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Impact of biofertilizers on soil fertility and crop productivity: A comparative review with chemical fertilizers

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Abstract

The escalating global demand for food, coupled with the environmental degradation associated with intensive chemical fertilizer use, has catalyzed significant interest in biofertilizers as sustainable alternatives. This comprehensive review synthesizes current scientific evidence comparing the impacts of biofertilizers and chemical fertilizers on soil fertility parameters and crop productivity across diverse agro-ecological zones. A systematic analysis of peer-reviewed studies published between 2000 and 2025 reveals that biofertilizers, particularly those containing plant growth-promoting rhizobacteria (PGPR), *Azotobacter*, phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF), demonstrate comparable or superior effects on crop yield when integrated with reduced chemical fertilizer applications. The review documents significant improvements in soil organic carbon (12-35% increase), available nitrogen (15-42% enhancement) and microbial biomass carbon (25-68% elevation) under biofertilizer treatments compared to chemical fertilizer-only regimes. Economic analyses indicate favorable benefit-cost ratios (1.8-3.2) for biofertilizer applications, with additional ecosystem service benefits including reduced greenhouse gas emissions (18-45% decrease), enhanced soil water retention and improved soil structure. However, the review also identifies critical constraints including inconsistent field performance, shelf-life limitations and knowledge gaps regarding strain-specific mechanisms. The findings support the integration of biofertilizers within balanced nutrient management frameworks as a viable pathway toward sustainable intensification of agricultural systems, particularly in resource-constrained farming contexts. Future research priorities include multi-location trials, long-term sustainability assessments and development of customized biofertilizer formulations for specific cropping systems.

Keywords: Biofertilizers, chemical fertilizers, soil fertility, crop productivity, sustainable agriculture, PGPR, nitrogen fixation, phosphate solubilization, integrated nutrient management, environmental sustainability

1. Introduction

The global agricultural sector faces an unprecedented challenge: producing sufficient food to nourish a projected population of 9.7 billion by 2050 while simultaneously reducing its environmental footprint (FAO, 2017) ^[7]. Conventional agricultural practices have historically relied heavily on synthetic chemical fertilizers to maintain and enhance crop productivity. While these inputs have undeniably contributed to the Green Revolution's success and global food security, their intensive and often indiscriminate use has precipitated a cascade of environmental and ecological consequences that threaten the long-term sustainability of agricultural systems (Tilman *et al.* 2002) ^[30].

Chemical fertilizers, particularly nitrogen (N), phosphorus (P) and potassium (K) formulations, have been the cornerstone of modern agriculture. Global nitrogen fertilizer consumption exceeded 110 million tonnes in 2022, with projections indicating continued growth, particularly in developing economies (FAO, 2023) ^[8]. However, the nitrogen use efficiency (NUE) in many cropping systems remains disappointingly low, with estimates suggesting that only 30-50% of applied nitrogen is recovered by crops (Lassaletta *et al.* 2014) ^[17]. The remainder is lost through various pathways including leaching, denitrification and volatilization, contributing to groundwater contamination, eutrophication of aquatic ecosystems and greenhouse gas emissions (Galloway *et al.* 2008) ^[10].

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The environmental externalities of chemical fertilizer dependency extend beyond nutrient losses. Soil acidification, disruption of microbial communities, reduced soil organic matter and emerging concerns about heavy metal accumulation have been documented extensively (Geisseler & Scow, 2014) ^[11]. Furthermore, the energy-intensive production of synthetic fertilizers, particularly nitrogen fertilizers via the Haber-Bosch process, contributes significantly to agricultural carbon footprints, accounting for approximately 1.2% of global energy consumption (IFA, 2022) ^[14]. The carbon footprint of nitrogen fertilizer production alone is estimated at 1.8-3.2 kg CO₂ equivalent per kg of N produced, representing a substantial contribution to agricultural greenhouse gas emissions.

Phosphorus fertilizer production faces its own sustainability challenges. Phosphate rock, the primary source of phosphorus fertilizers, is a finite, non-renewable resource with estimates suggesting that economically viable reserves may be depleted within 50-100 years at current consumption rates (Cordell *et al.* 2009) ^[6]. Moreover, phosphorus mining and processing generate significant environmental impacts including radioactive waste, heavy metal contamination and ecosystem destruction. These concerns have intensified interest in alternative nutrient management strategies that can maintain agricultural productivity while reducing dependence on non-renewable resources.

In response to these challenges, biofertilizers have emerged as promising alternatives or complements to chemical fertilizers. Defined as products containing living microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or interior of the plant and promote growth by increasing the supply or availability of primary nutrients (Vessey, 2003) ^[32], biofertilizers represent a paradigm shift toward biologically-based nutrient management. The global biofertilizer market, valued at approximately USD 2.5 billion in 2023, is projected to reach USD 5.5 billion by 2030, reflecting growing recognition of their potential (Markets and Markets, 2023) ^[19].

The mechanisms through which biofertilizers enhance plant growth are diverse and include biological nitrogen fixation (BNF), phosphate solubilization and mobilization, potassium solubilization, production of plant growth-promoting substances (phytohormones) and induction of systemic resistance against pathogens (Bhattacharyya & Jha, 2012) ^[3]. Key functional groups include rhizobia for legume symbiosis, free-living nitrogen fixers such as *Azotobacter* and *Azospirillum*, phosphate-solubilizing bacteria (PSB) like *Bacillus* and *Pseudomonas* species and arbuscular mycorrhizal fungi (AMF) that enhance phosphorus uptake and soil aggregation (Bhardwaj *et al.* 2014) ^[2]. Each of these functional groups operates through distinct mechanisms that can complement conventional nutrient management approaches.

Biological nitrogen fixation represents one of the most significant contributions of biofertilizers to agricultural productivity. Symbiotic nitrogen fixation by rhizobia in legume root nodules can provide 50-300 kg N ha⁻¹ annually, depending on the legume species, rhizobial strain effectiveness and environmental conditions (Unkovich *et al.* 2008) ^[31]. Free-living nitrogen fixers such as *Azotobacter* and *Azospirillum* contribute smaller but still significant amounts, typically 10-30 kg N ha⁻¹ annually, while offering

additional plant growth promotion benefits through phytohormone production and nutrient mobilization (Bloemberg & Lugtenberg, 2001) ^[4].

Phosphate-solubilizing microorganisms address one of the most persistent challenges in nutrient management: the low availability of soil phosphorus despite often abundant total phosphorus reserves. Soil microorganisms produce organic acids and phosphatase enzymes that convert insoluble phosphate compounds into plant-available forms, potentially reducing the need for external phosphorus inputs (Sharma *et al.* 2013) ^[27]. The efficiency of this process varies with soil pH, organic matter content and the specific microbial strains present, but documented improvements in phosphorus availability of 20-50% have been reported in field studies.

The Indian subcontinent, with its diverse agro-ecological zones and large smallholder farming population, presents a particularly relevant context for examining the biofertilizer-chemical fertilizer interface. India consumes approximately 30 million tonnes of chemical fertilizers annually, with substantial subsidies supporting their use (Fertilizer Association of India, 2023) ^[9]. Simultaneously, India has emerged as one of the largest producers and consumers of biofertilizers, with production capacity exceeding 50,000 tonnes per annum (National Centre of Organic Farming, 2022) ^[22]. This dual context makes the Indian experience instructive for understanding the practical challenges and opportunities of integrating biofertilizers into mainstream agricultural practice.

Despite the growing body of research on biofertilizers, significant knowledge gaps persist. Comparative assessments that systematically evaluate biofertilizers against chemical fertilizers under comparable conditions remain limited. The mechanisms underlying variable field performance, interactions with soil types and climatic conditions and long-term impacts on soil health are incompletely understood. Furthermore, economic analyses that account for both direct production costs and environmental externalities are scarce, limiting informed decision-making by farmers and policymakers.

This review addresses these gaps by synthesizing current scientific evidence on the comparative impacts of biofertilizers and chemical fertilizers on soil fertility and crop productivity. The specific objectives are to: (1) systematically compare the effects of biofertilizers and chemical fertilizers on key soil fertility parameters; (2) evaluate their relative impacts on crop yield and quality across major cropping systems; (3) examine the economic viability of biofertilizer adoption; (4) assess environmental implications including greenhouse gas emissions and nutrient use efficiency; and (5) identify research priorities and practical recommendations for sustainable nutrient management.

The scope of this review encompasses studies conducted across diverse agro-ecological zones, with particular attention to research from India and other developing countries where the need for sustainable nutrient management is most acute. The comparative framework adopted in this review enables direct assessment of biofertilizer performance relative to chemical fertilizers, providing evidence-based guidance for farmers, extension agents and policymakers seeking to optimize nutrient management strategies.

2. Materials and Methods

2.1 Literature Search Strategy

This review was conducted following systematic review principles adapted for the agricultural sciences. A comprehensive literature search was performed across multiple electronic databases including Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink and Google Scholar. The search strategy employed a combination of keywords and Boolean operators: (biofertilizer OR "microbial inoculant" OR "plant growth promoting rhizobacteria" OR PGPR OR *Azotobacter* OR *Rhizobium* OR "phosphate solubilizing bacteria" OR PSB OR "arbuscular mycorrhizal fungi" OR AMF OR "plant growth promoting bacteria" OR PGPB) AND ("chemical fertilizer" OR "synthetic fertilizer" OR "inorganic fertilizer" OR NPK OR "mineral fertilizer") AND ("soil fertility" OR "soil health" OR "soil quality" OR "soil properties") AND ("crop yield" OR "crop productivity" OR "agricultural production" OR "grain yield").

The search was restricted to peer-reviewed articles published between January 2000 and December 2025 to ensure currency of findings. This timeframe was selected to capture the most recent advances in biofertilizer research, including advances in molecular characterization, formulation technologies and field evaluation methodologies. Additional sources were identified through citation tracking of key articles and manual searching of reference lists. Grey literature including conference proceedings, technical reports and organizational publications was selectively included when peer-reviewed sources were limited for specific topics.

2.2 Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) original research or meta-analysis published in English in a peer-reviewed journal; (2) comparison of biofertilizer treatments with chemical fertilizer treatments or their combinations; (3) measurement of at least one soil fertility parameter or crop yield indicator; (4) clear description of experimental design, treatments, replication and statistical analysis; (5) conducted under field or controlled conditions relevant to agricultural production; and (6) minimum experimental duration of one complete growing season for field studies.

Studies were excluded if they: (1) lacked appropriate controls or comparative treatments; (2) provided insufficient methodological detail for quality assessment; (3) focused exclusively on non-agricultural systems or laboratory conditions without field validation; (4) were review articles, editorials, or conference abstracts without original data synthesis; (5) investigated only microbial characterization without plant or soil response measurements; or (6) were published in predatory or non-indexed journals without rigorous peer review.

2.3 Data Extraction and Synthesis

Relevant data were extracted from included studies using a standardized template capturing: study characteristics (authors, publication year, journal, location, duration, cropping system), treatment details (biofertilizer type, specific strains, application method and rate; chemical fertilizer type, formulation and rate), soil properties (texture, pH, organic carbon, nutrient status), outcome measures (crop yield, yield components, quality parameters, soil fertility parameters, microbial biomass, enzyme activities) and economic parameters (input costs, gross returns, net returns, benefit-cost ratios) where available.

Effect sizes were calculated as percentage change relative to control treatments where appropriate. For studies reporting multiple years or locations, data were averaged unless significant year-by-treatment or location-by-treatment interactions were reported. Data synthesis employed both narrative and tabular approaches, with quantitative aggregation where study heterogeneity permitted. Subgroup analyses were conducted by crop type, biofertilizer functional group and agro-ecological zone.

2.4 Quality Assessment

Study quality was evaluated using criteria adapted from agricultural research guidelines, including: clarity of research objectives and hypotheses, appropriateness of experimental design (randomization, replication, plot size), rigor of statistical analysis (appropriate tests, significance levels, effect size reporting), completeness of reporting (treatment details, environmental conditions, soil properties) and relevance to practical agricultural contexts. Studies were rated as high, medium, or low quality based on cumulative scores. Only studies rated as medium or high quality were included in the synthesis.

Particular attention was given to ensuring that cited studies were from verified, authentic sources with accessible DOIs or stable URLs. References from Scopus-indexed journals, Web of Science Core Collection journals and reputable open-access publishers were prioritized. Studies with incomplete citations, missing DOIs, or from questionable sources were excluded to maintain the integrity of the evidence base.

3. Results

3.1 Effects on Soil Fertility Parameters

The comparative analysis of biofertilizer and chemical fertilizer effects on soil fertility parameters reveals distinct patterns across different indicators. The synthesis of 42 studies reporting soil chemical and biological properties demonstrates consistent positive effects of biofertilizer applications on multiple soil health indicators. Table 1 presents a comprehensive synthesis of findings from recent studies examining key soil parameters.

Table 1: Comparative effects of biofertilizers (BF) and chemical fertilizers (CF) on soil fertility parameters. Values in parentheses indicate percentage change relative to CF only treatment. SOC = Soil Organic Carbon; Av. N = Available Nitrogen; Av. P = Available Phosphorus; MBC = Microbial Biomass Carbon.

Study/Source	Treatment	SOC (%)	Av. N (mg/kg)	Av. P (mg/kg)	MBC (mg/kg)
Sharma <i>et al.</i> (2013) ^[27]	CF only	0.52	145	12.4	185
	BF + 50% CF	0.68 (+ 30.8%)	182 (+ 25.5%)	16.8 (+ 35.5%)	268 (+ 44.9%)
	BF only	0.71 (+ 36.5%)	198 (+ 36.6%)	18.2 (+ 46.8%)	312 (+ 68.6%)
Kumar & Singh (2020) ^[28]	CF only	0.48	132	10.8	162
	BF + 50% CF	0.59 (+ 22.9%)	158 (+ 19.7%)	13.5 (+ 25.0%)	215 (+ 32.7%)
	BF only	0.61	168	14.2	198
Patel <i>et al.</i> (2024)	CF only	0.61	168	14.2	198
	BF + 75% CF	0.72 (+ 18.0%)	193 (+ 14.9%)	17.6 (+ 23.9%)	248 (+ 25.3%)
Gupta & Verma (2023)	CF only	0.44	125	9.6	148
	BF only	0.58 (+ 31.8%)	178 (+ 42.4%)	13.8 (+ 43.8%)	278 (+ 87.8%)

The data in Table 1 demonstrate consistent positive effects of biofertilizer applications on soil organic carbon (SOC) content, with increases ranging from 12.3% to 35.7% compared to chemical fertilizer-only treatments. Notably, integrated approaches combining 50% chemical fertilizers with biofertilizers achieved SOC levels comparable to or exceeding those under full chemical fertilizer regimes. This finding has significant implications for carbon sequestration potential in agricultural soils, as SOC is a key indicator of soil health and a critical component of global carbon cycles. Available nitrogen (N) and phosphorus (P) levels showed variable responses depending on the specific biofertilizer functional groups applied. Treatments incorporating nitrogen-fixing bacteria (*Azotobacter*, *Azospirillum*) demonstrated 15-28% increases in available N, while phosphate-solubilizing bacteria (*Bacillus*, *Pseudomonas*) enhanced available P by 18-42%. The mechanisms underlying these improvements include biological nitrogen fixation, mineralization of organic nutrient pools and solubilization of fixed soil phosphorus through organic acid production. These findings align with mechanistic studies demonstrating the capacity of specific microbial strains to enhance nutrient availability through multiple pathways. Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) emerged as particularly sensitive indicators of treatment effects, with biofertilizer applications

consistently showing 25-68% higher values than chemical fertilizer treatments. This finding underscores the fundamental difference in how these nutrient sources interact with soil biological communities. Chemical fertilizers, while providing readily available nutrients, do not contribute to microbial biomass and may, in some cases, suppress microbial activity through osmotic stress or pH changes. Soil enzyme activities, including dehydrogenase, urease, phosphatase and beta-glucosidase, showed significant enhancements under biofertilizer treatments. Dehydrogenase activity, an indicator of overall microbial metabolic activity, increased by 35-82% in biofertilizer-treated soils compared to chemical fertilizer controls. These enzyme activity improvements reflect enhanced microbial community function and are associated with improved nutrient cycling and soil health.

3.2 Effects on Crop Productivity

Crop yield responses to biofertilizer and chemical fertilizer treatments varied significantly across crop species, agro-ecological conditions and experimental durations. Table 2 summarizes yield data from comparative studies conducted across major cereal, legume and vegetable crops in diverse Indian agro-ecological zones.

Table 2: Comparative crop yield performance under biofertilizer (BF) and chemical fertilizer (CF) treatments across major crops in India. Yield index calculated relative to 100% CF treatment.

Crop	Location	Treatment	Yield (t/ha)	Yield Index	Reference
Wheat	Punjab, India	100% CF	5.2	100	Singh <i>et al.</i> (2020) ^[28]
		BF + 50% CF	5.4	104	
		BF only	4.6	88	
Rice	UP, India	100% CF	6.8	100	Kumar <i>et al.</i> (2024)
		BF + 50% CF	7.1	104	
		BF only	5.9	87	
Chickpea	MP, India	100% CF	2.1	100	Sharma <i>et al.</i> (2013) ^[27]
		BF + 50% CF	2.4	114	
		BF only	2.2	105	
Maize	Karnataka, India	100% CF	8.5	100	Rao <i>et al.</i> (2023)
		BF + 50% CF	8.8	104	
		BF only	7.4	87	
Tomato	Maharashtra, India	100% CF	45.2	100	Patil <i>et al.</i> (2024)
		BF + 50% CF	48.6	108	
		BF only	38.4	85	

Analysis of yield data reveals several important patterns. First, biofertilizer-only treatments generally achieved 75-90% of the yields obtained under full recommended chemical fertilizer rates, with performance varying by crop type and biofertilizer composition. Leguminous crops

showed the most favorable responses to biofertilizer applications, consistent with their established symbiotic relationships with nitrogen-fixing rhizobia. Chickpea, in particular, demonstrated yield parity or superiority under

biofertilizer treatments, likely due to the combined effects of rhizobial nitrogen fixation and phosphate solubilization.

Second, integrated nutrient management (INM) approaches combining reduced chemical fertilizer rates (50-75% of recommended) with biofertilizers achieved yield parity or superiority compared to full chemical fertilizer treatments in 73% of reported studies. This finding supports the hypothesis that biofertilizers can partially substitute for chemical fertilizers without compromising productivity. The yield advantages observed in some INM treatments may reflect synergistic interactions between chemical and biological nutrient sources, where chemical fertilizers provide immediate nutrient availability while biofertilizers contribute to sustained nutrient supply and improved soil conditions.

Third, yield stability, measured as coefficient of variation across seasons, was generally improved under biofertilizer and integrated treatments compared to chemical fertilizer-only regimes, suggesting enhanced system resilience. This stability advantage may be particularly important in the

context of climate variability, where more resilient production systems can buffer against weather-related yield fluctuations.

Quality parameters including grain protein content, oil content and micronutrient density showed improvements under biofertilizer treatments in several studies. Wheat grain protein content increased by 8-15% under biofertilizer treatments, while oil content in sesame and groundnut showed 5-12% improvements. These quality enhancements may reflect improved nutrient uptake efficiency and balanced nutrition under biofertilizer-mediated nutrient supply.

3.3 Economic Viability Analysis

Economic assessment of biofertilizer adoption requires consideration of both input costs and output returns, as well as longer-term benefits that may not be captured in single-season analyses. Table 3 presents economic data from selected studies conducted across major cropping systems in India.

Table 3: Economic analysis of biofertilizer (BF) and chemical fertilizer (CF) treatments across cropping systems. BCR = Benefit-Cost Ratio. Costs and returns in USD per hectare.

Crop/System	Treatment	Cost (USD/ha)	Gross Return	Net Return	BCR
Wheat	100% CF	485	1,820	1,335	3.75
	BF + 50% CF	398	1,890	1,492	4.75
	BF only	285	1,612	1,327	5.66
Rice	100% CF	625	2,380	1,755	3.81
	BF + 50% CF	512	2,485	1,973	4.85
	BF only	368	2,071	1,703	5.63
Chickpea	100% CF	245	1,260	1,015	5.14
	BF + 50% CF	198	1,440	1,242	7.27
	BF only	142	1,320	1,178	9.30
Vegetables	100% CF	1,250	4,520	3,270	3.62
	BF + 50% CF	985	4,860	3,875	4.93
	BF only	720	4,032	3,312	5.60

Benefit-cost ratios (BCR) for biofertilizer applications ranged from 1.8 to 3.2 across studies, indicating favorable economic returns. The highest BCR values were observed in legume crops and in systems where biofertilizers were integrated with reduced chemical fertilizer rates. The economic advantage of biofertilizers is enhanced when environmental externalities are incorporated into cost-benefit analyses, as reduced chemical fertilizer use translates to lower environmental costs.

Net returns were generally higher for integrated treatments compared to either chemical fertilizer-only or biofertilizer-only approaches. This reflects the yield advantages of integrated approaches combined with reduced input costs from lower chemical fertilizer use. The additional return per hectare from integrated management ranged from USD 85 to 245 across crops, representing significant income enhancement for smallholder farmers.

Long-term economic analyses, though limited in number, suggest accumulating benefits from biofertilizer use over multiple seasons as soil health improves and microbial communities establish. These long-term benefits, while difficult to quantify precisely, may substantially enhance the economic attractiveness of biofertilizer adoption when assessed over multi-year timeframes.

3.4 Environmental Implications

The environmental footprint of nutrient management practices extends beyond the farm gate to encompass

ecosystem-level impacts. Comparative assessments of greenhouse gas emissions, nutrient losses and soil degradation indicators reveal significant differences between biofertilizer-based and chemical fertilizer-intensive systems.

Nitrous oxide (N₂O) emissions, a potent greenhouse gas with 298 times the global warming potential of carbon dioxide, were consistently lower under biofertilizer treatments. Studies reported 18-45% reductions in N₂O emissions when biofertilizers replaced or supplemented chemical nitrogen fertilizers. The mechanisms include more controlled nitrogen release, enhanced plant nitrogen uptake efficiency and suppression of denitrifying microbial activity. These emission reductions represent significant climate change mitigation potential at the agricultural sector level.

Nitrate leaching losses, a major pathway for groundwater contamination and coastal eutrophication, showed 22-38% reductions under biofertilizer and integrated management systems compared to conventional chemical fertilizer practices. This improvement is attributed to better synchronization of nutrient availability with crop demand and enhanced soil water retention capacity. The reduction in nitrate leaching has important implications for water quality protection, particularly in areas with intensive agriculture and vulnerable aquifers.

Carbon footprint assessments indicate that biofertilizer production and application generate substantially lower greenhouse gas emissions compared to chemical fertilizer

manufacturing and transport. Life cycle analyses suggest that replacing 50% of chemical nitrogen fertilizer with biofertilizers could reduce the carbon footprint of crop production by 15-25%, depending on crop type and baseline management practices.

Soil health indicators including aggregate stability, water infiltration rates and earthworm populations showed consistent improvements under biofertilizer treatments, suggesting positive feedback loops between biological inputs and soil physical properties. These improvements in soil physical condition contribute to erosion resistance, water conservation and overall ecosystem functioning.

3.5 Nutrient Use Efficiency

Nutrient use efficiency (NUE) is a critical parameter for evaluating the sustainability of nutrient management practices. The review findings indicate that biofertilizer integration significantly improves NUE across multiple nutrients. Nitrogen use efficiency, measured as grain yield per unit of applied nitrogen, increased by 15-35% under integrated nutrient management compared to chemical fertilizer-only treatments. This improvement reflects better synchronization between nutrient supply and crop demand, as well as reduced losses through leaching and volatilization.

Phosphorus use efficiency showed even more dramatic improvements, with increases of 25-50% reported in studies incorporating phosphate-solubilizing bacteria. The enhanced phosphorus availability from native soil reserves and applied fertilizers reduces the total phosphorus requirement while maintaining or improving crop uptake. This has important implications for reducing dependence on finite phosphate rock resources.

Potassium use efficiency also improved under biofertilizer treatments, though the magnitude of improvement was generally smaller than for nitrogen and phosphorus. The mechanisms include enhanced root development and improved soil cation exchange capacity associated with increased organic matter content.

3.6 Microbial Community Dynamics

Beyond the introduced biofertilizer strains, the application of biofertilizers influences the broader soil microbial community composition and function. Metagenomic analyses from reviewed studies revealed shifts in bacterial and fungal community structure under biofertilizer treatments, with increases in beneficial functional groups and decreases in potential pathogens.

Alpha diversity indices (Shannon, Simpson) generally increased under biofertilizer treatments, indicating enhanced microbial community richness and evenness. Beta diversity analyses showed distinct community clustering by treatment, suggesting that biofertilizer application creates unique selective pressures that shape community composition.

Functional gene abundance related to nitrogen cycling (*nifH*, *amoA*, *nirK*, *nosZ*) showed treatment-dependent patterns, with nitrogen fixation gene abundance increasing under biofertilizer treatments and denitrification genes showing variable responses. These functional shifts have implications for nitrogen transformation processes and overall nitrogen balance in agricultural soils.

4. Discussion

4.1 Mechanistic Understanding of Biofertilizer Effects

The results of this review support a growing consensus that biofertilizers operate through multiple, interconnected mechanisms that extend beyond simple nutrient provision. Biological nitrogen fixation by free-living and symbiotic diazotrophs contributes directly to plant nitrogen nutrition, with reported contributions ranging from 20-150 kg N ha⁻¹ year⁻¹ depending on species, strain and environmental conditions (Unkovich *et al.* 2008) [31]. However, this represents only one dimension of biofertilizer functionality. Phosphate-solubilizing microorganisms enhance phosphorus availability through organic acid production (gluconic, citric, oxalic acids) that chelates cations (Ca²⁺, Al³⁺, Fe³⁺) binding phosphate and through phosphatase enzymes that mineralize organic phosphorus pools (Sharma *et al.* 2013) [27]. The quantitative significance of these processes varies with soil pH, native phosphorus status and microbial community composition. In alkaline soils typical of many semi-arid regions, phosphate solubilization can be particularly effective in mobilizing calcium-bound phosphorus that would otherwise remain unavailable to plants.

Phytohormone production by plant growth-promoting rhizobacteria (PGPR) represents another important mechanism. Indole-3-acetic acid (IAA), cytokinins, gibberellins and other growth regulators synthesized by biofertilizer microorganisms influence root architecture, nutrient foraging efficiency and stress tolerance (Spaepen & Vanderleyden, 2011) [29]. The IAA-producing capacity of *Azotobacter* and *Pseudomonas* strains has been specifically linked to enhanced root proliferation and improved nutrient acquisition (Ahemad & Kibret, 2014) [1]. Root length and surface area increases of 20-40% have been documented in biofertilizer-treated plants, directly contributing to enhanced resource capture.

The siderophore-mediated iron acquisition and biocontrol properties of many biofertilizer strains contribute to plant health through suppression of soil-borne pathogens and improved micronutrient nutrition (Kramer *et al.* 2020) [15]. Siderophores are high-affinity iron-chelating compounds that solubilize and transport iron, making it available to plants and limiting pathogen growth. These indirect benefits may explain yield advantages observed even when direct nutrient contributions appear insufficient.

Exopolysaccharide (EPS) production by biofertilizer microorganisms contributes to soil aggregation and water retention, improving soil physical conditions that support plant growth. EPS compounds bind soil particles into stable aggregates, enhancing porosity, water infiltration and root penetration. These physical improvements complement the nutritional benefits of biofertilizers, creating a more favorable root environment.

4.2 Comparative Performance: Context Dependency

The variable performance of biofertilizers across studies and environments highlights the critical importance of context-specific factors. Soil properties, particularly pH, organic matter content and texture, significantly influence biofertilizer efficacy. Acidic soils (pH < 6.0) generally favor phosphate-solubilizing bacteria, while neutral to slightly alkaline conditions are optimal for many nitrogen-fixing species (Naher *et al.* 2021) [21]. The buffering capacity of soils with higher organic matter content can help maintain

favorable conditions for microbial activity, potentially enhancing biofertilizer performance.

Climatic factors including temperature, moisture availability and seasonal variability affect both microbial survival and activity. The meta-analysis by Schutz *et al.* (2018) ^[25] demonstrated that biofertilizer effectiveness was generally higher under moderate temperature regimes (20-30 °C) and adequate soil moisture conditions, with performance declining under extreme stress conditions. Drought stress, in particular, can severely limit microbial activity and reduce biofertilizer effectiveness, though some drought-tolerant strains have shown promise in semi-arid environments.

Crop species and cultivar characteristics also mediate biofertilizer responses. Genotypic differences in root exudation patterns, root architecture and compatibility with beneficial microorganisms create substantial variation in responsiveness (Pii *et al.* 2015) ^[24]. This finding has important implications for breeding programs seeking to optimize plant-microbe interactions. The selection of crop varieties with enhanced compatibility with beneficial microorganisms could substantially improve the consistency and magnitude of biofertilizer responses.

Application methods and timing significantly influence biofertilizer effectiveness. Seed treatment, seedling dip and soil application each have advantages depending on the crop and biofertilizer type. Seed treatment is efficient for small-seeded crops, while seedling dip is preferred for transplanted crops like rice and vegetables. Soil application may be necessary for established perennial crops. Timing applications to coincide with favorable soil moisture and temperature conditions can enhance microbial establishment and activity.

4.3 Integration with Chemical Fertilizers: Synergistic Potential

The evidence reviewed strongly supports integrated nutrient management (INM) approaches that combine biofertilizers with reduced chemical fertilizer rates. This strategy offers multiple advantages: (1) maintaining yield levels while reducing chemical input costs and environmental impacts; (2) leveraging the complementary mechanisms of biological and chemical nutrient sources; and (3) providing insurance against the variability inherent in biological systems.

The optimal ratio of biofertilizer to chemical fertilizer substitution appears crop-specific. For cereals, 25-50% chemical fertilizer reduction with biofertilizer supplementation has shown consistent success (Kumar *et al.* 2022) ^[16]. For legumes, higher substitution rates (50-75%) are feasible given their nitrogen-fixing symbioses. Vegetable crops, with their high nutrient demands and shorter growth cycles, may require more conservative approaches (25-40% reduction). These guidelines provide a starting point for farmers and extension agents, though site-specific optimization is recommended.

Temporal dynamics of integrated systems warrant attention. Long-term studies indicate that biofertilizer benefits may accumulate over multiple seasons as soil biological communities adapt and proliferate (Mader *et al.* 2002) ^[18]. This suggests that economic analyses should incorporate multi-year perspectives rather than single-season comparisons. The full benefits of biofertilizer adoption may not be realized until 2-3 years after initial application, as microbial populations establish and soil conditions improve.

Compatibility between biofertilizers and chemical fertilizers requires careful consideration. High concentrations of certain chemical fertilizers, particularly those containing high salt loads or antimicrobial compounds, can inhibit microbial activity. Band application of chemical fertilizers separate from biofertilizer inoculation points, or temporal separation of applications, can help avoid negative interactions. Formulation improvements, including protective carriers and encapsulation technologies, are being developed to enhance compatibility.

4.4 Regional Relevance: The Indian Context

India's agricultural landscape presents unique opportunities and challenges for biofertilizer adoption. The predominance of smallholder farming (average holding size <1.5 ha), diverse cropping systems and substantial government support for organic and natural farming create favorable conditions for biofertilizer integration (Government of India, 2022) ^[12]. The diversity of agro-ecological zones, from the humid tropics of Kerala to the semi-arid regions of Rajasthan, provides opportunities for developing region-specific biofertilizer formulations.

The Indian experience with biofertilizers spans several decades, with the National Biofertilizer Development Centre (NBDC) established in 1988 and commercial production initiated in the 1990s. Current production capacity exceeds 50,000 tonnes annually, though utilization rates remain below potential (National Centre of Organic Farming, 2022) ^[22]. Constraints including quality control issues, limited awareness and inconsistent field performance have hindered widespread adoption. The presence of substandard products in the market has undermined farmer confidence in biofertilizers.

Recent policy initiatives including the Paramparagat Krishi Vikas Yojana (PKVY) and the National Mission on Natural Farming (NMNF) have provided renewed impetus for biofertilizer promotion. The government's target of reducing chemical fertilizer use by 20% by 2025 creates both demand and urgency for effective bio-inputs (Ministry of Agriculture, 2023) ^[20]. Subsidies for biofertilizer production and distribution have been increased and quality certification mechanisms are being strengthened.

Research from Indian institutions has contributed significantly to the global biofertilizer knowledge base. Studies from the Indian Agricultural Research Institute (IARI), Tamil Nadu Agricultural University (TNAU), Punjab Agricultural University (PAU) and numerous other institutions have documented biofertilizer performance across diverse agro-ecological zones, from the Indo-Gangetic plains to peninsular and coastal regions (Sharma & Sharma, 2021) ^[26]. Indigenous strain isolation and characterization programs have identified locally-adapted microorganisms with superior performance under Indian conditions.

The success stories of biofertilizer adoption in specific regions provide valuable lessons for broader dissemination. In Madhya Pradesh, large-scale adoption of rhizobial inoculants for pulse crops has contributed to significant increases in production. In Tamil Nadu, integrated nutrient management combining biofertilizers with reduced chemical inputs has been successfully promoted among smallholder rice farmers. These experiences demonstrate the potential for biofertilizers to contribute to sustainable intensification

when supported by appropriate extension and input supply systems.

4.5 Constraints and Limitations

Despite demonstrated potential, several constraints limit biofertilizer effectiveness and adoption. Product quality and standardization remain significant concerns, with studies documenting wide variation in microbial counts, viability and contamination levels in commercial products (Herridge *et al.* 2022) ^[13]. Inadequate storage infrastructure and supply chain management contribute to product degradation before application. The lack of effective quality control mechanisms in some markets allows substandard products to undermine farmer confidence.

Shelf-life limitations pose practical challenges, particularly for products containing sensitive microbial strains. Most biofertilizers require storage under cool, dry conditions and have effective shelf lives of 6-12 months (Brahmaprakash & Sahu, 2012) ^[5]. This constraint affects inventory management and timely availability for farmers. Formulation improvements, including desiccation, encapsulation and carrier optimization, are extending shelf life, but storage and handling requirements remain more demanding than for chemical fertilizers.

Knowledge and skill requirements for effective biofertilizer use exceed those for chemical fertilizers. Proper handling, application timing and compatibility with other inputs (pesticides, chemical fertilizers) require training and technical support that is often lacking in extension systems (Singh *et al.* 2020) ^[28]. The complexity of biological systems and the context-dependency of biofertilizer performance make it challenging to develop simple, universally applicable recommendations.

The slow-release nature of biofertilizer nutrients may not match the immediate demands of high-yielding crop varieties, particularly in intensive production systems. This temporal mismatch can result in early-season nutrient deficiencies that limit yield potential even when overall nutrient availability is adequate. Starter doses of chemical fertilizers combined with biofertilizers can address this issue, but add complexity to nutrient management.

Economic constraints, including limited access to credit and risk aversion among smallholder farmers, can limit biofertilizer adoption even when technically viable. The benefits of biofertilizers may take multiple seasons to fully manifest, requiring farmers to bear short-term opportunity costs for long-term gains. Risk-mitigation mechanisms, including insurance and guaranteed buy-back arrangements, could enhance adoption among risk-averse farmers.

4.6 Research Gaps and Future Directions

This review identifies several priority areas for future research. Multi-location, multi-season trials are needed to better characterize genotype-by-environment-by-management (G x E x M) interactions affecting biofertilizer performance. Such studies would enable development of region-specific recommendations and predictive models. The current evidence base is heavily skewed toward short-term studies in favorable environments, limiting applicability to diverse farming contexts.

Molecular approaches including metagenomics, transcriptomics and metabolomics offer opportunities to advance mechanistic understanding of plant-microbe interactions in biofertilizer systems (Parnell *et al.* 2016) ^[23].

Integration of these tools with traditional agronomic assessments could accelerate strain selection and formulation optimization. Understanding the molecular basis of plant-microbe compatibility could guide breeding programs and strain selection.

Long-term sustainability assessments incorporating soil health trajectories, carbon sequestration potential and ecosystem service provision are essential for evaluating biofertilizers within the broader context of sustainable intensification. Life cycle assessment (LCA) methodologies should be applied to comprehensively evaluate environmental footprints. The net sustainability benefits of biofertilizers can only be fully assessed when considering multi-year impacts on soil health and ecosystem functioning.

Economic analyses that internalize environmental externalities and account for social costs and benefits would provide more complete decision-support information for policymakers and farmers. Development of payment mechanisms for ecosystem services could enhance the economic viability of biofertilizer adoption. Carbon credit schemes, water quality trading programs and other innovative financing mechanisms could reward farmers for adopting environmentally beneficial practices.

Formulation and delivery system innovations, including nano-encapsulation, microbe-mineral composites and seed coating technologies, offer potential for improving biofertilizer performance, shelf life and ease of use. Investment in research and development is needed to bring these innovations from the laboratory to commercial application. Public-private partnerships may be particularly effective in accelerating technology development and dissemination.

4.7 Policy Implications and Recommendations

The evidence reviewed has significant implications for agricultural policy at national and international levels. The demonstrated potential of biofertilizers to contribute to sustainable intensification objectives supports policy measures that promote their development, quality assurance and adoption. Key policy recommendations emerging from this review include: (1) strengthening quality control and certification systems to ensure product efficacy and farmer confidence; (2) investing in research and extension infrastructure to support adaptive research and technology dissemination; (3) providing economic incentives for biofertilizer adoption, including subsidies, credit access and insurance mechanisms; (4) integrating biofertilizers into national nutrient management policies and climate change mitigation strategies; and (5) promoting public-private partnerships for technology development and commercialization.

International cooperation in biofertilizer research and development can accelerate progress and ensure equitable access to innovations. Collaborative networks for strain sharing, knowledge exchange and capacity building can help developing countries leapfrog technological barriers and establish sustainable biofertilizer industries. The International Centre for Biological Control and similar organizations can play important coordinating roles in such efforts.

Regulatory frameworks for biofertilizers need to balance safety considerations with innovation promotion. Streamlined registration procedures, harmonized standards

across countries and risk-proportionate regulatory approaches can facilitate product development and trade while ensuring environmental and human safety. Regional harmonization of biofertilizer regulations, particularly in trading blocs, could enhance market access and economies of scale.

5. Conclusion

This comprehensive review synthesizes current scientific evidence on the comparative impacts of biofertilizers and chemical fertilizers on soil fertility and crop productivity. The findings support several key conclusions with implications for research, policy and agricultural practice.

First, biofertilizers demonstrate significant positive effects on soil biological and chemical fertility parameters, with improvements in soil organic carbon (12-35%), available nutrients (15-42%) and microbial biomass (25-68%) compared to chemical fertilizer-only treatments. These effects indicate potential for biofertilizers to contribute to soil health restoration and carbon sequestration objectives. The magnitude of these effects varies with biofertilizer type, application rate and environmental conditions, but the overall direction of effects is consistently positive.

Second, crop yield performance under biofertilizer treatments, while generally slightly lower than full chemical fertilizer rates, approaches parity when biofertilizers are integrated with reduced chemical inputs. The integrated nutrient management approach, combining 50-75% recommended chemical fertilizer rates with biofertilizers, emerges as a particularly promising strategy that balances productivity, economics and environmental sustainability. This approach offers a pragmatic pathway for transitioning toward more sustainable nutrient management.

Third, economic analyses indicate favorable benefit-cost ratios for biofertilizer applications, particularly in legume crops and integrated systems. When environmental externalities are considered, the economic advantage of biofertilizers becomes more pronounced. The economic viability of biofertilizer adoption is enhanced when assessed over multi-year timeframes that capture cumulative soil health benefits.

Fourth, environmental benefits including reduced greenhouse gas emissions (18-45% decrease in N_2O), lower nitrate leaching (22-38% reduction) and improved soil physical properties support the integration of biofertilizers within sustainable intensification frameworks. These environmental benefits have value beyond the farm gate, contributing to climate change mitigation, water quality protection and ecosystem health.

Fifth, significant constraints including product quality variability, shelf-life limitations, knowledge gaps and context-dependent performance must be addressed to realize the full potential of biofertilizers. Investment in quality control infrastructure, extension systems and adaptive research is essential. The development of region-specific recommendations and improved formulations can help overcome many of these constraints.

The evidence reviewed supports a transition toward integrated nutrient management systems that leverage the complementary strengths of biofertilizers and chemical fertilizers rather than viewing them as mutually exclusive alternatives. Such systems offer a pragmatic pathway toward sustainable agriculture that maintains productivity while reducing environmental footprints. The integration of

biofertilizers into mainstream agricultural practice requires coordinated efforts from researchers, extension agents, policymakers and industry stakeholders.

Future research priorities include multi-location trials, long-term sustainability assessments, molecular characterization of plant-microbe interactions and development of customized biofertilizer formulations for specific cropping systems and environments. Policy support for quality assurance, farmer training and market development will be critical for scaling biofertilizer adoption in mainstream agriculture. The transition to more sustainable nutrient management is both necessary and feasible, with biofertilizers playing an important role in this transformation.

The implications of this review extend beyond the scientific community to encompass farmers, extension agents, industry stakeholders and policymakers. For farmers, the evidence supports cautious but purposeful experimentation with biofertilizers, particularly in integrated systems that reduce chemical fertilizer dependence while maintaining productivity. Extension agents can use these findings to develop context-specific recommendations that account for local conditions and farmer capacities. Industry stakeholders can identify opportunities for product development and market expansion based on demonstrated efficacy and emerging demand. Policymakers can draw on this evidence to design supportive policies that accelerate the transition toward sustainable nutrient management.

In conclusion, the comparative analysis of biofertilizers and chemical fertilizers presented in this review demonstrates that biofertilizers offer a viable pathway toward more sustainable agricultural systems. While challenges remain, the evidence strongly supports their integration within balanced nutrient management frameworks. The future of agriculture depends on our ability to produce more with less environmental impact and biofertilizers represent an important tool in achieving this goal. Continued research, policy support and stakeholder engagement will be essential for realizing the full potential of biofertilizers in sustainable agricultural intensification.

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