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Bio-Organic Fertilizers, Biofertilizers, and Nitrogen-Fixing Biofertilizers (N-Bio Booster) Improve Paddy Productivity: A Narrative Review with SWOT Perspectives

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Abstract

Rice (*Oryza sativa L.*) is the primary staple food for more than half of the global population, making sustainable rice production essential for food security, economic development, and environmental sustainability. Conventional rice cultivation has relied heavily on synthetic fertilizers, particularly nitrogen fertilizers, to maximize grain yield. Although chemical fertilizers have significantly increased rice production over recent decades, their excessive application has contributed to declining soil fertility, nutrient imbalance, greenhouse gas emissions, reduced microbial diversity, water pollution, and increasing production costs. Consequently, bio-organic fertilizers, biofertilizers, and nitrogen-fixing microbial inoculants have emerged as environmentally sustainable alternatives that improve soil health while maintaining or enhancing rice productivity. Bio-organic fertilizers improve soil physical, chemical, and biological properties through organic matter enrichment, whereas biofertilizers containing Plant Growth-Promoting Rhizobacteria (PGPR) enhance nutrient availability, stimulate plant growth, and suppress soil-borne pathogens. Nitrogen-fixing biofertilizers, commonly referred to as N-Bio Boosters, further contribute by biologically converting atmospheric nitrogen into plant-available forms, thereby reducing dependence on synthetic nitrogen fertilizers. Numerous studies have demonstrated that integrated application of bio-organic fertilizers and nitrogen-fixing microorganisms increases rice yield, nutrient use efficiency, root development, microbial activity, and long-term soil fertility while reducing environmental impacts. This narrative review synthesizes current knowledge regarding the mechanisms, agronomic benefits, and practical applications of bio-organic fertilizers, biofertilizers, and N-Bio Booster technologies in rice cultivation. Their advantages and limitations are further evaluated using a Strengths, Weaknesses, Opportunities, and Threats (SWOT) perspective. The review concludes that integrated biological nutrient management represents an important strategy for improving sustainable paddy production while simultaneously supporting environmental conservation, climate resilience, and long-term agricultural productivity.

Keywords: Bio-Organic Fertilizer; Biofertilizer; Nitrogen Fixation; Plant Growth-Promoting Rhizobacteria; Rice Productivity; Sustainable Agriculture

Introduction

Rice (*Oryza sativa L.*) is one of the world's most important cereal crops and serves as the principal source of calories for more than 3.5 billion people worldwide. Approximately 90% of global rice production occurs in Asia, where increasing population growth continues to place substantial pressure on agricultural systems to produce higher yields using increasingly limited land and water resources. Achieving sustainable rice production therefore represents one of the greatest challenges facing modern agriculture because future food security must be balanced with environmental conservation and responsible resource management [1].

The remarkable increase in global rice production during the Green Revolution was largely achieved through improved crop varieties, irrigation systems, mechanization, and intensive application of synthetic fertilizers, particularly nitrogen (N), phosphorus (P), and potassium (K). Among these nutrients, nitrogen remains the primary limiting factor for rice productivity because it is directly involved in chlorophyll formation, photosynthesis, protein synthesis, enzyme activity, and vegetative growth. Consequently, farmers frequently apply large quantities of nitrogen fertilizers to maximize grain yield. However, crop nitrogen use efficiency generally remains below 50%, meaning that a substantial proportion of applied nitrogen is lost through leaching, runoff, denitrification, volatilization, or immobilization. These nutrient losses reduce fertilizer efficiency while contributing to groundwater contamination, eutrophication, greenhouse gas emissions, and soil degradation [2].

Continuous dependence on chemical fertilizers has also altered soil biological properties. Long-term intensive fertilizer application often reduces soil organic matter, decreases microbial diversity, disrupts nutrient cycling, increases soil acidity, and lowers soil structural stability. Such degradation gradually diminishes soil productivity and increases farmers' dependence on even greater fertilizer inputs to maintain crop yields. These environmental and economic concerns have stimulated considerable interest in alternative nutrient management strategies capable of maintaining productivity while restoring soil health [3].

Bio-organic fertilizers have emerged as promising components of sustainable agriculture because they combine organic materials with beneficial microorganisms that enhance nutrient availability and improve soil fertility. Organic amendments derived from compost, manure, crop residues, and other biodegradable materials increase soil organic carbon, improve water retention, enhance soil aggregation, and stimulate beneficial microbial communities. Unlike synthetic fertilizers that primarily provide readily available nutrients, bio-organic fertilizers contribute to long-term improvements in soil quality by supporting biological processes essential for nutrient cycling and ecosystem functioning [4].

Closely related to bio-organic fertilizers are biofertilizers, which contain living microorganisms capable of promoting plant growth through multiple mechanisms. Plant Growth-Promoting Rhizobacteria (PGPR), arbuscular mycorrhizal fungi, phosphate-solubilizing bacteria, potassium-mobilizing bacteria, and nitrogen-fixing microorganisms colonize plant roots and improve nutrient acquisition, stimulate root development, produce phytohormones, suppress plant pathogens, and enhance plant tolerance to environmental stresses. Their multifunctional characteristics distinguish biofertilizers from conventional fertilizers because they improve both plant nutrition and soil biological activity simultaneously [5, 6].

Nitrogen-fixing biofertilizers represent one of the most important groups of beneficial microorganisms used in rice cultivation. Free-living and associative diazotrophic bacteria, including species of *Azospirillum, Azotobacter, Herbaspirillum, Burkholderia,* and several cyanobacteria, possess the nitrogenase enzyme complex that converts atmospheric nitrogen (N_2) into ammonium, a form readily available for plant uptake. This biological nitrogen fixation naturally supplements soil nitrogen while reducing the requirement for synthetic nitrogen fertilizers. Commercial formulations marketed as nitrogen-fixing biofertilizers or "N-Bio Boosters" have therefore gained increasing attention as environmentally friendly technologies for sustainable rice production [7].

Beyond nutrient supply, beneficial microorganisms contribute to improved crop performance through numerous physiological mechanisms. Many PGPR synthesize phytohormones such as indole-3-acetic acid, gibberellins, cytokinins, and abscisic acid that stimulate root elongation, increase nutrient absorption, and improve overall plant vigor. Others produce siderophores that enhance iron availability, solubilize phosphate minerals, produce antimicrobial compounds that suppress plant pathogens, or induce systemic resistance against diseases. These multiple mechanisms explain why biofertilizers frequently improve crop performance beyond their direct contribution to nutrient availability [6].

Numerous field investigations have demonstrated the agronomic potential of integrated nutrient management involving bio-organic fertilizers and biofertilizers. Banayo *et al.,* [8] reported that biofertilizers significantly enhanced irrigated rice yield, particularly when combined with reduced rates of inorganic fertilizers. Similarly, Afify *et al.,* [4] observed that plant growth-promoting rhizobacteria improved onion productivity while reducing chemical fertilizer requirements, illustrating the broad applicability of microbial inoculants across agricultural systems. Khan [7] further emphasized that biofertilizers represent an effective strategy for supplementing inorganic fertilizers while improving nitrogen use efficiency and environmental sustainability. Simarmata *et al.,* [9] likewise demonstrated that integrated application of bioameliorants and biofertilizers improved soil health and increased rice productivity under tropical agricultural conditions.

Despite these promising results, widespread adoption of biofertilizers remains inconsistent. Variability in microbial survival, differences in soil characteristics, climatic conditions, crop management practices, formulation quality, and farmer awareness often influence field performance. Consequently, understanding both the advantages and limitations of bio-organic fertilizers and nitrogen-fixing biofertilizers is essential for maximizing their practical effectiveness in sustainable rice production.

This narrative review aims to synthesize current scientific knowledge regarding the roles of bio-organic fertilizers, biofertilizers, and nitrogen-fixing biofertilizers (N-Bio Booster) in improving paddy productivity. The review further evaluates their agronomic benefits, biological mechanisms, environmental significance, and practical applications while discussing their future potential through Strengths, Weaknesses, Opportunities, and Threats (SWOT) perspectives.

Bio-Organic Fertilizers and Biofertilizers in Rice Production

Bio-organic fertilizers and biofertilizers have become integral components of sustainable rice cultivation because they simultaneously improve soil fertility, enhance nutrient use efficiency, and reduce the environmental impacts associated with intensive chemical fertilizer application. Unlike conventional inorganic fertilizers that primarily supply mineral nutrients, bio-organic fertilizers combine decomposed organic materials with beneficial microorganisms that actively improve soil biological processes (Figure 1). Biofertilizers, on the other hand, consist of living microbial inoculants that colonize the rhizosphere or plant tissues and promote plant growth through multiple biological mechanisms. Together, these biological inputs represent an integrated nutrient management strategy that supports high rice productivity while maintaining long-term soil health and ecosystem sustainability [5, 6].

The importance of bio-organic fertilizers has increased because many rice-growing regions have experienced declining soil fertility following decades of intensive cultivation. Continuous application of synthetic nitrogen, phosphorus, and potassium fertilizers often accelerates the depletion of soil organic matter, disrupts microbial diversity, and weakens soil structure. As soil biological activity declines, nutrient cycling becomes less efficient, resulting in reduced

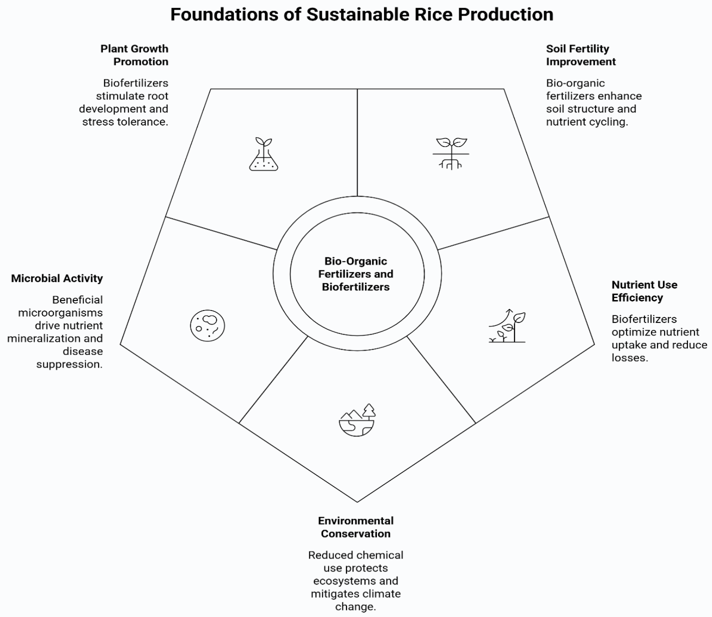

Figure 1: Foundation of sustainable rice production.

fertilizer use efficiency and increasing dependence on external chemical inputs. Incorporating bio-organic fertilizers replenishes soil organic carbon, improves soil aggregation, increases water-holding capacity, enhances cation exchange capacity, and stimulates beneficial microbial communities responsible for nutrient mineralization and organic matter decomposition. These improvements create a healthier soil environment that supports sustainable rice production over multiple cropping seasons [3].

One of the principal mechanisms through which bio-organic fertilizers improve rice productivity is the gradual release of essential nutrients. Organic materials undergo microbial decomposition, allowing nitrogen, phosphorus, potassium, sulphur, and micronutrients to become available progressively throughout crop development. This slow nutrient release minimizes nutrient losses through leaching, volatilization, and surface runoff while improving synchronization between nutrient availability and plant demand. Consequently, rice plants experience a more balanced nutrient supply than is often achieved through large single applications of soluble chemical fertilizers.

In addition to supplying nutrients, bio-organic fertilizers stimulate soil microbial activity. Soil microorganisms play indispensable roles in decomposition, nutrient mineralization, humus formation, biological nitrogen fixation, phosphate solubilization, and suppression of soil-borne pathogens. Increased microbial diversity enhances ecosystem resilience by improving nutrient cycling and maintaining soil ecological balance. Beneficial microorganisms also produce extracellular enzymes that accelerate decomposition of crop residues, thereby increasing nutrient recycling within paddy ecosystems. Healthy microbial communities therefore represent an essential foundation for sustainable rice cultivation.

Biofertilizers complement these functions by introducing selected beneficial microorganisms into the rhizosphere. Among the most widely studied groups are plant growth-promoting rhizobacteria (PGPR), which colonize rice roots and enhance plant growth through numerous physiological mechanisms. Rather than functioning solely as nutrient suppliers, PGPR influence plant development by producing phytohormones such as indole-3-acetic acid, gibberellins, cytokinins, and auxins that stimulate root elongation, lateral root formation, and root hair development. A more extensive root system increases the soil volume explored by plants, thereby improving uptake of water and nutrients while enhancing tolerance to environmental stresses such as drought, salinity, and nutrient deficiency [6].

Another important contribution of biofertilizers involves improving nutrient availability within the rhizosphere. Many phosphate-solubilizing bacteria convert insoluble phosphorus compounds into plant-available forms by secreting organic acids and phosphatase enzymes. Similarly, potassium-solubilizing microorganisms release potassium from silicate minerals, increasing nutrient availability without additional fertilizer application. Iron availability is enhanced through microbial production of siderophores that chelate ferric ions and facilitate plant uptake. These biological processes improve nutrient use efficiency while reducing dependence on synthetic fertilizers.

Biofertilizers also contribute to biological disease management. Many beneficial microorganisms compete with pathogenic fungi and bacteria for nutrients and ecological niches within the rhizosphere. Others produce antibiotics, lytic enzymes, hydrogen cyanide, or antimicrobial peptides that directly inhibit plant pathogens. Certain PGPR induce systemic resistance in rice plants by activating defence pathways before pathogen infection occurs. These mechanisms reduce disease incidence while decreasing the need for chemical pesticides, thereby contributing to more environmentally sustainable rice production systems [5].

Field studies consistently demonstrate that integrated nutrient management involving bio-organic fertilizers and biofertilizers can substantially improve rice productivity. Banayo *et al.,* [8] evaluated biofertilizer application under different fertilizer rates and reported significant improvements in grain yield, particularly when microbial inoculants were combined with reduced rates of inorganic fertilizers. Their findings indicate that biofertilizers can partially substitute

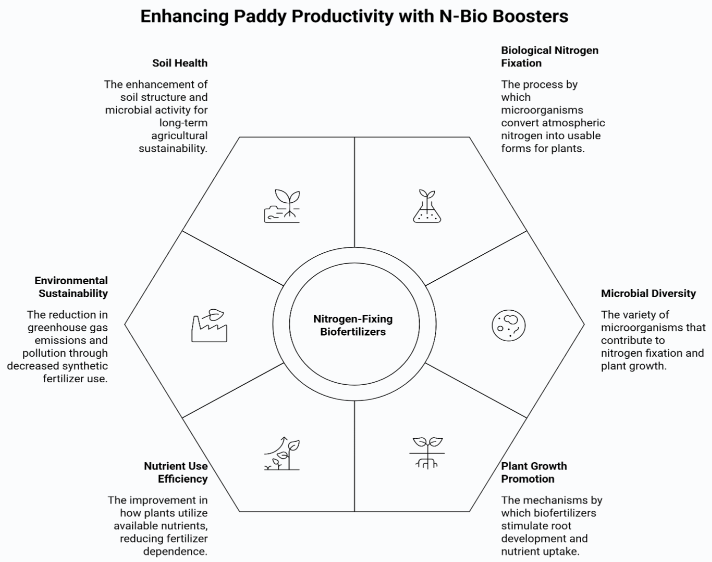

Figure 2: The enhancement of paddy productivity with N-Bio Boosters.

chemical fertilizers while maintaining comparable productivity. Similarly, Khan [7] concluded that biofertilizers should be viewed as supplements rather than complete replacements for mineral fertilizers because integrated nutrient management generally produces the greatest agronomic and economic benefits.

Evidence from other crop species further supports the broad effectiveness of beneficial microorganisms. Afify *et al.,* [4] demonstrated that plant growth-promoting rhizobacteria significantly enhanced onion growth and productivity while reducing the requirement for chemical fertilization. Although conducted on onion rather than rice, the physiological mechanisms responsible for improved nutrient acquisition, hormone production, and root development are common across numerous agricultural crops, supporting the wider applicability of microbial inoculants in sustainable agriculture.

Simarmata *et al.,* [9] similarly demonstrated that combining bioameliorants with biofertilizers improved soil health and rice productivity under tropical agricultural conditions. Improvements in soil biological activity, nutrient cycling, and root development collectively contributed to enhanced crop performance. Their study emphasized that soil restoration should accompany nutrient management because maintaining healthy soil ecosystems is fundamental for achieving long-term agricultural sustainability.

Beyond yield improvement, bio-organic fertilizers contribute significantly to environmental conservation. Reduced dependence on synthetic nitrogen fertilizers lowers greenhouse gas emissions associated with fertilizer manufacture while decreasing nitrate leaching and ammonia volatilization from agricultural fields. Improved soil organic matter also enhances carbon sequestration, contributing to climate change mitigation. Furthermore, increased soil aggregation reduces erosion and sediment loss, thereby protecting adjacent aquatic ecosystems from nutrient enrichment and eutrophication. These environmental benefits align closely with the principles of sustainable agriculture and climate-smart farming promoted by international organizations such as the Food and Agriculture Organization.

Nevertheless, the effectiveness of bio-organic fertilizers and biofertilizers varies considerably among locations because microbial performance is influenced by soil type, pH, temperature, moisture, organic matter content, indigenous microbial communities, and crop management practices. Beneficial microorganisms introduced into one environment may fail to establish successfully in another due to competition with native microbial populations or unsuitable environmental conditions. Consequently, site-specific evaluation remains necessary before recommending large-scale adoption.

Quality control also remains an important challenge for commercial biofertilizer production. The effectiveness of microbial inoculants depends upon maintaining adequate populations of viable microorganisms throughout manufacturing, storage, transportation, and field application. Inappropriate storage temperatures, prolonged shelf life, or poor formulation techniques may substantially reduce microbial viability before products reach farmers. Standardization of production protocols, quality assurance systems, and regulatory guidelines is therefore essential for ensuring consistent field performance.

Overall, accumulated scientific evidence clearly demonstrates that bio-organic fertilizers and biofertilizers represent valuable components of integrated nutrient management for rice cultivation. Their ability to improve soil physical, chemical, and biological properties while simultaneously enhancing nutrient availability, stimulating plant growth, suppressing diseases, and reducing environmental impacts makes them attractive alternatives to exclusive reliance on synthetic fertilizers. Rather than replacing chemical fertilizers entirely, their greatest potential lies in complementing conventional fertilization strategies to achieve high productivity while preserving soil health and environmental quality for future generations.

Nitrogen-Fixing Biofertilizers (N-Bio Booster) and Their Mechanisms in Enhancing Paddy Productivity

Nitrogen is the nutrient required in the largest quantity by rice plants and is often the principal factor limiting paddy productivity. It is indispensable for chlorophyll synthesis, amino acid formation, protein metabolism, nucleic acid synthesis, photosynthesis, and overall plant growth. Modern rice production has therefore become highly dependent on synthetic nitrogen fertilizers such as urea, ammonium sulphate, and ammonium nitrate. Although these fertilizers have contributed substantially to increased global rice production, their inefficient utilization remains a major agronomic and environmental concern. Typically, rice plants absorb only 30-50% of applied nitrogen, while the remainder is lost through ammonia volatilization, nitrate leaching, surface runoff, and denitrification. These losses not only reduce fertilizer efficiency but also contribute to greenhouse gas emissions, eutrophication of aquatic ecosystems, soil acidification, and increasing production costs [2].

To address these challenges, nitrogen-fixing biofertilizers, often referred to as N-Bio Boosters, have emerged as environmentally sustainable alternatives that complement inorganic fertilization while improving nitrogen use efficiency (Figure 2). Unlike chemical fertilizers that directly supply mineral nitrogen, N-Bio Boosters contain living diazotrophic microorganisms capable of converting atmospheric nitrogen (N_2) into ammonium through the biological nitrogen fixation process. This naturally available nitrogen is subsequently utilized by rice plants, thereby reducing dependence on synthetic fertilizers while supporting sustainable crop production [7].

Biological nitrogen fixation is mediated by the nitrogenase enzyme complex, one of the most important enzymatic systems in terrestrial ecosystems. Diazotrophic microorganisms possess the ability to break the strong triple bond of atmospheric nitrogen molecules, converting inert nitrogen gas into biologically available ammonium under ambient environmental conditions. This remarkable biological process represents one of nature's most efficient mechanisms for maintaining the global nitrogen cycle and sustaining agricultural productivity without excessive reliance on industrial nitrogen fertilizers.

Several groups of microorganisms have demonstrated considerable potential as nitrogen-fixing biofertilizers for rice cultivation. Among the most extensively studied are free-living bacteria belonging to the genera Azotobacter, *Azospirillum, Beijerinckia, Herbaspirillum, Burkholderia*, and Gluconacetobacter. In flooded paddy ecosystems, cyanobacteria, commonly known as blue-green algae, and the aquatic fern Azolla containing the symbiotic cyanobacterium Anabaena azollae have also been widely utilized because of their substantial nitrogen-fixing capacities. These microorganisms establish close associations with rice roots or flooded soils, continuously contributing biologically fixed nitrogen throughout the growing season [5].

Among these beneficial microorganisms, *Azospirillum* species have attracted particular attention because they associate closely with cereal crop roots while simultaneously promoting plant growth through multiple mechanisms. Besides nitrogen fixation, *Azospirillum* synthesizes plant growth regulators including indole-3-acetic acid, gibberellins, and cytokinins, which stimulate root elongation, lateral root formation, and root hair proliferation. Improved root architecture increases nutrient and water uptake, enabling rice plants to utilize both soil nutrients and applied fertilizers more efficiently. Consequently, the benefits of N-Bio Boosters extend well beyond biological nitrogen fixation alone.

Similarly, Azotobacter species contribute to rice productivity through multiple physiological pathways. These free-living aerobic bacteria not only fix atmospheric nitrogen but also produce vitamins, amino acids, phytohormones, siderophores, and antimicrobial compounds that enhance plant health. Siderophores improve iron availability by chelating ferric ions within the rhizosphere, whereas antimicrobial metabolites suppress several soil-borne pathogens that adversely affect rice production. These multifunctional characteristics explain why biofertilizers frequently produce greater yield improvements than would be expected solely from their nitrogen contribution.

Nitrogen-fixing biofertilizers also improve nutrient use efficiency by interacting synergistically with other beneficial microorganisms. Phosphate-solubilizing bacteria convert insoluble phosphorus compounds into forms readily available for plant uptake, while potassium-solubilizing bacteria mobilize potassium from soil minerals. Arbuscular mycorrhizal fungi further extend the effective root system through extensive hyphal networks that enhance phosphorus, zinc, copper, and water absorption. Consequently, integrated microbial communities improve overall plant nutrition while reducing the need for multiple chemical fertilizer inputs.

The beneficial effects of N-Bio Boosters are reflected in several aspects of rice growth and development. Numerous studies have reported increased seed germination, greater seedling vigor, enhanced tillering, improved chlorophyll concentration, higher photosynthetic activity, greater biomass accumulation, longer panicles, increased grain filling, and ultimately higher grain yields following application of nitrogen-fixing biofertilizers. Improved physiological performance results from enhanced nutrient availability together with hormonal stimulation and healthier rhizosphere microbial communities.

Field investigations consistently demonstrate the agronomic value of integrating nitrogen-fixing biofertilizers with conventional fertilizer management. Banayo *et al.,* [8] observed that biofertilizer application increased irrigated rice grain yield across several fertilizer regimes, with the greatest benefits occurring when microbial inoculants supplemented rather than completely replaced inorganic fertilizers. Similarly, Khan [7] concluded that biofertilizers should be viewed as complementary technologies capable of improving nitrogen use efficiency while reducing excessive fertilizer dependence. These findings support the concept of integrated nutrient management rather than complete substitution of mineral fertilizers.

Additional evidence is provided by Afify *et al.,* [4], who demonstrated that plant growth-promoting rhizobacteria enhanced onion productivity while reducing chemical fertilizer requirements. Although conducted on onion, the physiological mechanisms involved, including improved nutrient uptake, enhanced root development, and phytohormone production, are directly relevant to rice cultivation because similar PGPR species colonize cereal crop rhizospheres. Likewise, Simarmata *et al.,* [9] reported that bioameliorants combined with biofertilizers improved soil health and increased rice productivity, illustrating the synergistic interactions between soil restoration and microbial inoculation.

Beyond yield improvement, N-Bio Boosters contribute significantly to environmental sustainability. Manufacturing synthetic nitrogen fertilizers requires substantial fossil energy through the Haber–Bosch process and contributes considerably to global carbon dioxide emissions. Reducing synthetic fertilizer consumption therefore lowers both production costs and greenhouse gas emissions. Furthermore, biologically fixed nitrogen is generally released gradually according to microbial activity and plant demand, reducing nitrogen losses through leaching and volatilization compared with conventional fertilizer applications. This improved

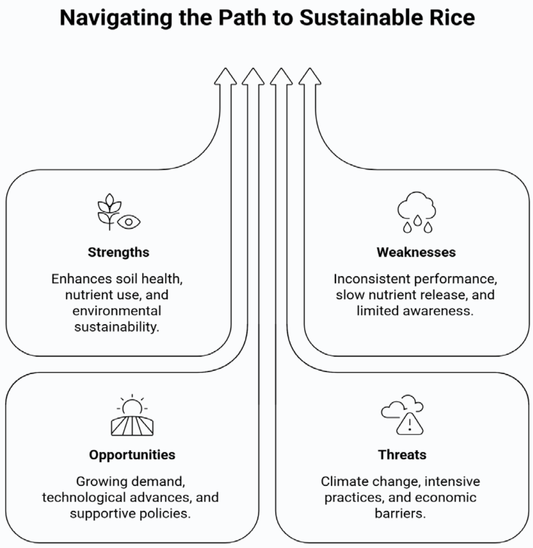

Figure 3: Navigating the path to sustainable rice production with the SWOT perspectives.

synchronization between nitrogen release and plant uptake enhances fertilizer use efficiency while minimizing environmental pollution.

Another important advantage of nitrogen-fixing biofertilizers is their contribution to long-term soil health. Continuous application of beneficial microorganisms increases microbial biomass, enzyme activity, and nutrient cycling while improving soil aggregation and organic matter decomposition. Healthy soils containing diverse microbial communities exhibit greater resilience to drought, nutrient stress, and disease outbreaks, thereby supporting sustainable agricultural production under increasingly variable climatic conditions.

Despite these considerable advantages, several practical challenges remain. Biological nitrogen fixation is highly sensitive to environmental conditions including soil pH, temperature, moisture, salinity, oxygen availability, and organic carbon content. Inappropriate environmental conditions may reduce microbial survival and nitrogenase activity, thereby limiting field performance. Competition with indigenous soil microorganisms may further reduce establishment of introduced inoculants, particularly in soils with diverse native microbial populations.

Commercial production of N-Bio Boosters also requires rigorous quality control to ensure sufficient populations of viable microorganisms remain throughout manufacturing, storage, transportation, and field application. Variability among commercial products continues to influence farmer confidence and adoption rates. Consequently, standardized production methods, certification systems, and quality assurance protocols are essential to ensure consistent agronomic performance across different environments.

Overall, nitrogen-fixing biofertilizers represent one of the most promising biological innovations for sustainable rice production. Their ability to biologically supply nitrogen while simultaneously stimulating root growth, improving nutrient uptake, enhancing soil microbial activity, and reducing environmental pollution makes them valuable components of integrated nutrient management systems. Rather than functioning as complete replacements for synthetic fertilizers, N-Bio Boosters should be viewed as complementary technologies that improve fertilizer efficiency, maintain soil fertility, and enhance long-term sustainability of paddy cultivation. Such integrated approaches are increasingly important for ensuring global food security while minimizing the environmental footprint of modern rice agriculture.

SWOT Perspectives on the Application of Bio-Organic Fertilizers, Biofertilizers, and Nitrogen-Fixing Biofertilizers (N-Bio Booster) in Paddy Production

The transition from intensive chemical fertilizer application toward biologically based nutrient management has become an important strategy for sustainable rice production. Bio-organic fertilizers, biofertilizers, and nitrogen-fixing biofertilizers (N-Bio Booster) collectively offer opportunities to improve crop productivity while maintaining soil health and reducing environmental degradation. However, their successful adoption depends on biological, technical, economic, and policy factors. Evaluating these technologies through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) perspective provides a comprehensive understanding of their current status and future potential in modern rice cultivation (Figure 3).

Strengths

The greatest strength of bio-organic fertilizers and N-Bio Boosters lies in their ability to improve rice productivity while simultaneously enhancing soil health. Unlike synthetic fertilizers that primarily provide mineral nutrients, biological fertilizers stimulate the entire soil ecosystem by increasing microbial diversity, improving organic matter decomposition, and enhancing nutrient cycling. Consequently, improvements occur not only in crop yield but also in long-term soil fertility, which is fundamental for sustainable agricultural production [5].

Another major advantage is their capacity to improve nutrient use efficiency. Nitrogen-fixing microorganisms convert atmospheric nitrogen into plant-available forms, while phosphate-solubilizing and potassium-mobilizing bacteria increase the availability of otherwise inaccessible soil nutrients. This biological nutrient mobilization enables rice plants to absorb nutrients more efficiently, thereby reducing fertilizer losses through volatilization, leaching, and surface runoff. Improved nutrient use efficiency ultimately lowers fertilizer requirements while maintaining comparable or even higher grain yields [7].

Biofertilizers also provide multiple plant growth-promoting functions beyond nutrient supply. Many Plant Growth-Promoting Rhizobacteria (PGPR) produce phytohormones such as indole-3-acetic acid, gibberellins, and cytokinins that stimulate root development, tillering, and vegetative growth. Other beneficial microorganisms produce siderophores, antibiotics, and extracellular enzymes that suppress soil-borne pathogens while enhancing nutrient acquisition. Such multifunctional characteristics distinguish biofertilizers from conventional fertilizers and explain their broad agronomic benefits [6].

Field studies consistently demonstrate positive yield responses following integrated application of biofertilizers with reduced rates of inorganic fertilizers. Banayo *et al.,* [8] reported that biofertilizer application significantly increased irrigated rice yield across different fertilizer regimes, while Afify *et al.,* [4] demonstrated that plant growth-promoting rhizobacteria improved crop productivity with reduced chemical fertilizer requirements. Simarmata *et al.,* [9] further showed that combining bioameliorants with biofertilizers enhanced soil health and rice productivity under tropical conditions.

Environmental sustainability represents another important strength. Reduced application of synthetic nitrogen fertilizers decreases greenhouse gas emissions associated with fertilizer production, minimizes nitrate contamination of groundwater, reduces eutrophication risks, and lowers ammonia volatilization. Simultaneously, increased soil organic matter contributes to carbon sequestration and improved soil resilience against climate variability. These environmental benefits align closely with global sustainable development goals promoting environmentally responsible agricultural production.

Economically, biofertilizers may reduce production costs over time by decreasing dependence on increasingly expensive chemical fertilizers. As fertilizer prices continue to fluctuate globally, biological nutrient management provides farmers with greater resilience against market instability while improving long-term farm profitability.

Weaknesses

Despite their considerable advantages, bio-organic fertilizers and N-Bio Boosters possess several limitations that restrict widespread adoption. One of the primary weaknesses is the inconsistency of field performance. Unlike chemical fertilizers that provide relatively predictable nutrient responses, microbial inoculants are living organisms whose survival and effectiveness depend heavily on environmental conditions including soil pH, temperature, moisture, salinity, oxygen availability, and organic matter content. Consequently, identical products may produce different results under different field conditions.

Another important limitation involves the relatively slow release of nutrients from organic materials. While gradual nutrient release benefits long-term soil fertility, it may not satisfy the immediate nutrient demands of rapidly growing rice plants during critical developmental stages. Therefore, complete replacement of inorganic fertilizers with biological fertilizers is often impractical, particularly under intensive rice production systems.

Shelf life and product quality also remain significant concerns. The effectiveness of biofertilizers depends upon maintaining adequate populations of viable microorganisms throughout manufacturing, storage, transportation, and field application. Exposure to excessive temperatures, prolonged storage periods, or poor packaging may substantially reduce microbial viability before products reach farmers. Variability among commercial formulations therefore contributes to inconsistent agronomic performance and reduced farmer confidence.

Limited farmer awareness further restricts adoption. Many farmers remain unfamiliar with the biological mechanisms underlying biofertilizers and may expect immediate responses similar to those obtained from chemical fertilizers. Without adequate extension services and technical support, incorrect application methods may reduce microbial establishment and consequently lower field effectiveness.

Furthermore, successful biofertilizer application often requires site-specific management. Soil fertility, irrigation practices, crop varieties, climate, and indigenous microbial communities all influence product performance. Such variability complicates the development of universal recommendations applicable across different rice-growing regions.

Opportunities

Growing international interest in sustainable agriculture provides significant opportunities for expanding the use of bio-organic fertilizers and N-Bio Boosters. Increasing awareness of environmental degradation, soil health deterioration, and climate change has stimulated strong demand for environmentally friendly agricultural technologies capable of maintaining productivity while reducing ecological impacts. Biofertilizers directly address these challenges by improving nutrient use efficiency and reducing chemical fertilizer dependence.

Rapid advances in microbiology, biotechnology, and molecular biology provide additional opportunities for developing more effective microbial inoculants. Modern genomic techniques enable identification of highly efficient nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and stress-tolerant microbial strains capable of performing under diverse environmental conditions. Such technological advances are expected to improve product consistency and field performance considerably.

Precision agriculture offers another promising opportunity. Integration of biofertilizer application with remote sensing, soil sensors, Geographic Information Systems (GIS), drone technology, and artificial intelligence enables farmers to optimize nutrient management according to site-specific conditions. Such precision management can maximize microbial effectiveness while minimizing unnecessary fertilizer applications.

Government policies promoting sustainable agriculture also create favourable conditions for wider adoption. Many countries are introducing incentives for reducing chemical fertilizer consumption while encouraging organic farming, integrated nutrient management, and environmentally responsible agricultural practices. Support through subsidies, farmer training programmes, quality certification systems, and research funding can substantially accelerate adoption of biological fertilizers.

Increasing consumer demand for environmentally sustainable food production represents another important opportunity. Rice produced using integrated biological nutrient management may attract greater market acceptance as consumers increasingly value environmentally responsible farming practices. Certification systems for sustainable agriculture could further enhance the commercial value of rice produced using reduced chemical inputs.

Scientific research continues to generate new opportunities through the development of multifunctional microbial consortia. Rather than relying on single microbial species, future biofertilizers are likely to combine nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing bacteria, mycorrhizal fungi, and biocontrol agents within integrated formulations capable of simultaneously improving nutrient availability, disease resistance, and environmental stress tolerance.

Threats

Despite increasing scientific support, several external challenges threaten the successful implementation of bio-organic fertilizers and N-Bio Boosters. Climate change represents one of the greatest long-term threats because rising temperatures, prolonged droughts, flooding, salinity intrusion, and unpredictable rainfall patterns directly influence microbial survival and biological nitrogen fixation. Environmental stress may substantially reduce microbial activity, thereby limiting biofertilizer effectiveness under future climatic conditions.

Intensive agricultural practices also threaten long-term microbial sustainability. Continuous overuse of pesticides, fungicides, herbicides, and synthetic fertilizers may suppress beneficial microbial populations within the soil, reducing the effectiveness of introduced biofertilizers. Similarly, excessive tillage and declining soil organic matter create less favourable environments for microbial establishment.

Poor regulation of commercial biofertilizer products constitutes another important threat. Markets containing products with low microbial viability, contamination, inaccurate labelling, or poor-quality control may undermine farmer confidence even when scientifically validated products are available. Strengthening national standards and certification systems is therefore essential for ensuring consistent product quality.

Economic barriers may also limit adoption. Although biofertilizers often reduce long-term production costs, farmers may hesitate to adopt unfamiliar technologies because of uncertainty regarding short-term economic returns. Smallholder farmers, particularly in developing countries, frequently lack access to technical guidance, quality products, or financial resources needed for implementing new technologies.

Competition from highly subsidized chemical fertilizers presents another challenge. In many countries, government fertilizer subsidy programmes continue to favour conventional inorganic fertilizers, reducing incentives for farmers to adopt biological alternatives. Rebalancing agricultural policies to support integrated nutrient management will therefore be important for promoting wider adoption.

Finally, increasing global food demand may encourage intensive production systems that prioritize immediate yield maximization over long-term sustainability. Under such circumstances, farmers may continue relying heavily on synthetic fertilizers because of their rapid and predictable responses, despite the long-term environmental consequences.

Overall, the SWOT evaluation indicates that the strengths and opportunities of bio-organic fertilizers, biofertilizers, and N-Bio Boosters considerably outweigh their weaknesses and threats. Their capacity to improve rice productivity, restore soil fertility, enhance nutrient use efficiency, reduce environmental pollution, and support sustainable agriculture positions them as important components of future integrated nutrient management systems. Nevertheless, maximizing their potential will require continued scientific innovation, rigorous quality assurance, supportive agricultural policies, effective extension services, and greater farmer awareness. By integrating biological fertilizers with appropriate inorganic fertilizer management rather than viewing them as complete replacements, sustainable rice production can achieve both high productivity and long-term environmental resilience.

Future Perspectives

The future of sustainable rice cultivation will increasingly depend on agricultural practices that simultaneously enhance crop productivity, maintain soil fertility, and minimize environmental degradation. Bio-organic fertilizers, biofertilizers, and nitrogen-fixing biofertilizers (N-Bio Booster) have demonstrated considerable potential to contribute toward these objectives by improving nutrient use efficiency while reducing dependence on synthetic fertilizers. However, their successful integration into mainstream rice production requires continuous scientific innovation, supportive agricultural policies, farmer education, and multidisciplinary collaboration among researchers, industry, and policymakers.

One important future direction involves developing next-generation microbial inoculants with greater adaptability to diverse environmental conditions. Current commercial biofertilizers often exhibit variable performance because microbial survival is influenced by soil pH, temperature, moisture, salinity, and competition with indigenous microorganisms. Advances in microbial genomics, molecular ecology, and synthetic biology now allow researchers to identify highly efficient nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and stress-tolerant plant growth-promoting rhizobacteria capable of maintaining consistent performance under a wide range of field conditions. Such improvements will increase farmer confidence and facilitate wider adoption of biological nutrient management technologies.

Future formulations should also move beyond single microbial inoculants toward multifunctional microbial consortia. Naturally occurring soil ecosystems contain highly diverse microbial communities that interact synergistically to support plant growth. Combining nitrogen-fixing bacteria with phosphate-solubilizing bacteria, potassium-mobilizing microorganisms, arbuscular mycorrhizal fungi, and biological control agents within a single formulation may provide more stable and comprehensive benefits than individual microbial strains. Such integrated biofertilizer systems have the potential to simultaneously improve nutrient availability, stimulate root growth, suppress pathogens, and enhance tolerance to abiotic stresses.

Advances in precision agriculture present another promising opportunity for maximizing the effectiveness of N-Bio Boosters. Artificial Intelligence (AI), remote sensing, drone technology, satellite imagery, Geographic Information Systems (GIS), soil sensors, and Internet of Things (IoT) technologies now enable farmers to monitor crop nutritional status and soil conditions in real time. These technologies allow site-specific fertilizer recommendations that optimize microbial inoculant application according to local environmental conditions. Precision nutrient management can therefore increase fertilizer use efficiency while minimizing unnecessary fertilizer applications and reducing environmental pollution.

Climate change further highlights the importance of biological nutrient management. Increasing temperatures, prolonged droughts, flooding, salinity intrusion, and erratic rainfall patterns threaten rice production worldwide. Future research should therefore focus on identifying microbial strains capable of functioning effectively under climate-induced stresses. Stress-tolerant nitrogen-fixing microorganisms, together with drought-resistant and salt-tolerant PGPR, may significantly enhance rice resilience while maintaining productivity under increasingly variable climatic conditions. Such biological adaptations will become increasingly important as global climate change intensifies.

Another important research priority involves understanding the interactions between beneficial microorganisms and soil microbial communities. Modern molecular techniques including metagenomics, transcriptomics, proteomics, and metabolomics now provide unprecedented opportunities to investigate rhizosphere ecology at the genomic level. These approaches can identify microbial interactions responsible for improved nutrient cycling, disease suppression, and stress tolerance while supporting development of more effective biofertilizer formulations based on ecological principles rather than empirical observations alone.

Long-term field experiments should also become a greater priority. Many published studies evaluate biofertilizer performance over one or two cropping seasons, whereas relatively few investigations assess long-term impacts on soil fertility, microbial diversity, carbon sequestration, nutrient cycling, and overall ecosystem resilience. Multi-year field trials conducted across different climatic regions, soil types, and rice production systems will provide stronger scientific evidence regarding the sustainability of integrated biological nutrient management.

Farmer education and extension programmes remain equally important for future success. Successful application of biofertilizers depends not only on product quality but also on correct handling, storage, timing, and application methods. Training programmes should therefore emphasize the biological principles underlying microbial inoculants while providing practical guidance regarding integrated nutrient management. Demonstration farms, participatory research, and farmer field schools can significantly improve technology transfer and encourage wider adoption among smallholder farmers.

Policy support will play a crucial role in accelerating the transition toward sustainable fertilizer management. Governments should strengthen quality control regulations for commercial biofertilizers, establish certification standards, support research and development, and provide incentives encouraging integrated nutrient management rather than excessive chemical fertilizer use. Such policies will enhance product reliability while promoting greater farmer confidence in biological technologies.

International collaboration also offers substantial opportunities for advancing biofertilizer research. Rice is cultivated under highly diverse agroecological conditions across Asia, Africa, and Latin America. Collaborative research networks can facilitate exchange of microbial germplasm, standardized evaluation protocols, and comparative field trials that accelerate development of broadly applicable technologies. Such international cooperation is particularly important for addressing global challenges associated with food security, climate change, and sustainable agriculture.

Ultimately, the future of rice production should not be viewed as a choice between chemical fertilizers and biofertilizers. Instead, the most effective strategy is likely to involve integrated nutrient management, where biological fertilizers complement judicious applications of inorganic fertilizers according to crop requirements and environmental conditions. This balanced approach maximizes nutrient use efficiency while preserving soil fertility, protecting environmental quality, and ensuring stable rice production for future generations.

Conclusions

Bio-organic fertilizers, biofertilizers, and nitrogen-fixing biofertilizers (N-Bio Booster) have emerged as important components of sustainable rice production systems because they improve crop productivity while simultaneously enhancing soil health and reducing environmental impacts associated with intensive chemical fertilizer use. Unlike conventional fertilizers that function primarily as nutrient sources, biological fertilizers improve soil physical, chemical, and biological properties while stimulating beneficial microbial activities essential for long-term ecosystem functioning.

This narrative review demonstrates that bio-organic fertilizers improve soil organic matter, water-holding capacity, nutrient cycling, and microbial diversity, thereby creating favourable conditions for sustained rice production. Biofertilizers containing plant growth-promoting rhizobacteria further enhance nutrient acquisition through nitrogen fixation, phosphate solubilization, phytohormone production, siderophore synthesis, and biological disease suppression. Nitrogen-fixing biofertilizers, particularly N-Bio Boosters, provide additional environmental and economic benefits by biologically supplying nitrogen, improving fertilizer use efficiency, and reducing dependence on synthetic nitrogen fertilizers.

The SWOT perspectives indicate that the strengths of biological fertilizers clearly outweigh their weaknesses. Their principal strengths include improved soil fertility, enhanced nutrient use efficiency, increased rice productivity, environmental sustainability, and long-term agricultural resilience. Weaknesses mainly relate to variability in field performance, microbial survival, product quality, and farmer awareness. Nevertheless, advances in biotechnology, microbial ecology, precision agriculture, artificial intelligence, and molecular biology create substantial opportunities for improving microbial formulations and increasing adoption. External threats, including climate change, poor product regulation, excessive pesticide use, and continued dependence on chemical fertilizers, highlight the importance of coordinated scientific research and supportive agricultural policies.

Future sustainable rice production will depend upon integrating biological nutrient management with appropriate inorganic fertilization rather than replacing mineral fertilizers entirely. Such integrated approaches optimize nutrient availability, improve soil ecosystem functioning, reduce environmental pollution, and strengthen resilience against climate variability while maintaining high crop productivity.

In conclusion, bio-organic fertilizers, biofertilizers, and nitrogen-fixing biofertilizers should be regarded as strategic components of climate-smart and sustainable agriculture. Continued investment in scientific research, quality assurance, farmer education, and policy support will be essential for maximizing their contribution toward global food security while safeguarding soil resources and environmental quality. Their successful adoption will not only improve paddy productivity but also contribute significantly to achieving sustainable agricultural development in the twenty-first century.

Declaration on the Use of Artificial Intelligence

The authors declare that generative artificial intelligence tools were used in a supportive capacity during the preparation of this manuscript. These tools assisted with language refinement, structural organisation, and stylistic clarity of the text. All ideas, interpretations, reflections, and conclusions presented in this paper are the authors' own and are grounded in personal experience and scholarly judgment. The authors retain full responsibility for the content, accuracy, originality, and integrity of the manuscript.

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