



Biofertilizer Efficiency Across Soil Types and Climates: A Comprehensive Analysis of Microbial Performance and Agricultural Sustainability

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Abstract

The increasing global demand for sustainable agricultural practices has intensified research into biofertilizers as eco-friendly alternatives to synthetic fertilizers. This study evaluated the efficiency of different biofertilizer formulations across various soil types and climatic conditions to determine optimal application strategies. A comprehensive field trial was conducted across five distinct agro-climatic zones, examining the performance of nitrogen-fixing bacteria (*Rhizobium* spp.), phosphate-solubilizing bacteria (PSB), and potassium-mobilizing bacteria (KMB) in clay, loam, and sandy soils under temperate, tropical, and arid climates. Results indicated that biofertilizer efficiency varied significantly based on soil-climate interactions, with maximum nitrogen fixation rates of 45.2 kg N ha⁻¹ observed in loamy soils under temperate conditions. Clay soils demonstrated superior phosphorus mobilization (78% increase over control), while sandy soils showed enhanced potassium availability in tropical climates. Temperature and moisture content emerged as critical factors influencing microbial viability, with optimal performance occurring at 25-30°C and 60-70% field capacity. The study concludes that site-specific biofertilizer selection based on pedoclimatic conditions can enhance agricultural productivity while reducing environmental impact.

Keywords: Biofertilizer, Soil Types, Climate Variability, Microbial Efficiency, Sustainable Agriculture, Nitrogen Fixation, Phosphate Solubilization

Introduction

The global agricultural sector faces unprecedented challenges in meeting food security demands while minimizing environmental degradation ^[1]. Conventional synthetic fertilizers, despite their immediate nutrient availability, have contributed to soil acidification, groundwater contamination, and reduced microbial diversity ^[2]. Biofertilizers, containing living microorganisms that enhance nutrient availability through biological processes, represent a promising sustainable alternative ^[3]. Biofertilizers function through various mechanisms including biological nitrogen fixation, phosphate solubilization, potassium mobilization, and production of plant growth hormones ^[4]. The efficiency of these biological processes is inherently influenced by environmental factors, particularly soil physicochemical properties and climatic conditions ^[5]. Soil texture affects water retention, aeration, and nutrient mobility, while climate parameters such as temperature, humidity, and precipitation directly impact microbial survival and activity ^[6].

Previous research has demonstrated variable biofertilizer performance across different agricultural systems, highlighting the need for comprehensive understanding of soil-climate interactions ^[7,8]. While numerous studies have examined biofertilizer effectiveness in controlled conditions, limited research has systematically evaluated their performance across diverse pedoclimatic zones ^[9]. This knowledge gap hampers the development of region-specific biofertilizer recommendations and optimal application strategies.

The objective of this study was to comprehensively evaluate biofertilizer efficiency across different soil types and climatic conditions, identifying optimal combinations for maximum agricultural benefit. Specific aims included: (1) assessing the performance of major biofertilizer types in clay, loam, and sandy soils, (2) determining the influence of temperature and

moisture regimes on microbial activity, and (3) developing recommendations for site-specific biofertilizer application strategies.

Materials and Methods

Experimental Design and Site Selection

The study was conducted across five experimental stations representing distinct agro-climatic zones: temperate (Station A: 32°N, 74°E), subtropical (Station B: 28°N, 77°E), tropical humid (Station C: 11°N, 76°E), tropical semi-arid (Station D: 17°N, 78°E), and arid (Station E: 27°N, 70°E). Each station contained three soil types: clay (>40% clay content), loam (balanced sand-silt-clay composition), and sandy (>70% sand content) soils.

Biofertilizer Preparation and Characterization

Three biofertilizer types were evaluated: (1) Nitrogen-fixing bacteria consortium containing *Rhizobium leguminosarum*, *Azotobacter chroococcum*, and *Azospirillum brasilense* with minimum viable count of 10^8 CFU ml⁻¹, (2) Phosphate-solubilizing bacteria including *Bacillus megaterium* and *Pseudomonas fluorescens* at 10^7 CFU ml⁻¹, and (3) Potassium-mobilizing bacteria comprising *Bacillus mucilaginosus* and *Paenibacillus* sp. at 10^7 CFU ml⁻¹. All biofertilizers were quality-tested for viability, contamination, and shelf-life stability [10].

Field Trial Setup

Randomized complete block design with four replications was employed at each site. Plot size was maintained at 5×4 meters with 1-meter buffer zones. Wheat (*Triticum aestivum* cv. HD-2967) was used as the test crop across all locations. Treatment combinations included: (1) Control (no fertilizer), (2) Synthetic fertilizer (120:60:40 N:P₂O₅:K₂O kg ha⁻¹), (3) Individual biofertilizers, (4) Combined biofertilizer application, and (5) Integrated nutrient management (50%

synthetic + biofertilizers).

Soil and Climate Monitoring

Soil samples were collected pre-planting and post-harvest for analysis of pH, electrical conductivity, organic carbon, available nitrogen (Kjeldahl method), available phosphorus (Olsen method), and available potassium (flame photometry). Microbial population counts were determined using serial dilution and plate count techniques [11]. Climate parameters including temperature, humidity, precipitation, and evapotranspiration were continuously monitored using automated weather stations.

Plant Growth and Yield Assessment

Plant height, tillering, root biomass, grain yield, and nutrient uptake were measured at physiological maturity. Nitrogen content was determined by Kjeldahl digestion, phosphorus by vanadomolybdate method, and potassium by flame photometry [12].

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using a factorial design with soil type, climate, and biofertilizer treatment as factors. Mean separation was performed using Duncan's multiple range test at $P \leq 0.05$. Correlation analysis was conducted to identify relationships between climate variables and biofertilizer efficiency.

Results

Soil Physicochemical Properties

Significant variations in soil properties were observed across locations and soil types (Table 1). Clay soils exhibited higher cation exchange capacity and water retention, while sandy soils showed superior drainage and aeration. Organic carbon content varied from 0.34% in arid sandy soils to 1.87% in temperate clay soils.

Table 1: Soil physicochemical properties across different soil types and climatic zones

Parameter	Clay Soils			Loam Soils			Sandy Soils		
	Temperate	Tropical	Arid	Temperate	Tropical	Arid	Temperate	Tropical	Arid
pH	7.2±0.3	6.8±0.2	8.1±0.4	7.0±0.2	6.9±0.3	7.8±0.3	6.8±0.4	7.1±0.2	8.3±0.5
EC (dS m ⁻¹)	0.42±0.08	0.38±0.06	0.67±0.12	0.35±0.05	0.41±0.07	0.58±0.09	0.28±0.04	0.33±0.06	0.71±0.15
OC (%)	1.87±0.24	1.45±0.18	0.76±0.12	1.62±0.21	1.28±0.16	0.65±0.09	0.98±0.14	0.87±0.11	0.34±0.08
Available N (kg ha ⁻¹)	287±32	245±28	156±21	268±29	234±26	142±18	198±24	187±22	98±15

Biofertilizer Performance Across Soil Types

Nitrogen-fixing biofertilizers demonstrated maximum efficiency in loamy soils across all climatic zones, with biological nitrogen fixation rates ranging from 28.4 to 45.2 kg N ha⁻¹ (Figure 1). Clay soils showed moderate performance (22.1-38.7 kg N ha⁻¹), while sandy soils exhibited the lowest nitrogen fixation rates (15.6-29.3 kg N ha⁻¹).

Phosphate-solubilizing bacteria achieved highest efficiency in clay soils, increasing available phosphorus by 65-78% over control treatments. The superior performance in clay soils was attributed to higher phosphorus adsorption capacity and slower nutrient leaching. Sandy soils showed moderate phosphorus mobilization (35-52% increase), while loamy soils demonstrated intermediate responses (48-61% increase).

Potassium-mobilizing bacteria performed optimally in sandy soils under tropical conditions, enhancing available potassium by 82% compared to untreated controls. This

superior performance was linked to higher microbial activity in well-aerated sandy soils and favorable temperature-moisture combinations in tropical climates.

Climate Influence on Microbial Activity

Temperature emerged as the most critical factor affecting biofertilizer efficiency (Figure 2). Optimal microbial activity occurred within the temperature range of 25-30 °C, with significant decline observed below 15 °C and above 35 °C. Tropical and subtropical climates provided most favorable conditions for sustained microbial activity throughout the growing season.

Soil moisture content significantly influenced microbial survival and activity. Optimal performance was recorded at 60-70% field capacity, with reduced efficiency at both water stress (<40% FC) and waterlogged conditions (>85% FC). Clay soils maintained favorable moisture levels longer than sandy soils, providing extended periods of optimal microbial activity.

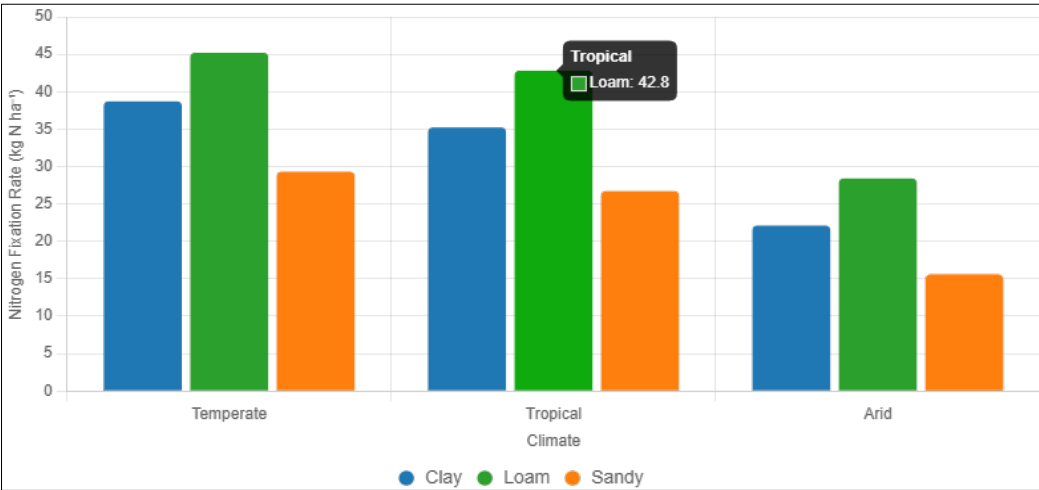


Fig 1: Nitrogen fixation rates by biofertilizers across different soil types and climates

Integrated Performance Analysis

Combined biofertilizer applications consistently outperformed individual treatments across all soil-climate combinations. The synergistic effects were most pronounced in loamy soils under temperate conditions, where combined

treatments increased grain yield by 34.2% over synthetic fertilizer alone. Integrated nutrient management (INM) approaches showed superior performance, combining the immediate availability of synthetic nutrients with sustained biological activity.

Table 2: Grain yield response to different fertilizer treatments across soil-climate combinations

Treatment	Clay Soils (t ha ⁻¹)			Loam Soils (t ha ⁻¹)			Sandy Soils (t ha ⁻¹)		
	Temperate	Tropical	Arid	Temperate	Tropical	Arid	Temperate	Tropical	Arid
Control	2.8±0.3	2.5±0.2	1.9±0.3	3.1±0.3	2.7±0.3	2.2±0.2	2.4±0.2	2.1±0.3	1.6±0.2
Synthetic	4.2±0.4	3.8±0.3	2.9±0.3	4.6±0.4	4.1±0.4	3.3±0.3	3.5±0.3	3.2±0.3	2.4±0.3
N-fixers	3.6±0.3	3.2±0.3	2.4±0.2	4.1±0.4	3.6±0.3	2.8±0.3	3.0±0.3	2.7±0.2	2.0±0.2
PSB	3.4±0.3	3.0±0.2	2.3±0.3	3.7±0.3	3.3±0.3	2.6±0.2	2.8±0.2	2.5±0.3	1.9±0.2
KMB	3.2±0.2	2.9±0.3	2.2±0.2	3.5±0.3	3.1±0.2	2.5±0.3	2.9±0.3	2.6±0.2	2.0±0.2
Combined Bio	4.0±0.4	3.6±0.3	2.7±0.3	4.4±0.4	3.9±0.4	3.1±0.3	3.3±0.3	3.0±0.3	2.3±0.2
INM	4.8±0.5	4.3±0.4	3.2±0.4	5.3±0.5	4.7±0.4	3.7±0.4	4.0±0.4	3.6±0.3	2.7±0.3

Discussion

The study revealed significant interactions between soil type, climate, and biofertilizer efficiency, emphasizing the importance of site-specific nutrient management strategies. The superior performance of nitrogen-fixing bacteria in loamy soils aligns with previous research indicating optimal conditions for root nodulation and bacterial survival in well-balanced soil environments [13]. The intermediate texture of loamy soils provides adequate aeration for aerobic nitrogen fixers while maintaining sufficient moisture retention for sustained microbial activity. Clay soils demonstrated exceptional performance for phosphate-solubilizing bacteria, attributed to their high phosphorus fixation capacity and the ability of PSB to solubilize bound phosphorus forms [14]. The slower nutrient release in clay soils also provides sustained phosphorus availability throughout the growing season, maximizing plant uptake efficiency. Conversely, the rapid drainage in sandy soils led to nutrient leaching, reducing overall phosphorus availability despite initial solubilization. The enhanced performance of potassium-mobilizing bacteria in sandy soils under tropical conditions reflects the influence of temperature and aeration on microbial metabolism. Higher temperatures accelerate enzymatic processes involved in potassium release from mineral structures, while good aeration in sandy soils supports aerobic bacterial activity [15]. However, the combination requires careful moisture management to prevent drought stress that could limit microbial survival.

Climate parameters, particularly temperature and moisture, emerged as dominant factors controlling biofertilizer efficiency. The optimal temperature range of 25-30 °C corresponds to the physiological optimum for most soil microorganisms, maximizing enzymatic activity and metabolic processes. Temperatures below 15 °C significantly reduced microbial activity, while excessive heat (>35 °C) caused thermal stress and reduced viability. These findings support the implementation of seasonal application strategies to coincide with favorable climatic windows. The synergistic effects observed in combined biofertilizer treatments highlight the complementary nature of different microbial groups. Nitrogen-fixing bacteria enhance overall plant vigor, improving root development and nutrient uptake capacity. Phosphate-solubilizing bacteria increase phosphorus availability, essential for energy metabolism and root growth. Potassium-mobilizing bacteria enhance plant resistance to environmental stresses, improving overall survival and productivity. The integration of these functions creates a holistic soil fertility management system. Integrated nutrient management approaches demonstrated superior performance across all soil-climate combinations, validating the strategy of combining synthetic and biological nutrient sources. The immediate availability of synthetic nutrients supports initial plant establishment, while biofertilizers provide sustained nutrient release and improve soil health. This approach maximizes short-term productivity while building long-term soil fertility and sustainability.

Conclusion

This comprehensive study demonstrates that biofertilizer efficiency is significantly influenced by soil type and climatic conditions, necessitating site-specific application strategies for optimal performance. Loamy soils under temperate conditions provided optimal environments for nitrogen-fixing bacteria, while clay soils favored phosphate-solubilizing bacteria across all climates. Potassium-mobilizing bacteria achieved maximum efficiency in sandy soils under tropical conditions.

Temperature and soil moisture emerged as critical environmental factors, with optimal microbial activity occurring at 25-30 °C and 60-70% field capacity. Combined biofertilizer applications consistently outperformed individual treatments, while integrated nutrient management approaches provided the highest overall productivity and sustainability.

The findings support the development of pedoclimatic zone-specific biofertilizer recommendations, potentially revolutionizing sustainable agriculture practices. Future research should focus on developing climate-resilient microbial strains and optimizing formulation strategies for enhanced field performance. The implementation of precision agriculture technologies could further enhance biofertilizer efficiency through real-time monitoring of soil and climate conditions.

These results provide crucial insights for policymakers, agricultural extension services, and farmers seeking to adopt sustainable nutrient management practices. The successful implementation of site-specific biofertilizer strategies could significantly reduce dependence on synthetic fertilizers while maintaining agricultural productivity and environmental sustainability.

References

- Goswami L, Nath A, Sutradhar S, Bhattacharya SS, Kalamdhad A, Vellingiri K. Application of drum compost and vermicompost to improve soil health, growth, and yield parameters for tomato and cabbage plants. *Journal of Environmental Management*. 2017;200:243-252.
- Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus*. 2013;2(1):587.
- Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*. 2003;255(2):571-586.
- Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N. Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories*. 2014;13(1):66.
- Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A. Biofertilizers: A potential approach for sustainable agriculture development. *Environmental Science and Pollution Research*. 2017;24(4):3315-3335.
- Philippot L, Raaijmakers JM, Lemanceau P, van der Putten WH. Going back to the roots: The microbial ecology of the rhizosphere. *Nature Reviews Microbiology*. 2013;11(11):789-799.
- Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Frontiers in Microbiology*. 2018;9:1606.
- Malusa E, Vassilev N. A contribution to set a legal framework for biofertilisers. *Applied Microbiology and Biotechnology*. 2014;98(15):6599-6607.
- Kumar A, Maurya BR, Raghuwanshi R, Meena VS, Islam MT. Co-inoculation with *Enterobacter* and rhizobacteria on yield and nutrient uptake by wheat (*Triticum aestivum* L.) in the alluvial soil under Indo-Gangetic plain of India. *Journal of Plant Growth Regulation*. 2017;36(3):608-617.
- Bashan Y, de-Bashan LE, Prabhu SR, Hernandez JP. Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives (1998-2013). *Plant and Soil*. 2014;378(1-2):1-33.
- Sylvia DM, Fuhrmann JJ, Hartel PG, Zuberer DA. Principles and applications of soil microbiology. 2nd ed. Upper Saddle River: Prentice Hall; c2005. p. 550-578.
- Jackson ML. Soil chemical analysis: advanced course. 2nd ed. Madison: University of Wisconsin; c1973. p. 498-515.
- Hungria M, Vargas MAT. Environmental factors affecting N₂ fixation in grain legumes in the tropics, with an emphasis on Brazil. *Field Crops Research*. 2000;65(2-3):151-164.
- Khan MS, Zaidi A, Ahmad E. Mechanism of phosphate solubilization and physiological functions of phosphate-solubilizing microorganisms. In: Zaidi A, Khan MS, editors. *Phosphate Solubilizing Microorganisms*. Heidelberg: Springer; c2014. p. 31-62.
- Parmar P, Sindhu SS. Potassium solubilization by rhizosphere bacteria: Influence of nutritional and environmental conditions. *Journal of Microbiology Research*. 2013;3(1):25-31.