves root development, crop growth, and phosphorus-use efficiency while reducing the dependence on chemical phosphorus fertilizers, contributing to sustainable nutrient management.

6.3 Potassium Mobilization

Potassium mobilization is a biological process in which beneficial microorganisms release potassium from insoluble potassium-bearing minerals through the production of organic acids and other metabolites. These compounds dissolve mineral-bound potassium, making it available for plant uptake. Improved potassium availability enhances photosynthesis, enzyme activation, water regulation, and stress tolerance. Potassium-mobilizing microorganisms therefore improve potassium-use efficiency, reduce dependence on chemical fertilizers, and contribute to sustainable nutrient management.

6.4 Micronutrient Solubilization

Micronutrient-solubilizing microorganisms enhance the availability of essential micronutrients by converting insoluble mineral forms into soluble forms that plants can readily absorb. These beneficial microbes improve the uptake of zinc, iron, copper, and manganese through the production of organic acids, chelating compounds, and enzymes. Adequate micronutrient availability supports chlorophyll formation, enzyme activity, protein synthesis, and overall plant growth. This process improves crop productivity, nutrient-use efficiency, and soil fertility while reducing the need for chemical micronutrient fertilizers.

6.5 Production of Plant Growth Regulators

Beneficial microorganisms produce plant growth regulators (phytohormones) that

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stimulate plant growth and development. Important hormones include Indole-3-Acetic Acid (IAA), which promotes root elongation; gibberellins, which stimulate stem growth and seed germination; cytokinins, which encourage cell division and delay leaf senescence; and abscisic acid (ABA), which enhances plant tolerance to drought and other environmental stresses. These microbial phytohormones improve root architecture, nutrient uptake, crop productivity, and overall plant health, supporting sustainable agricultural production.

6.6 Siderophore Production

Siderophores are iron-chelating compounds produced by beneficial microorganisms under iron-deficient conditions. They bind insoluble iron in the soil and convert it into forms that are readily available for plant uptake. By efficiently acquiring iron, siderophores also limit its availability to pathogenic microorganisms, thereby suppressing their growth. This dual function improves plant nutrition, enhances disease resistance, supports healthy plant development, and contributes to sustainable nutrient management.

6.7 ACC Deaminase Production

ACC deaminase is an enzyme produced by certain plant growth-promoting microorganisms that lowers plant ethylene levels by breaking down 1-aminocyclopropane-1-carboxylate (ACC), the precursor of ethylene. Reduced ethylene production minimizes stress-induced growth inhibition, enabling plants to better tolerate drought, salinity, flooding, and heavy metal toxicity. As a result, ACC deaminase-producing microorganisms promote root growth, improve nutrient uptake, enhance crop productivity, and increase resilience under adverse environmental conditions.

7. Applications in Sustainable Nutrient Management

Next-generation biofertilizers have wide applications in sustainable nutrient management across diverse agricultural systems, including cereals, pulses, oilseeds, vegetables, fruits, plantation crops, and medicinal plants. They are also valuable in organic farming, protected cultivation, and precision agriculture due to their ability to enhance nutrient availability, improve crop growth, and maintain soil health. These advanced microbial formulations are integrated with sustainable approaches such **as** Integrated Nutrient Management (INM), Climate-Smart Agriculture (CSA), Conservation Agriculture, Natural Farming, and Organic Agriculture. Their adoption promotes efficient nutrient utilization, reduces chemical fertilizer dependency, and supports environmentally sustainable crop production.

8. Benefits of Next-Generation Biofertilizers

Next-generation biofertilizers provide multiple benefits by improving crop productivity, enhancing soil health, protecting the environment, and increasing economic sustainability. Their advanced microbial formulations promote efficient nutrient cycling, reduce dependency on chemical fertilizers, and support long-term agricultural sustainability.

8.1 Agronomic Benefits

Next-generation biofertilizers enhance crop performance through improved nutrient availability and plant growth promotion. Beneficial microorganisms increase nutrient uptake efficiency, stimulate root development, and improve seed germination. They enhance biological nitrogen fixation, phosphorus solubilization, potassium mobilization, and micronutrient availability, resulting in increased crop yield and higher fertilizer-use efficiency. These biofertilizers also improve plant tolerance against drought, salinity, and other environmental stresses.

8.2 Soil Health Benefits

These advanced microbial formulations contribute significantly to maintaining and restoring soil fertility. They improve soil microbial diversity by increasing beneficial microbial populations and strengthening biological activity. Biofertilizers enhance soil organic carbon accumulation, improve soil structure through better aggregation, and increase soil enzyme activities involved in nutrient cycling. Healthy soil microbial communities support sustainable nutrient availability and improve overall soil productivity.

8.3 Environmental Benefits

Next-generation biofertilizers reduce the environmental impacts associated with excessive chemical fertilizer use. They help lower fertilizer application rates, decrease greenhouse gas emissions, minimize nitrate leaching, and reduce contamination of water resources. By promoting natural nutrient cycling and ecological balance, they contribute to improved ecosystem sustainability and climate-smart agricultural practices.

8.4 Economic Benefits

The use of next-generation biofertilizers reduces input costs by improving fertilizer efficiency and lowering dependence on expensive chemical fertilizers. Enhanced crop productivity and resource-use efficiency contribute to higher farmer income. Their role in sustainable production systems ensures long-term agricultural profitability while maintaining environmental quality and resource conservation.

9. Future Prospects

The future of next-generation biofertilizers is highly promising due to continuous advancements in agricultural biotechnology, microbiome science, and digital technologies. Emerging innovations include AI-guided microbial selection**,** CRISPR-based microbial improvement**,** microbiome engineering, and the development of climate-resilient microbial inoculants. Personalized biofertilizers based on soil microbiome analysis, nano-enabled smart delivery systems, IoT-based precision application, drone-assisted spraying, and integration with digital agriculture platforms will further enhance efficiency. These technologies will support sustainable nutrient management, carbon farming, regenerative agriculture, and climate-resilient food production systems.

CONCLUSION

Next-generation biofertilizers represent a transformative approach to sustainable nutrient management by combining beneficial microorganisms with advanced technologies such as genomics, synthetic biology, nanotechnology, and artificial intelligence. These innovative formulations enhance nutrient availability, improve fertilizer use efficiency, strengthen plant resilience to environmental stresses, and restore soil health while reducing dependence on chemical fertilizers. Their integration into precision agriculture, integrated nutrient management, and climate-smart farming systems can significantly improve agricultural productivity with minimal environmental impact. Although challenges related to shelf life, quality assurance, and field consistency remain, continued research, supportive policies, farmer training, and commercialization of advanced microbial technologies will accelerate their adoption. Ultimately, next-generation biofertilizers will play a pivotal role in achieving resilient, resource-efficient, and environmentally sustainable agricultural systems while ensuring long-term food and nutritional security.

REFERENCES

Arora, P. K., Tripathi, S., Omar, R. A., Chauhan, P., Sinhal, V. K., Singh, A., ... & Singh, V. P. (2024). Next-generation fertilizers: the impact of bionanofertilizers on sustainable agriculture. *Microbial cell factories*, *23*(1), 254.

Karunakaran, A., Fathima, Y., Singh, P., Beniwal, R., Singh, J., & Ramakrishna, W. (2024). Next-generation biofertilizers: nanoparticle-coated plant growth-promoting bacteria biofertilizers for enhancing nutrient uptake and wheat growth. *Agriculture*, *14*(4), 517.

Qadri, T. A., Khan, M. R., Anas, M., Khan, A., Khattak, W. A., Abbas, S., ... &

Abbasi, B. A. (2026). Optimizing Next-Generation Fertilizer Use Through Integrated Green Manure and Reduction Strategies for Sustainable Agriculture. *Next-Generation Fertilizers for Sustainable Agricultural Practices and Food Security*, 297-320.

Shahzad, M., Hayat, R., Mujtaba, G., Rehman, W. U., & Nadeem, M. (2025). Biofertilizers in sustainable agriculture: mechanisms, applications, and future prospects. *Discover Agriculture*, *3*(1), 224.

Swain, S., Sukla, L. B., & Samal, D. K. (2026). Revolutionizing agroecosystems through next-generation bio-nanofertilizers: an overview toward sustainable agriculture. *Nanoscale Advances*, *8*(7), 2138-2158.