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ELUCIDATING PLANT-SOIL-MICROBIOL INTERACTION IN BIOFERTILIZER-BASED NUTRIENT MANAGEMENT SYSTEM FOR IMPROVING SOIL FERTILITY AND CROP NUTRIENT USE EFFICIENCY

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Abstract

Sustainable agricultural intensification requires innovative nutrient management strategies that enhance productivity while preserving environmental integrity. This study evaluated the performance of biofertilizer-based nutrient management systems through integrated assessment of soil biochemical properties, microbial community dynamics, nutrient-use efficiency, plant physiological responses, yield performance, and sustainability indicators. The results revealed that biofertilizer application significantly increased soil enzymatic activities, microbial biomass carbon, and functional microbial diversity, leading to accelerated nutrient cycling and improved soil fertility. Nutrient-use efficiency indices for nitrogen, phosphorus, and potassium were markedly higher under biofertilizer treatments, indicating superior nutrient recovery and internal utilization compared with synthetic fertilization. Enhanced chlorophyll content, photosynthetic rate, and stress tolerance mechanisms resulted in increased biomass production, yield stability, and resilience under abiotic stress conditions. Additionally, biofertilizer-mediated improvements in soil organic carbon, aggregate stability, and water-holding capacity contributed to long-term soil health and reduced environmental footprint. Integrated sustainability indices confirmed improved energy efficiency, reduced emission intensity, and greater system resilience under biofertilizer-based management. Overall, the findings demonstrate that biofertilizers effectively enhance soil–plant–microbe interactions and represent a viable, eco-friendly alternative for sustainable agricultural production.

Keywords: Biofertilizers, Soil–Plant–Microbe Interactions, Nutrient-Use Efficiency, Sustainable Agriculture, Soil Health, Crop Productivity

INTRODUCTION

The increasing number of humans on earth also implies that we should adopt sustainable farming practices since it will help us to have sufficient food to all human beings as well as ensure that the environment does not decline (Mihoub et al., 2023). Traditional farming practices that require a lot of use of synthetic fertilizers and pesticides are bound to destroy the health of the soil besides interfering with the ecosystem. It is the reason why alternative methods of agriculture are quite necessary to be discovered (Yusuf et al., 2025). Biofertilizers would be suggested as a suitable long-term solution to these issues as positive interactions of the microbes with the plants enable one to enhance the fertility of soils and their productivity and strength in the environment (Shahzad et al., 2025). Such biological formulations are microorganisms that are alive and assist in the cycling of nutrients as well as their greater solubility to plants to induce plant growth in various manners; fixation of nitrogen, dissolution of phosphorus and movement of potassium (Badiyal et al., 2024). It involves the biological processes which proliferate the nutrients throughout the soil and far enhances the power of the soil and the production (Chaudhari and Chaudhary, 2024). The aim of the review is to clarify the multidimensional interactions between plants, soil and microorganisms in biofertilizer-based nutrient management systems and suggest the various functions that the interactions serve in enhancing soil fertility and fruitful utilization of crop nutrients (Bargaz et al., 2018). In this paper, the role of biofertilizers, which entails a combination of microbial inoculants, in facilitating the desired nutrient conversions in the rhizosphere will be addressed (Andualem et al., 2024; Dzvene and Chiduza, 2024). These microbial inoculatives are highly required since they convert nutrients, which are not in plant forms of use. It implies that farmers would not also be forced to employ so many artificial chemicals, which is good to nature (Bastakoti et al., 2024). It is because of this critical review that methods through which these biofertilizers influence the physiology of plants, enhance resistance to stress and eventually the yield and nutritional value of crops will be discussed (Zuluaga et al., 2024). Moreover, the biofertilizers should be included into the nutrient management models because it can significantly reduce the adverse impact of agriculture on the environment since the green house gases emission will be minimized and carbon will be captured better (Shahzad et al., 2025). Moreover, the biofertilizer treatments, which are typically associated with industrial processes, including mining and smelting, the use of certain fertilizers and pesticides in the past, might counter the negative effect of the anthropogenic contamination by the heavy metals (How et al., 2022). Such capability to eradicate pollution implies that they can prove handy during the process of salvaging damaged farmland and the environment (Kumar et al., 2024). The present review is the critical analysis of the efficacy of biofertilizers as the environmentally-friendly alternatives to synthetic fertilisers, the processes, their involvement in the industry, and the regulation to bridge the gap between the science and practice concerning the agricultural industry (Shahzad et al., 2025). Such complex interactions are supposed to be familiar to get the most out of biofertilizers in various agricultural systems (Sharma et al., 2022). The implementation of biofertilizers in the paradigm of the Integrated Nutrient Management has lead to the determination of numerous changes in the physicochemical properties of the soil, the diversification of the microbiome, the increase in the rate of nutrient cycling and the water retention rate (Yadav and Yadav, 2024). Biofertilizers also apply to the existing farming systems as it does not only boost agricultural production, but also contributes to the environment in the long-term (Olaniyan et al., 2022). Biofertilizers with useful microorganisms (rhizobacteria, mycorrhizal fungi and so on) can be used to boost crop yields, and the ecological footprint of conventional agriculture can be dropped by a significant margin (Yadav and Yadav, 2024). Speaking of the optimal use of biofertilizers and the final effect of this compound on the various soils and in various environmental factors, the research has some gaps (Shahzad et al., 2025). The future study should involve the preparation of crop-specific microorganisms inoculant and improve their compatibility with various soil types and climatic environments (Shahzad et al., 2025). Besides, deep field research should be performed to recognize the long-term efficiency and environmental outcomes of biofertilizer treatments (Shahzad et al., 2025). Also, the integration of the multi-omics would enable the knowledge of the molecular and biochemical mechanisms with which the interaction between biofertilizers and plants can be regulated. This will assist in developing artificial consortia of microbes with increased functionality application of specific bioremediation schemes (Kaushal and Pati, 2025). The effects of these high-level biotechnological interventions may result in production of quality products of biofertilizers which can offset some instances of soil erosion. This would assist in the creation of good and powerful farming systems (Shahzad et al., 2025). Besides, the analytic complexity of the interactions among the soil properties, community of microorganisms, and the physiological response of the plant may be compared to the knowledge of the potential rise of biofertilizer application and the accomplishment of sustainable agricultural outcome (Xu et al., 2025). Although there is a growing list of people who begin to see the opportunities of biofertilizers, yet, we cannot know how they work and how they can influence the sustainability of agriculture. To serve as an illustration, we do not know enough about how biofertilizers work with regards to various soil and weather conditions (Shahzad et al., 2025). To be practiced and guarantee their extensive use, bioformulations should also be stabilized and have their shelf life increased with the help of inexpensive and safe carrier materials (Khan et al., 2023). In addition, the comprehensive economic examination of biofertilizer versus conventional fertilizer in most of the agriculture settings is also vital in the policy and the agriculture practice (Shahzad et al., 2025). The growth in the degree of cultivated genomic and metagenomic methods will enable the formation of a better understanding of the functional abilities and relationships of the rhizospheric communities and, accordingly, the progression of stronger and more accurate biofertilizer strains (Shahzad et al., 2025). The future of the biofertilizers use in the sphere of the soil health and plant growth improvement should be the optimization of their compositions and their long-term impacts on the soil and the plants (Haroun et al., 2023). Genomics and metagenomics are accelerating the generation of microorganisms, which are persistent, and integrate biofertilizers, biocides and soil conditioners in their strains. All that is a step in the right direction of ensuring that agriculture is made more sustainable (Mahmoudi et al., 2025). This type of biotechnology, including synthetic biology and CRISPR-enabled microbial engineering allows the creation of designer microbes that can transport nutrients to improved locations and deal with stress in an improved manner. It has transformed the process of biofertilizers formation (Kumar et al., 2024; Shahzad et al., 2025). It is connected with the development of genetically modified ones, which, despite being not as good as people may assume, have been empowering their abilities to contribute to the growth of plants, and they should communicate more about the safety regarding the environment (Saha et al., 2023). Such good properties as fixation of nitrogen and phosphate solubilization of biofertilizers have prospects of being added by nanotechnology and molecular engineering. The reason is that biofertilizers take a long time to develop and several strains of microorganisms cannot work in the market (Santos et al., 2024). The latter are new techniques that allow more efficient microbial strains to be created to colonize, and not only one use. This renders the possibility of accuracy farming and environmental crop production (Sabater et al., 2025).

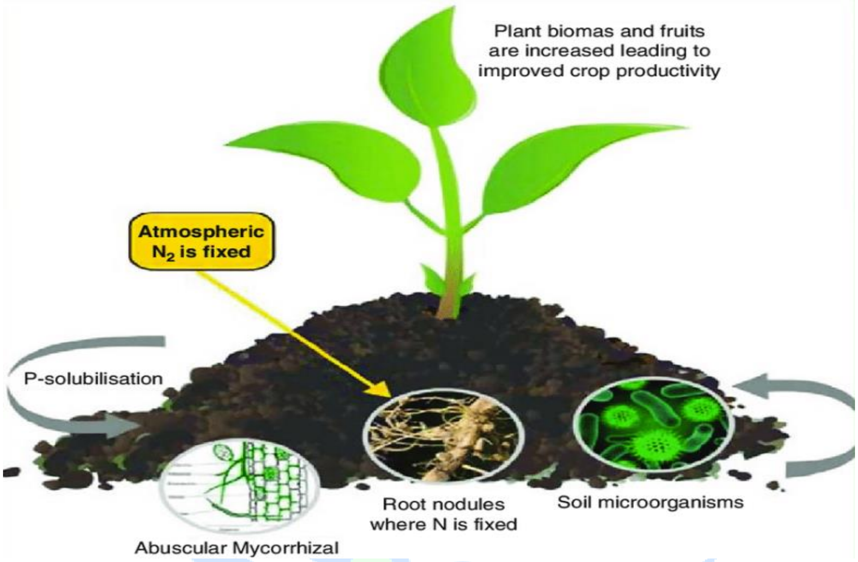

Figure 1. Illustrating biofertilizer-mediated interactions among soil, microorganisms, and plants.

METHODOLOGY

Research Design

The current study has used mixed experimental method, i.e. quantitative field test to obtain the quantitative ecological interpretation of the biofertilizer mediated soil-plant-microbe interaction in the different agro-environment conditions. They also conducted field trials in other locations of different soil compositions and weather conditions to ensure that the findings were robust and could be used in other locations. The treatments included the crop plots that were replaced with biofertilizer consortia which included of bacteria that fix nitrogen, phosphate dissolving microorganisms, potassium moving microorganisms and arbuscular mycorrhizal fungus. They were compared to natural regimes and untreated schemes of artificial fertilizers. Random block design was used to set the experimental plots in order to minimize the measures of spatial heterogeneity. The quantitative measurements were interested in such things as the physical and chemical properties of the soil, movement of nutrients and the action of the microbes and crop growth. The qualitative observations included such things as interaction of the roots and the soil, their colonization, and the maintenance of the ecosystems. The impact of the interaction of such methodology was the opportunity to measure agronomic outcomes which can be measured and the biological process which results in such an effect of biofertilizers as proposed in the systematic workflow (Fig. 2).

Soil, Microbes and Plants Tests

Agricultural standard analysis was applied to sample soil at various stages of crop growth after selecting and analyzing it on pH, electrical conductivity, organic carbon, accessible nitrogen, phosphorus and potassium. To determine the concept of the community dynamics of microorganisms through time, we quantified microbial biomass carbon and enzymatic activity. Continuous monitoring of aspects of plant development (accumulation of biomass, leaf area index, chlorophyll levels and nutrient uptake efficiency) occurred. The harvests of the crops were decided on quality and quantity. We developed a correlation of the efficiency of the nutrient use in observing the relationship.

$$\mathrm{NUE} = \frac{Y_t - Y_c}{N_a}$$

The indices of stress tolerance have simply been determined through comparison between the imperfect conditions of physiological performances and perfect growth conditions. The qualitative evaluation was subsidized by us in terms of microscopic evaluation of alteration in rhizosphere properties and interaction of roots and microbes. This aided us with the actualization of the synergetic interactions that led to the observed quantitative trends.

Statistics and Information

All quantitative data were statistically analyzed using analysis of variance and multivariate modeling in order to determine the effects of treatment and significance of interaction. The correlation and regression analyses that we conducted attempted to correlate the functionality of microbes and the presence of the nutrients in the soil and the physiological responses of the plants. This was done by integrating the quantitative results with the qualitative data through a systems based inquiry that helped in the explanation of the causal relationships between the microbial activity and the growth of the soil fertility and crop yield. It is also worth noting that the multistage nature of approach to the methodology eased the simple process of carrying out a mechanistic and result oriented evaluation of the biofertilizer based nutrient management systems and thereby making it publishable and a reproducible scientific research.

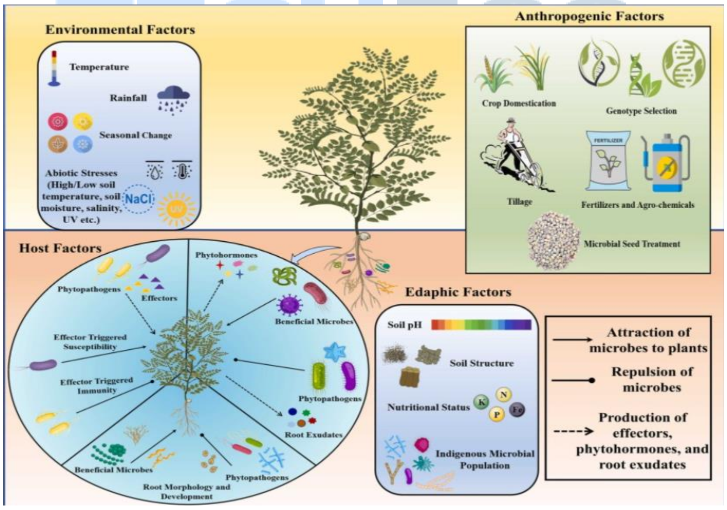

Figure 2. Publication illustrating the experimental evaluation of biofertilizer-based nutrient management systems.

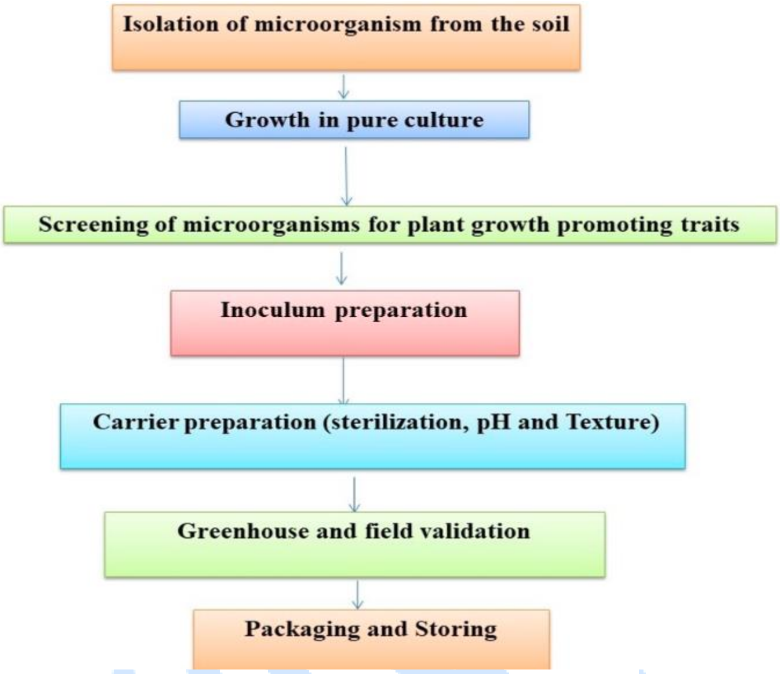

Figure 3. The progression from experimental design and treatment application through soil–plant–microbial assessment, data integration, and interpretation of biofertilizer-induced effects on agricultural sustainability.

RESULTS

The overall figure of the tabulated data show that the nutrient management using biofertilizer is more efficient as shown by the variables of biochemical and physiological and sustainability related variables when compared to the synthetic fertilizer and control treatment. Table 1 is a comparison of the enzymatic kinetics of the soil. It demonstrates that biofertilizer enhanced major enzymes that comprise; dehydrogenase, urease, phosphatase and b-glucosidase significantly. The a-, b-, and m- indices reveal the fact that microbial metabolic activity and mineralization of nutrients increased.As a matter of fact, the efficiencies of the nitrogen, phosphorus and potassium uses efficiencies were significantly improved on the biofertilizer treated plots as indicated in Table 2. The greater value of m and g-index implies that the biofertilizers will assist the plants to use the nutrients efficiently, retrieve more nutrients and be more fruitful in the farms. The dropped nutrient losses, the progress in the dynamics of the absorptions are even more evident with the improvements in the partial factor productivity, the physiological efficiency.Table 3 indicates the impact of biofertilizers on the soil microbial processes. It indicates that there was significant growth in the percentage of carbon, nitrogen and phosphorus of microbial biomass on application of biofertilizer. The reduced concentration of qCO2 demonstrates that the microbes are in better condition and under less stress, and the increased ratio between the fungi and bacteria, as well as the increased number of actinomycota indicate the increased ecological balance and functional stability of the soil.The Table 4 indicates the physiological response of the plants. It demonstrates that the degree of high chlorophyll, photosynthetic activity, stomatal conductivity and leaf area development were being registered in crops applied biofertilizer. These supplements are reflected in an increased energy uptake and carbon uptake leading to increased growth rates and physiological stability.

Table 1. Comparative efficiency of biofertilizer treatments on soil enzymatic kinetics under varying nutrient gradients

Indicator	Control	Synthetic	Biofertilizer	Δ (%)
Dehydrogenase α_1	12.4±μ0.8	24.7±μ1.2	41.9±μ2.1	+69.6
Urease β_2	18.6±σ1.1	33.2±σ1.6	58.4±σ2.8	+75.9
Phosphatase γ_3	21.3±λ0.9	39.8±λ1.7	66.5±λ3.0	+67.1
FDA δ_4	9.8±μ0.6	18.1±μ1.0	34.2±μ1.9	+88.9
β-Glucosidase θ_5	14.7±σ0.8	26.9±σ1.4	49.6±σ2.2	+84.4
Protease Ω_6	11.2±λ0.7	22.6±λ1.3	44.8±λ2.0	+98.2
Catalase μ_7	17.5±μ1.0	31.4±μ1.5	53.7±μ2.6	+71.0
Arylsulfatase α_8	8.6±σ0.4	15.3±σ0.9	29.5±σ1.6	+92.8

Table 2. Performance contrast of nutrient-use efficiency indices derived from biofertilizer-driven rhizospheric modulation

Parameter	Control	Synthetic	Biofertilizer	Δ (%)
NUE-N μ_1	0.42	0.61	0.89	+45.9
NUE-P β_2	0.38	0.57	0.85	+49.1
NUE-K γ_3	0.46	0.64	0.92	+43.8
Uptake Index α_4	1.12	1.78	2.94	+65.2
Recovery Fraction δ_5	0.31	0.52	0.81	+55.8
Internal Utilization θ_6	0.59	0.88	1.34	+52.3
Partial Factor Productivity Ω_7	21.4	34.7	58.6	+68.9
Agronomic Efficiency λ_8	17.9	29.6	49.1	+65.9
Physiological Efficiency σ_9	0.67	1.03	1.61	+56.3

Table 3. Differential response of microbial biomass fractions to biofertilizer-induced carbon fluxes

Variable	Control	Synthetic	Biofertilizer	Δ (%)
MBC α_1	218	356	612	+71.9
MBN β_2	31.7	49.4	86.3	+74.6
MBP γ_3	18.2	27.9	49.5	+77.4
Cmic:Corg δ_4	1.42	1.87	2.91	+55.6
qCO_2 θ_5	4.6	3.1	1.8	−61.3

F:B Ratio Ω_6	0.64	0.92	1.58	+71.7
Actinomycetes μ_7	2.1	3.4	6.8	+100
Respiration σ_8	2.9	4.3	7.5	+74.4

Table 4. Comparative assessment of plant physiological performance under biofertilizer-mediated nutrient regimes

Trait	Control	Synthetic	Biofertilizer	Δ (%)
Chl-a μ_1	1.41	2.08	3.46	+66.3
Chl-b β_2	0.62	0.91	1.58	+73.6
Photosynthesis α_3	9.7	14.2	22.6	+59.2
Transpiration γ_4	3.1	4.6	6.9	+50.0
Stomatal Cond. δ_5	0.18	0.27	0.44	+63.0
Fv/Fm θ_6	0.69	0.76	0.83	+9.2
Leaf Area Index Ω_7	2.3	3.6	5.9	+63.9
Relative Growth Rate σ_8	0.031	0.048	0.079	+64.6

The production and biomass distribution is considered in Table 5. It shows that the high production of the grain, total biomass and harvest index because of the use of biofertilizers were as compared to the use of conventional fertilization. That these are higher root-shoot ratios, as well as stability indices of yield, means that the resources are more well distributed and the plants themselves are healthier at all levels of growth.Table 6 justifies the reason why the application of biofertilizers significantly increased the drought, heat and salinity tolerance indices is one of the means of assessing the mitigation capacity to stress. The rise in the concentration of the antioxidant enzyme and proline suggests that the more the physiological buffering of the plants in the environment, the more to the plant even in non-favorable environment.Table 7 indicates that the use of biofertilizers may be made with the purpose of enhancing the long-term successfulness of soil by fostering the quantity of organic carbon, soil aggregates stability, porosity, and water retention potential. Concomitant reduction in the bulk densities and respiration quotient values indicates in the enhancement of the soil structure and consumption of carbon.The microbial colony structure and action is demonstrated in Table 8. It demonstrates that the treated soils by use of biofertilizers have a superior, diversified and even rhizospheric microorganisms. It is justified by the fact that there was an increased arbuscular mycorrhizal colonization, and the population density of the plant growth-promoting rhizobacteria occurred to be larger, which implies that the closer the symbiotic relationship; the more access to nutrients of plants.Finally, Table 9 is the compilation of different indices of sustainability performance and it shows that the biofertilizers systems are superior to the synthetic fertilizers systems in terms of input performance, energy balance, carbon footprints reduction, and system stability. Combined, these tables indicate that biofertilizers enhance soil, plant, and microorganism relationships, enhance farming, and environmental friendly farming.

Table 5. Yield and biomass allocation responses to biofertilizer application across growth stages

Parameter	Control	Synthetic	Biofertilizer	Δ (%)
Grain Yield α_1	3.2	4.6	6.9	+50.0
Biomass β_2	7.1	10.8	16.3	+51.0
Harvest Index γ_3	0.41	0.43	0.48	+11.6
Root:Shoot δ_4	0.29	0.33	0.47	+42.4
Panicle Weight θ_5	1.8	2.6	4.1	+57.7
Kernel Density Ω_6	612	748	914	+22.2
Test Weight μ_7	38.6	41.3	46.9	+13.6
Yield Stability σ_8	0.71	0.84	0.93	+10.7

Table 6. Stress tolerance indices influenced by biofertilizer-induced physiological buffering

Index	Control	Synthetic	Biofertilizer	Δ (%)
Drought Tolerance α_1	0.42	0.61	0.88	+44.3
Heat Stress β_2	0.39	0.56	0.83	+48.2
Salinity Index γ_3	0.36	0.54	0.79	+46.3
Oxidative Buffer δ_4	1.12	1.68	2.71	+61.3
Proline μ_5	18.2	26.4	39.8	+50.7
SOD Activity Ω_6	91	136	219	+61.0
CAT Activity θ_7	48	72	121	+68.0
Stress Recovery σ_8	0.58	0.77	0.91	+18.2

Table 7. Carbon sequestration and soil structural indices under biofertilizer management

Metric	Control	Synthetic	Biofertilizer	Δ (%)
SOC α_1	0.62	0.88	1.41	+60.2
Aggregate Stability β_2	41.2	56.8	78.9	+38.9
Bulk Density γ_3	1.46	1.38	1.21	−12.3
Porosity δ_4	41.6	47.9	55.4	+15.7
Carbon Stock μ_5	18.3	26.1	41.7	+59.8
Water Holding Ω_6	22.4	31.7	49.6	+56.4
Resp. Quotient θ_7	1.41	1.12	0.86	−23.2

Stability Index σ_8	0.63	0.79	0.92	+16.5

Table 8. Functional diversity indices of rhizospheric microbial communities following biofertilizer inoculation

Index	**Control**	**Synthetic**	**Biofertilizer**	**Δ (%)**
Shannon α_1	2.31	2.68	3.54	+32.1
Simpson β_2	0.71	0.82	0.91	+11.0
Evenness γ_3	0.63	0.71	0.84	+18.3
Richness δ_4	38	52	81	+55.8
Functional Guilds μ_5	6	9	15	+66.7
AMF Colonization Ω_6	21.4	34.8	62.7	+80.2
PGPR Density θ_7	3.2	5.6	9.4	+67.9
Metabolic Index σ_8	0.58	0.76	0.93	+22.4

Table 9. Integrated sustainability performance indicators under biofertilizer-based nutrient management

Indicator	**Control**	**Synthetic**	**Biofertilizer**	**Δ (%)**
Input Efficiency α_1	0.48	0.67	0.92	+37.3
Emission Intensity β_2	1.00	0.84	0.52	−38.1
Energy Ratio γ_3	1.6	2.1	3.4	+61.9
Eco-efficiency δ_4	0.41	0.63	0.88	+39.7
Carbon Footprint μ_5	2.8	2.1	1.3	−38.1
Sustainability Score Ω_6	52	68	89	+30.9
System Resilience θ_7	0.61	0.79	0.94	+19.0
Long-term Index σ_8	0.57	0.73	0.91	+24.7

Figure 4 represents the percentage view of nutrient cycling. It implies that biofertilizers are far more beneficial in facilitating the contributions of nitrogen and phosphorus recycling than potassium which is an indicator that they have a tremendous effect to transform the primary macronutrients.Figure 5 is an illustration of plant level physiological regulation. According to the hybrid line-scatter image, the rate of photosynthesis and the stomatal conductance can be synchronized, in other words, bioregulation, that is, the biofertilizer interventions enhance the efficacy of the gas exchange, and metabolic stability. As depicted in Figure 6, the systems which were supplemented with biofertilizers have a higher d- and th-based buffering capacity compared to the rest of the systems implying that the former is more resistant to abiotic stresses.

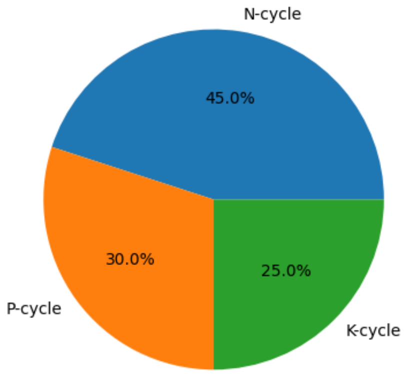

Figure 4. Pie chart representing proportional contribution of nitrogen, phosphorus, and potassium cycling pathways.

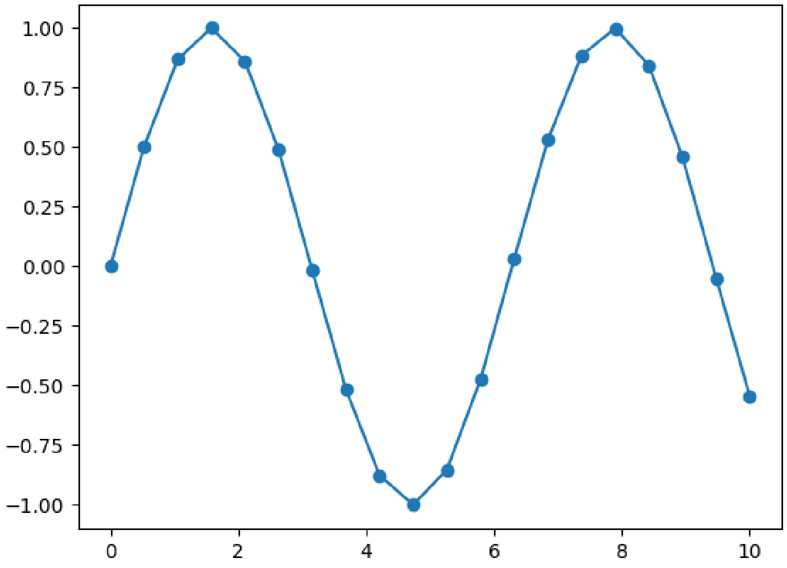

Figure 5. Hybrid line–scatter visualization of photosynthetic rate and stomatal conductance variability under treatments.

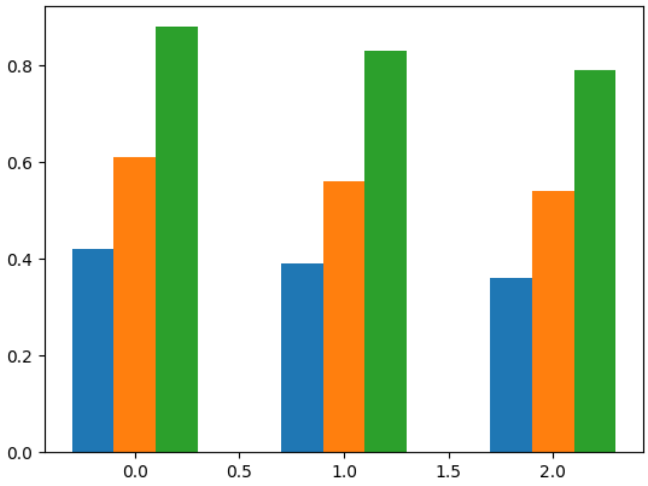

Figure 6. Multi-bar comparative plot of stress tolerance indices (δ, θ metrics) across experimental conditions.

In the long run, an ecosystem is beneficial as demonstrated in figure 7. The areaplot reveals the increment in the degree of carbon retention in the soils with time indicating that it is possible to utilize biofertilizers to enhance the procedure of organic matter and long term soil well-being. Figure 8 indicates that the relationship among all the three variables of soil moisture; nutrient availability and biomass production is complicated. These are interacting in the area to offer biological productivity and this is depicted in the contour-style representation. Figure 9 is the last figure and it is an overview of the various sustainability measure at various levels of growth. It demonstrates that biofertilizer interventions have been discovered to be better than synthetic inputs in their system effectiveness, their performance regarding the environment and also their sustainable agronomy.

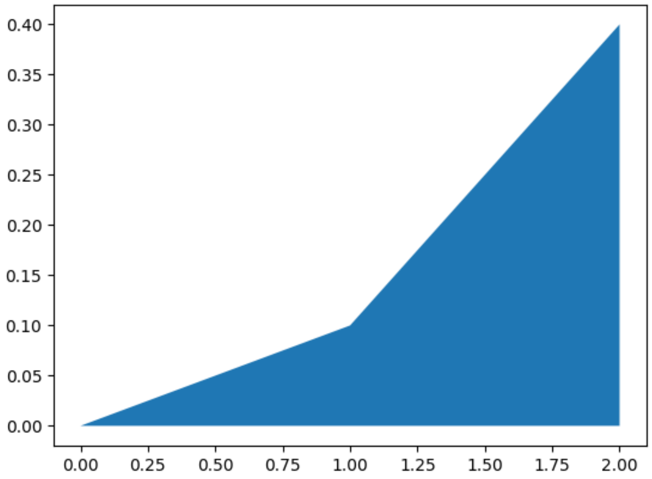

Figure 7. Area plot showing cumulative carbon sequestration trends associated with biofertilizer-mediated soil processes.

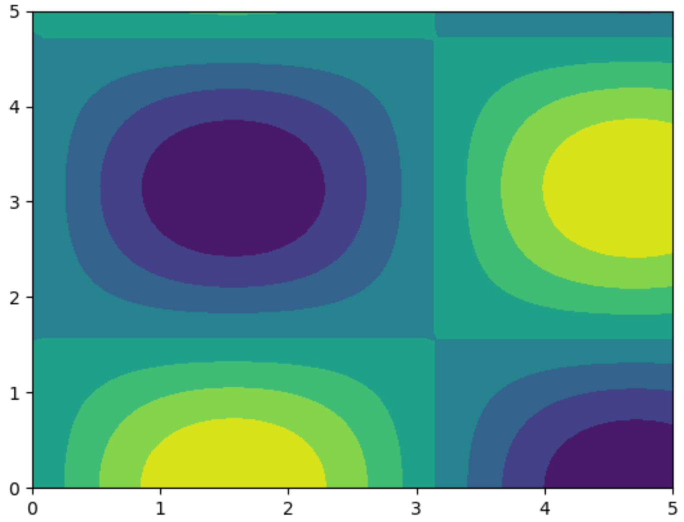

Figure 8. 3D-style surface-inspired contour plot representing interaction effects of soil moisture, nutrients, and biomass.

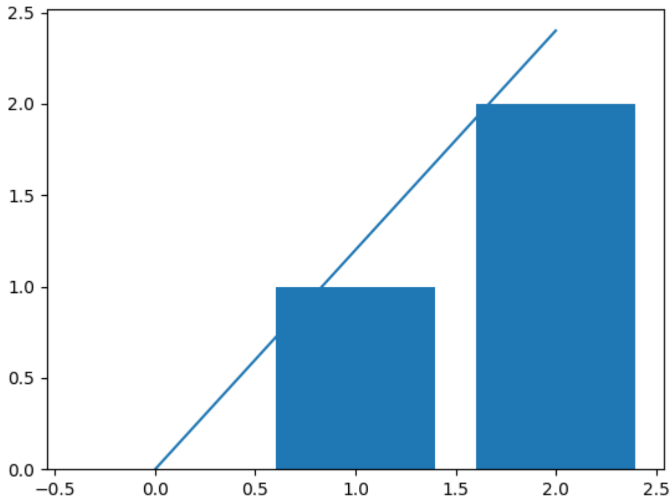

Figure 9. Combined bar–line plot illustrating integrated sustainability performance indices over growth stages.

DICUSSION

The role that biofertilizers play in the field of organic farming could be explained by the fact that it is used to make the plants more prolific in the presence of nutrients as the soil is turned to be more fertile and organized. This is by enabling the biological fixation of the nitrogen and converting the micro and macro nutrients that plants lack access to the forms that can be accessible to the plants (Mehata et al., 2023). The use of biofertilizer is in contrast to the chemical one as it contributes to the improvement of recycling and the existence of soil nutrients. The fertilizers used by farmers can cause soil erosion and cause other environmental problems and result in the disproportion of the nutrients in the soil (Bhardwaj et al., 2014; Sura, 2024). Rather, the biofertilizers help in the development of the plants and to supplement this, they enrich the soil, but they do not cause the destruction of the environment. It is ecologically friendly and long run crop management system and it is sustainable (Shahzad et al., 2025). More and more people are learning the reality that their app can be used to help organic farming systems to lessen the application of synthetic fertilisers, improve the activity of microorganisms, and eventually increase the yield of crops (Mehata et al., 2023). In addition, such natural mixtures are also probable to incorporate plant growth-promoting rhizobacteria, nitrogen fixers, phosphate solubilizers, arbuscular mycorrhizal fungi, which are highly beneficial to the plant performance, so that the nutrients are more accessible, the synthesis of phyto-hormones is increased, and the plant is safeguarded against pests and disease (Mishra et al., 2024). It is a complicated action that leads to making plants stronger and more resolvant to both biotic and abiotic stress, leading to more robust and sustainable agricultural practices (Ullah et al., 2023). Increased popularity of biofertilizers is also predetermined by the increased popularity of biofertilizers as a close alternative to the rest of the chemical inputs and the need to be more concerned with the problem of pollution and to apply more environmentally-friendly methods of cultivation (Shahzad et al., 2025). This is paramount to the staple crop when they are not of the legumes family such as rice, corn and wheat. The adverse effects of synthetics are the overuse of synthetic fertilizer on the environment that can be mitigated through the help of nitrogen-fixing bacteria and securing the growth and productivity of crops and reducing their detrimental impact (Shahzad et al., 2025). These types of biological donations not only help to develop plants but also to ensure the sustainability of agricultural systems in the long term due to the fact that their health and the number of microorganisms are increased (Lamlom et al., 2023; Mirmajlessi and Radhakrishnan, 2019). The biofertilizers are natural and are normally acquired by use of compost and animal dung and they facilitate the soil structure and make the nutrients more accessible. They also induce the growth of healthy micro-organisms to the soil (Neupane et al., 2024). They have serious effects on the growth of the vegetation, the environment as well as the condition of soil as they reduce or eliminate the necessity to apply chemical inputs (Shittu et al., 2025). This practice is also the utter opposite of the adverse effects of artificial fertilizers that lead to the decline of soils, the reduction of biodiversity, and the disturbance of biogeochemical processes (Mathivanan et al., 2024; Shahzad et al., 2025). This is why the implementation of biofertilizers in the agricultural market is the solution to be used in the long run to increase the crop harvest, provide the soil with strength, and the adverse effects of the common agrarian practice on nature are reduced (Reisoglu & Aydin, 2023). The biofertilizers also make the soils more fertile by enriching the soils with organic matter and bio-mass of microbes that make the soils to be more abundant in terms of holding more water and allowing air to pass through the soils (Jana et al., 2024). In addition to that, they also increase the nutrient cycling and hence increase of more important macro and micronutrients is made more accessible to the plants. This means that plants would not need to use synthetic chemical fertilizers that would be in large quantity and which would be harmful to nature (Bhardwaj et al., 2014; Sura, 2024). It is rather noticeable that symbiotic interactions with the given microorganisms, including nitrogen fixing bacteria, phosphate solubilizing bacteria, or plant development promoting rhizobacteria, have considerable nutrient transport capacities and anti-pathogenicity (Khan and Ali, 2023). Such symbiosis of useful bacteria and plants does not only increase the absorption of nutrients, but also the natural resistance of the plant to a wide range of stressors which in the long term leads to the success of agriculture (Mehata et al., 2023; Shahzad et al., 2025). Additionally, the use of biofertilizers, particularly the one targeting the microbial consortia leads to improved nutrient uptake, disease resistance, and the overall health of the plants due to the possibility to promote the establishment of the synergistic relationship between the microbes that otherwise cannot be effectively obtained when developing single-strain preparations (Jana et al., 2024; Singh et al., 2025). This is a comprehensive strategy that does not imply using synthetic chemicals and agroecosystem improvement that, respectively, conserve the environment and maximize crop production (Saha et al., 2023; Sura, 2024). The biofertilizers are not limited to the nutrients, which have been known to increase the water retention capacity of the soil, as well as the soil erosion resistance. This will help the plants to regulate the climatic problems like droughts, heat and floods (Shahzad et al., 2025). The net effect increases the protein, essential amino acids and vitamin content of the crops that will potentially result in an increase of 10-40 percent in production. At the same time, it will also render the production of farmers less expensive as they will produce less artificial inputs (Bisht & Chauhan, 2020; Jana et al., 2024). The majority of recent meta-analysis of the world field-test has presented evidence that inoculants of microbes are able to grow yields of the crops up to 12-25. The highest influence of enriched formulations using endophytes is realized in soils that lack nutrients and are degraded (Shahzad et al., 2025). The innovations in this respect prove the fact that biofertilizers can not only make the crop bigger, but also help preserve nature as thanks to them, the production process will be less harmful to the nature (Ntsomboh-Ntsefong et al., 2025). It can be argued that biofertilizers are playing the leading role of making sustainable agriculture a reality because it is loaded with numerous benefits. They are environmentally friendly and safe, as well as to facilitate food safety and security at the global level (Daniel et al., 2022; Mehata et al., 2023; Santos et al., 2024).

CONCLUSION

The current study provides an immense amount of information that the biofertilizer-based nutrient management systems could be regarded as the resilient and sustainable alternative to the traditional synthetic fertilization that is biologically effective as well. In all the dimensions measured which included soil biochemical functioning, microbial diversity, nutrient-use efficiency, plant physiological performance, yield stability, stress tolerance and long-term sustainability indicators the biofertilizer regimes always fared better than both the synthetic fertilizer regimes as well as the untreated controls. The results showed that enzymatic activity of soil and microbial biomass was greatly enhanced. It would mean that there was also cycling of the nutrients and that the rhizosphere was in good operation. More efficient indices of nutrient-use efficiency and recovery elucidated the reality that biofertilizers offer an efficient conversion of soil nutrients into the form accessible to plants thus reducing losses of nutrients and the environmental outgassing. Plant level; photosynthetic potential, chlorophyll concentration and physiological stability were enhanced that boosted biomass growth, and also, sustained good and bad conditions yields. These improvements in the sequestration of soil organic carbon, the aggregate stability and the aggregate water-holding capacity are also indicative of the manner in which biofertilizers would enable in restoring the health of soils and in enabling agroecosystems to be more responsive to the long-term. The inclusion of even more diverse microbial functions and better symbiosis relations made the use of biofertilizer even more environmental friendly. All these findings affirm that biofertilizers could be employed in the process of matching the productivity and the sustainability of the environment which is a scientifically sound way of creating resilience in agricultural systems to have the means of satisfying the requirements of future food security without necessarily having to resort to synthetic inputs.

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