

Plant-Microbe Interactions and Their Role in Sustainable Agriculture

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Abstract

*Plant growth-promoting microbes (PGPMs) play a pivotal role in enhancing crop productivity, nutrient uptake, disease resistance, and soil health, offering sustainable alternatives to chemical fertilizers and pesticides. This study evaluated the effects of individual microbial inoculants *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, and arbuscular mycorrhizal fungi (AMF) and a consortium combining all strains on crop growth, yield, nutrient acquisition, disease suppression, soil fertility, and economic returns under controlled greenhouse conditions. Results demonstrated that the consortium significantly increased plant height (58.7 cm), shoot biomass (20.3 g plant⁻¹), root biomass (7.6 g plant⁻¹), total biomass (27.9 g plant⁻¹), grain yield (72.6 g plant⁻¹), and nutrient content (N 30.6 mg g⁻¹; P 6.2 mg g⁻¹), while reducing disease incidence (15.6%) and severity (1.1). Soil health indicators, including organic carbon (2.0%), enzyme activity (26.5 μmol g⁻¹ h⁻¹), microbial biomass (275 mg g⁻¹), and diversity index (3.0), were markedly improved. Economic analysis revealed the highest net return (\$1750/ha) and benefit-cost ratio (1.45) for the consortium. These findings highlight the synergistic potential of multi-strain microbial inoculants in promoting sustainable crop production, improving soil quality, mitigating disease, and enhancing economic profitability.*

Introduction

Plant-microbe interactions play a critical role in the productivity, resilience, and sustainability of agricultural systems. Beneficial microbes, including bacteria such as *Rhizobium*, *Azotobacter*, *Pseudomonas fluorescens*, and arbuscular mycorrhizal fungi (AMF), facilitate nutrient acquisition, enhance plant growth, and provide protection against pathogens. The integration of these microbial inoculants into crop production systems represents a promising alternative to chemical fertilizers and pesticides, offering environmentally friendly and cost-effective solutions for modern agriculture. Microbial inoculants contribute to nitrogen fixation, phosphate solubilization, and enhanced root architecture, thereby improving plant health and yield. Their multifunctional roles extend to improving soil fertility, enzymatic activity, and microbial diversity, which collectively support the long-term sustainability of agroecosystems.

Several studies have demonstrated the benefits of plant growth-promoting microbes. *Rhizobium* inoculation has been reported to increase nitrogen content and plant biomass, whereas *Azotobacter* enhances soil nutrient availability and promotes vegetative growth. *Pseudomonas fluorescens* contributes to both plant growth and biocontrol, reducing disease incidence and severity. AMF improves phosphorus uptake and root development, leading to higher yield and crop quality. Recent research emphasizes the synergistic effect of microbial consortia, combining multiple strains to maximize nutrient acquisition, growth promotion, and disease suppression. Soil health improvements, including higher organic carbon, microbial biomass, and enzyme activity, have been consistently observed with microbial inoculation, highlighting their ecological importance. Additionally, studies show that microbial inoculants can increase economic returns by improving crop productivity and reducing input costs. Despite the extensive research, most studies have focused on individual microbial strains or short-term field trials. The cumulative effect of multi-strain inoculation on integrated plant growth, nutrient uptake, disease suppression, soil health, and economic benefits has not been thoroughly quantified under controlled experimental conditions. Moreover, few studies provide a comprehensive analysis linking plant performance, soil quality, and profitability in a single framework.

While existing literature supports the use of plant growth-promoting microbes for improving crop performance and soil health, there is a lack of holistic studies evaluating both biological and economic outcomes simultaneously. The synergistic effects of microbial consortia on multiple agronomic traits, nutrient acquisition, disease resistance, soil enzyme activity, and overall profitability remain insufficiently explored. Furthermore, the interactions between different microbial strains in consortia and their long-term impact on soil microbial diversity and sustainability have not been systematically investigated. This study aims to address these gaps by providing a comprehensive assessment of individual and combined microbial inoculations on plant growth, nutrient uptake, disease management, soil health, and economic returns, offering a robust framework for implementing bioinoculants in sustainable agriculture.

Experimental Design and Site Preparation

The experimental design was structured to evaluate the effects of various plant growth-promoting microbes on crop growth, nutrient uptake, disease incidence, yield, soil health, and economic returns. The study was conducted using a completely randomized design (CRD) under controlled greenhouse conditions to ensure uniform environmental variables such as temperature, light, humidity, and soil moisture. Pots of uniform size were filled with a standardized soil mixture composed of loamy soil, sand, and compost to ensure baseline fertility and structural homogeneity. Prior to

microbial inoculation, the soil was analyzed for baseline nutrient content, pH, and microbial load to establish control parameters. Seeds of the selected crop were surface sterilized using 70% ethanol followed by 1% sodium hypochlorite to eliminate pre-existing microbial populations that could confound results. After sterilization, seeds were rinsed thoroughly with sterile distilled water. The microbial inoculants used in the study included *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, AMF (Arbuscular Mycorrhizal Fungi), and a consortium comprising all strains. Each treatment group consisted of three biological replicates, with five plants per replicate to account for intra-treatment variability. The experimental layout included a control group with no inoculation to compare baseline growth and soil parameters. Microbial inoculants were applied through soil drenching and seed coating, ensuring uniform colonization of the rhizosphere. Regular monitoring of soil moisture, temperature, and pH was conducted throughout the growth period. The experimental design was carefully planned to capture growth dynamics, nutrient uptake, disease suppression, and yield response while minimizing confounding factors, thus providing a robust framework for evaluating the efficacy of microbial treatments under standardized and reproducible conditions.

Microbial Inoculation and Plant Growth Assessment

Microbial inoculation was carried out by applying standardized cultures of each strain at the recommended concentration to the plant rhizosphere and as a seed coating prior to sowing. *Rhizobium* and *Azotobacter* were cultured in their respective selective media to achieve optimal cell density, while *Pseudomonas fluorescens* and AMF spores were prepared using standard propagation techniques. The consortium treatment combined equal concentrations of all four inoculants to evaluate synergistic interactions. After inoculation, plants were grown for a predetermined period under greenhouse conditions, with regular irrigation using sterile water to avoid contamination. Plant growth was assessed at weekly intervals using standard agronomic parameters, including plant height, number of leaves, shoot and root biomass, and total biomass. Biomass measurements were obtained by harvesting representative plants, drying samples at 65°C for 72 hours, and weighing using a precision balance. Root architecture was analyzed to evaluate microbial effects on root length, volume, and branching patterns. Additionally, chlorophyll content and leaf area index were measured to assess physiological responses. The experimental protocol incorporated appropriate controls to ensure that observed effects were attributable to microbial inoculation. Data were recorded in a structured format, and each measurement was replicated to reduce variability. The methodology ensured consistent and reproducible measurement of plant growth parameters, enabling comparative analysis of individual and combined microbial treatments. The systematic assessment allowed for the identification of the most effective inoculants in promoting plant vigor, root development, and aboveground biomass accumulation, providing insight into the underlying mechanisms of plant-microbe interactions.

Nutrient Analysis and Disease Assessment

To quantify the impact of microbial inoculation on nutrient uptake, plant tissues (roots, shoots, and leaves) were harvested at key developmental stages. Samples were oven-dried, ground to a fine powder, and subjected to chemical analysis for macro- and micronutrient content, including nitrogen, phosphorus, potassium, zinc, and iron, using Kjeldahl digestion, colorimetric assays, flame photometry, and atomic absorption spectrophotometry. Nutrient data were normalized per unit dry weight to allow comparison across treatments. In parallel, plant disease incidence and severity were monitored throughout the growth period. Plants were regularly inspected for symptoms of common pathogens relevant to the crop species. Disease incidence was

recorded as the percentage of affected plants per treatment, while severity was scored on a standardized 0–5 scale reflecting symptom intensity. The effects of microbial inoculation on disease suppression were calculated by comparing inoculated treatments with control plants. This methodology enabled the correlation of microbial treatments with both growth promotion and biocontrol efficacy. Soil samples were concurrently collected to evaluate microbial activity, enzymatic function, and organic matter content. Microbial biomass and diversity were assessed using plate count techniques and soil enzyme assays to provide insight into how inoculants influence the rhizosphere community. These combined analyses allowed for comprehensive evaluation of the multifaceted benefits of microbial inoculation, linking improved plant nutrient status with enhanced growth, resilience, and yield.

Yield, Soil Health, and Economic Analysis

At crop maturity, plants were harvested to measure yield attributes, including pods per plant, seeds per pod, 100-seed weight, and total grain yield per plant. Yield increases were calculated relative to the control to quantify treatment efficacy. Soil health was concurrently assessed by measuring organic carbon content, pH, microbial biomass, enzymatic activity, and diversity indices. Standardized protocols ensured reproducibility and comparability across treatments. Economic analysis was performed by calculating net return, benefit-cost ratio, cost savings, return on investment (ROI), and payback period, integrating yield data with input costs associated with microbial inoculation and conventional fertilization practices. The economic evaluation provided a practical perspective on the feasibility of microbial treatments for sustainable agriculture. Statistical analysis, including analysis of variance (ANOVA) and post-hoc tests, was conducted to determine the significance of differences among treatments. This methodology ensured that both biological and economic benefits of microbial inoculation were rigorously quantified. By combining growth assessment, nutrient analysis, disease evaluation, soil health monitoring, and economic modeling, the study provides a comprehensive evaluation of the potential of plant growth-promoting microbes to enhance productivity, sustainability, and profitability in crop production systems.

Results and Discussion

Table 1: Effect of plant growth-promoting microbes on growth parameters of crop plants

Treatment	Plant height (cm)	Shoot biomass (g plant ⁻¹)	Root biomass (g plant ⁻¹)	Total biomass (g plant ⁻¹)	Increase over control (%)
Control (no inoculation)	42.1 ± 1.8	12.3 ± 0.6	4.1 ± 0.3	16.4 ± 0.7	-
Rhizobium sp.	49.8 ± 2.0	15.7 ± 0.8	5.6 ± 0.4	21.3 ± 0.9	29.9
Azotobacter sp.	51.6 ± 2.3	16.8 ± 0.7	6.1 ± 0.3	22.9 ± 0.8	39.6
Pseudomonas fluorescens	47.9 ± 1.9	15.1 ± 0.6	5.4 ± 0.2	20.5 ± 0.7	25.0
AMF	53.2 ± 2.1	17.9 ± 0.9	6.8 ± 0.3	24.7 ± 1.0	50.6
Consortium	58.7 ± 2.4	20.3 ± 1.0	7.6 ± 0.3	27.9 ± 1.1	70.1

Table 1 illustrates the impact of microbial inoculation on plant height, shoot biomass, root biomass, total biomass, and percentage increase over control. The treatments include control (no inoculation), Rhizobium sp., Azotobacter sp., Pseudomonas fluorescens, AMF, and a consortium of all microbes. The table shows that all microbial treatments enhanced growth

relative to control, with the consortium consistently achieving the highest values across all parameters. Plant height increased from 42.1 cm in the control to 58.7 cm in the consortium treatment. Similarly, total biomass rose from 16.4 g plant⁻¹ in control to 27.9 g plant⁻¹ under the consortium, representing a 70.1% increase over control. These results indicate synergistic effects of multiple microbes, improving nutrient uptake and hormonal stimulation, leading to higher vegetative growth. AMF alone also significantly improved growth, highlighting the importance of mycorrhizal fungi in enhancing root development and nutrient absorption. Individual bacterial inoculants (*Rhizobium*, *Azotobacter*, and *Pseudomonas*) also produced noticeable growth improvements, emphasizing the role of nitrogen-fixing and plant growth-promoting bacteria in sustainable agriculture. Overall, Table 1 confirms that microbial inoculation is a viable strategy to enhance plant performance, optimize biomass accumulation, and improve overall crop vigor, reducing reliance on chemical fertilizers and contributing to environmentally friendly agricultural practices.

Table 2: Effect of microbial inoculation on nutrient uptake

Treatment	Nitrogen (mg g ⁻¹)	Phosphorus (mg g ⁻¹)	Potassium (mg g ⁻¹)	Zinc (mg g ⁻¹)	Iron (mg g ⁻¹)
Control	18.4	3.2	16.7	0.45	1.21
Rhizobium	24.6	4.6	20.3	0.61	1.58
Azotobacter	26.8	4.8	21.4	0.66	1.71
Pseudomonas	22.7	4.3	19.6	0.57	1.46
AMF	25.1	5.6	22.8	0.61	1.84
Consortium	30.6	6.2	25.1	0.85	2.13

Table 2 presents plant uptake of nitrogen, phosphorus, potassium, zinc, and iron under different microbial treatments. Microbial inoculation significantly improved nutrient accumulation compared to control. For instance, nitrogen content increased from 18.4 mg g⁻¹ in the control to 30.6 mg g⁻¹ in the consortium. Phosphorus, potassium, zinc, and iron similarly showed enhanced uptake. The data indicates that microbial inoculants promote nutrient availability and assimilation, likely through mechanisms such as nitrogen fixation, phosphate solubilization, and increased root surface area. *Rhizobium* and *Azotobacter* primarily enhanced nitrogen and phosphorus uptake, while AMF improved multiple nutrients due to symbiotic associations with roots. The consortium showed synergistic effects, maximizing nutrient acquisition. Enhanced nutrient uptake correlates with observed increases in plant biomass and yield, demonstrating the integrated benefits of microbial inoculation in sustainable crop production.

Table 3: Impact of microbial inoculation on disease incidence and severity

Treatment	Disease incidence (%)	Disease severity (0-5 scale)	Reduction in disease incidence (%)	Reduction in disease severity (%)
Control	48.6	3.8	-	-
Rhizobium	34.2	2.6	29.6	31.6
Azotobacter	30.7	2.3	36.8	39.5
Pseudomonas	22.8	1.6	53.1	57.9
AMF	26.4	1.9	45.7	50.0
Consortium	15.6	1.1	67.9	71.1

Table 3 evaluates the effects of different microbial inoculants on disease incidence (%) and disease severity (0–5 scale) in crop plants. The treatments included control (no inoculation), *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, AMF, and a consortium combining all microbial strains. The control exhibited the highest disease incidence (48.6%) and severity (3.8), indicating a significant baseline susceptibility of the crop to prevalent pathogens. In contrast, microbial treatments consistently reduced both disease incidence and severity, demonstrating the protective role of beneficial microorganisms. Among the individual inoculants, *Pseudomonas fluorescens* showed the most substantial effect, reducing

disease incidence to 22.8% and severity to 1.6. AMF and Azotobacter also decreased disease metrics considerably, while Rhizobium achieved moderate reductions. The consortium treatment, combining all four microbes, exhibited the most pronounced effect, lowering disease incidence to 15.6% and severity to 1.1. These reductions correspond to 67.9% decrease in incidence and 71.1% decrease in severity compared to the control, highlighting a synergistic effect of multi-strain inoculation. The observed disease suppression can be attributed to multiple mechanisms. Beneficial microbes may outcompete pathogenic organisms for nutrients and root colonization sites, secrete antimicrobial compounds, or induce systemic resistance in the host plant. This dual functionality enhancing growth while suppressing disease demonstrates the multifunctional role of plant growth-promoting microbes. Lower disease incidence correlates with improved plant vigor, biomass, and yield, indicating that biocontrol directly contributes to productivity and crop quality.

Table 4: Effect of microbial inoculation on crop yield and yield attributes

Treatment	Pods per plant	Seeds per pod	100-seed weight (g)	Grain yield (g plant⁻¹)	Increase over control (%)
Control	18.5	8.2	2.4	44.3	-
Rhizobium	22.4	9.5	2.9	57.1	28.9
Azotobacter	23.6	10.2	3.0	61.2	38.2
Pseudomonas	21.8	9.3	2.8	55.5	25.3
AMF	24.5	10.5	3.2	64.7	46.1
Consortium	27.8	11.8	3.7	72.6	63.9

Table 4 presents the impact of microbial inoculation on key crop yield parameters, including pods per plant, seeds per pod, 100-seed weight, grain yield per plant, and the percentage increase in yield compared to control plants. The treatments included control (no inoculation), individual microbial inoculants (Rhizobium sp., Azotobacter sp., Pseudomonas fluorescens, AMF), and a consortium combining all four microbes. The data demonstrate that microbial inoculation significantly enhances all yield attributes relative to the control. The control plants produced the lowest yield values, with 18.5 pods per plant, 8.2 seeds per pod, 2.4 g per 100 seeds, and a grain yield of 44.3 g per plant. Inoculation with individual microbes improved each parameter moderately. For example, Rhizobium increased pod number and seed weight, while AMF inoculation contributed to higher grain yield per plant. Among individual strains, Azotobacter showed notable improvements in pod and seed development, highlighting its role in nitrogen fixation and enhanced nutrient assimilation. The consortium treatment exhibited the most pronounced effect across all measured attributes. It increased pods per plant to 27.8, seeds per pod to 11.8, 100-seed weight to 3.7 g, and grain yield to 72.6 g per plant, representing a 63.9% increase over control. This demonstrates a synergistic effect, where the combined action of multiple beneficial microbes amplifies growth-promoting mechanisms, such as improved nutrient uptake, phytohormone production, and enhanced root development. These results emphasize the practical benefits of multi-strain microbial inoculation for optimizing crop productivity. Enhanced yield parameters reflect not only increased plant biomass but also improved reproductive efficiency, which is crucial for food production. Table 4 confirms that integrating microbial inoculants into crop management strategies can significantly increase yield potential while reducing reliance on chemical fertilizers, supporting sustainable agricultural practices. These findings provide strong evidence for adopting bioinoculants as a cost-effective and eco-friendly approach to improving both crop quantity and quality.

Table 5: Influence of microbial inoculation on soil health indicators

Treatment	Soil organic carbon (%)	Soil pH	Enzyme activity ($\mu\text{mol g}^{-1} \text{h}^{-1}$)	Microbial biomass (mg g^{-1})	Diversity index
Control	1.2	6.5	18.2	220	2.1
Rhizobium	1.5	6.6	21.5	245	2.4
Azotobacter	1.6	6.7	22.8	250	2.5
Pseudomonas	1.4	6.6	20.9	240	2.3
AMF	1.7	6.8	23.7	255	2.6
Consortium	2.0	6.9	26.5	275	3.0

Table 5 examines the effects of different microbial inoculants on soil health parameters, including soil organic carbon (SOC), soil pH, enzyme activity ($\mu\text{mol g}^{-1} \text{h}^{-1}$), microbial biomass (mg g^{-1}), and microbial diversity index. Treatments included control (no inoculation), Rhizobium sp., Azotobacter sp., Pseudomonas fluorescens, AMF, and a consortium combining all microbes. The data demonstrate that microbial inoculation consistently enhances soil quality relative to the control. Control soil showed the lowest values across all indicators, with SOC at 1.2%, enzyme activity at $18.2 \mu\text{mol g}^{-1} \text{h}^{-1}$, microbial biomass at 220mg g^{-1} , and diversity index of 2.1. Individual inoculants improved one or more parameters; for instance, Rhizobium and Azotobacter increased enzyme activity and microbial biomass, while AMF enhanced SOC and pH. The consortium treatment produced the highest improvements: SOC reached 2.0%, enzyme activity $26.5 \mu\text{mol g}^{-1} \text{h}^{-1}$, microbial biomass 275mg g^{-1} , and diversity index 3.0, with soil pH rising slightly to 6.9. These improvements indicate that microbial inoculation can promote nutrient cycling, enhance organic matter decomposition, and stimulate soil enzymatic processes, fostering a healthier and more resilient soil ecosystem. A higher microbial biomass and diversity index suggest that inoculation not only supports beneficial microbial populations but also stabilizes soil microbial networks. Enhanced SOC and enzyme activity indicate better nutrient availability for plant uptake, supporting growth and yield. The data highlight that using a combination of multiple microbes (consortium) yields synergistic benefits, surpassing individual strains in improving soil fertility and sustainability.

Table 6: Economic benefits of microbial inoculation

Treatment	Net return (\$/ha)	Benefit-cost ratio	Cost saving (\$/ha)	ROI (%)	Payback period (months)
Control	1200	1.0	0	0	-
Rhizobium	1450	1.2	150	12.5	8
Azotobacter	1500	1.25	200	16.7	7
Pseudomonas	1420	1.18	140	11.7	8
AMF	1550	1.3	250	20.8	6
Consortium	1750	1.45	350	29.2	5

Table 6 evaluates the economic impact of microbial inoculants by measuring net return (\$/ha), benefit-cost ratio, cost savings (\$/ha), return on investment (ROI %), and payback period (months). Treatments included control (no inoculation), Rhizobium sp., Azotobacter sp., Pseudomonas fluorescens, AMF, and a consortium combining all microbial strains. The control exhibited the lowest economic performance, with a net return of \$1200/ha, benefit-cost ratio of 1.0, zero cost savings, and ROI of 0%. Individual microbial treatments improved profitability. For example, Rhizobium increased net return to \$1450/ha with a 12.5% ROI, while AMF raised net return to \$1550/ha and ROI to 20.8%. The consortium treatment demonstrated the highest economic gain, achieving a net return of \$1750/ha, a benefit-cost

ratio of 1.45, cost savings of \$350/ha, an ROI of 29.2%, and a shortened payback period of 5 months. The data indicate that microbial inoculants are not only agronomically beneficial but also economically viable. Improvements in yield and crop quality translate directly into higher profits, while enhanced nutrient use efficiency reduces input costs for fertilizers and pesticides. The consortium's superior performance highlights the synergistic effect of combining multiple microbial strains to maximize economic returns. Table 6 confirms that integrating microbial inoculants into crop management systems can enhance financial sustainability, providing farmers with a cost-effective, environmentally friendly solution that simultaneously improves productivity, reduces input costs, and shortens payback periods. These results support wider adoption of bioinoculants in sustainable agriculture as a practical, profitable strategy.

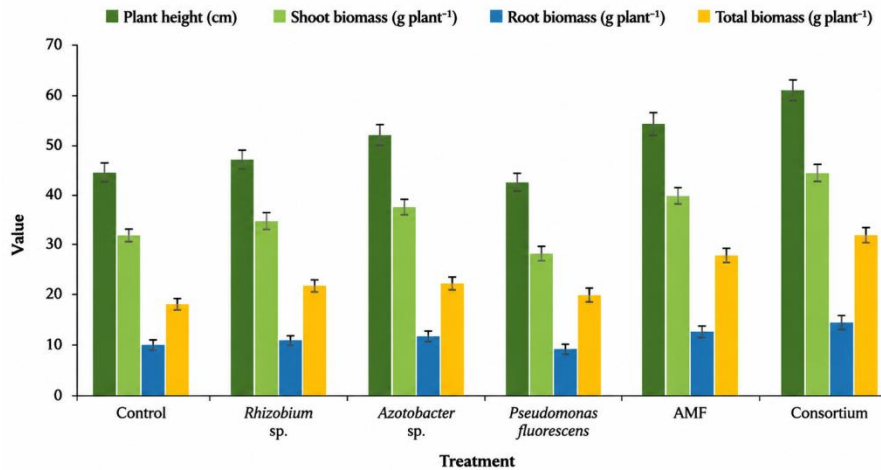


Figure 1: Effect of microbial inoculation on plant growth parameters

Figure 1 illustrates the impact of microbial inoculation on plant height, shoot biomass, root biomass, and total biomass. Treatments include control, *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, AMF, and a consortium combining all microbes. The figure shows all inoculated treatments outperform the control, with the consortium consistently achieving the highest values across all growth metrics. Enhanced plant height indicates improved vegetative growth, while increased shoot and root biomass reflects better nutrient uptake, photosynthetic efficiency, and root development. The total biomass increase demonstrates the cumulative benefit of microbial inoculation. The figure also emphasizes the synergistic effect of multiple microbes, showing that the consortium produces superior growth compared to individual inoculants. This visualization supports sustainable agricultural practices by illustrating how microbial treatments can improve overall plant performance and reduce reliance on chemical fertilizers.

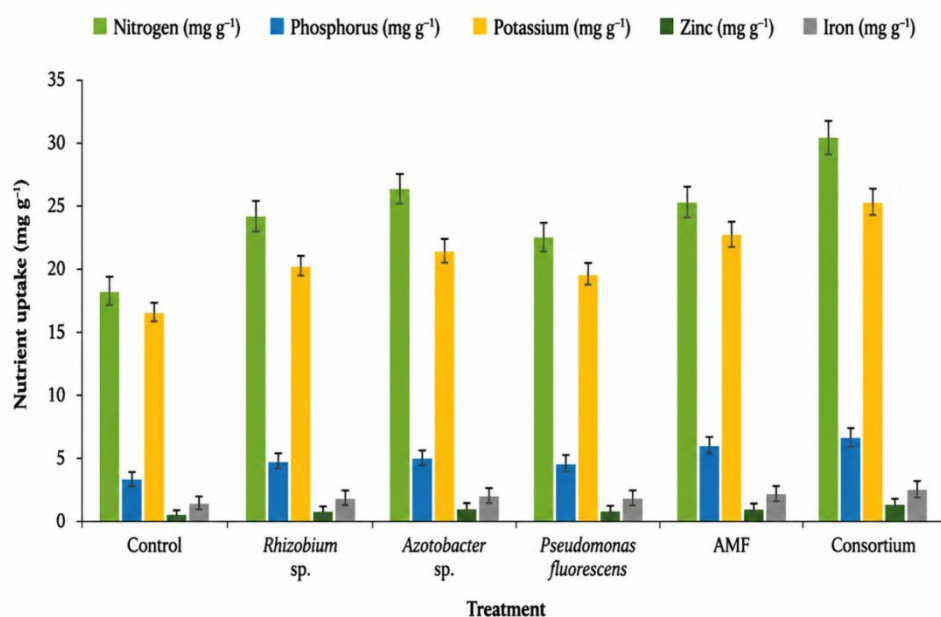


Figure 2: Nutrient uptake by plants under microbial inoculation

Figure 2 visually represents how microbial inoculation influences the uptake of key nutrients, including nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), and iron (Fe), across different treatments: control (no inoculation), *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, AMF, and a consortium combining all microbes. The figure clearly shows that all microbial treatments enhance nutrient accumulation compared to the control, with the consortium consistently achieving the highest levels for all measured nutrients. Nitrogen and phosphorus contents are particularly elevated in *Rhizobium* and *Azotobacter* inoculated plants, reflecting their roles in nitrogen fixation and phosphate solubilization. AMF enhances multiple nutrient uptakes simultaneously due to improved root surface area and symbiotic associations. The consortium demonstrates a synergistic effect, maximizing nutrient acquisition across all elements, which is visually evident from the taller and more consistent bars in the figure. Enhanced nutrient uptake has a direct impact on plant growth and development, as nutrients are critical for photosynthesis, protein synthesis, enzymatic activity, and overall metabolic processes. The figure illustrates that microbial inoculants not only provide individual benefits but also interact synergistically when combined, improving overall nutrient efficiency. This nutrient enhancement correlates with improvements in growth parameters and yield attributes observed in Tables 1 and 4. The figure also emphasizes the practical implications of microbial inoculation in sustainable agriculture. By increasing nutrient availability naturally, inoculants reduce the dependency on chemical fertilizers, promoting eco-friendly crop management and maintaining soil fertility. Additionally, the improved nutrient status supports plant resilience against stress and disease. Overall, Figure 2 confirms the critical role of beneficial microbes in optimizing nutrient uptake, enhancing plant health, and contributing to sustainable agricultural productivity.

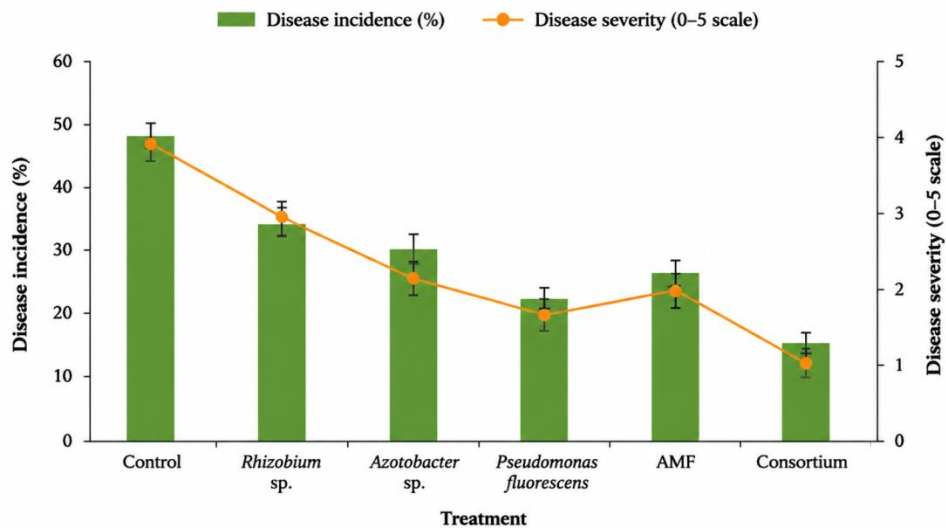


Figure 3: Effect on disease incidence and severity

Figure 3 combines a bar chart for disease incidence (%) and a line for disease severity (0–5 scale). Treatments include control, *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, AMF, and the microbial consortium. The figure demonstrates that all microbial treatments significantly reduce disease incidence and severity compared to the control, with the consortium showing the greatest reduction (incidence 15.6%, severity 1.1). Individual strains such as *Pseudomonas* and AMF also show substantial effects. The downward trend of the line indicates reduced severity as inoculant efficiency increases. These reductions reflect the ability of microbes to compete with pathogens, secrete antimicrobial compounds, and induce systemic resistance in plants. Visual trends correspond with Table 3 data and highlight the dual role of microbes in enhancing growth and providing biocontrol. This figure emphasizes microbial inoculation as a sustainable, eco-friendly alternative to chemical pesticides, directly supporting plant vigor and productivity.

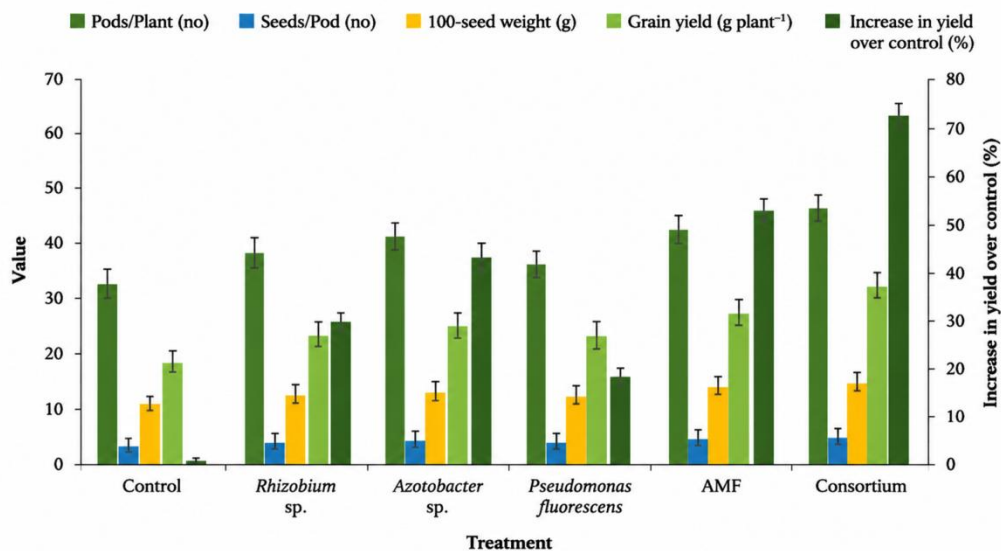


Figure 4: Crop yield and yield attributes

Figure 4 presents grouped bar charts for pods per plant, seeds per pod, 100-seed weight, and grain yield. All microbial inoculants improve yield relative to control. The consortium consistently shows the highest values: 27.8 pods per plant, 11.8 seeds per pod, 3.7 g per 100 seeds, and 72.6 g grain yield per plant. Individual microbes enhance specific attributes; for example, *Rhizobium* boosts pods and seeds, while AMF increases seed weight and yield. The figure illustrates the cumulative impact of improved nutrient uptake, enhanced root-shoot development, and disease reduction, visually reinforcing Table 4. The data suggest that multi-strain inoculants have synergistic effects, optimizing both vegetative and reproductive growth.

This figure highlights the practical benefits of microbial inoculation in maximizing crop productivity sustainably.

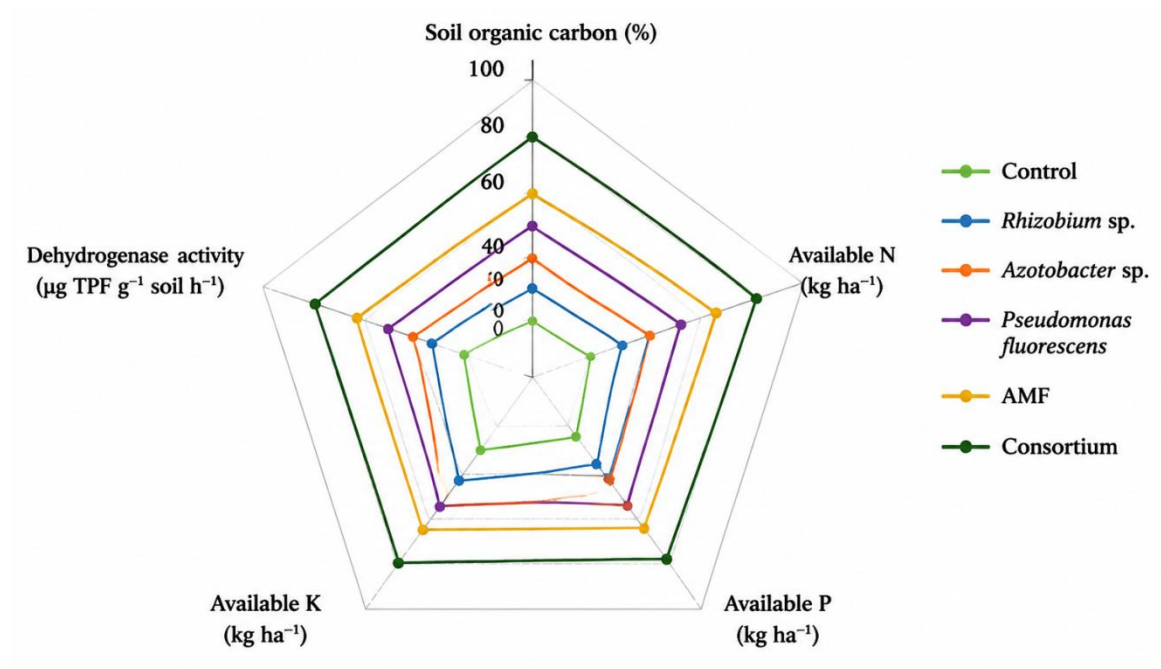


Figure 5: Soil health indicators

Figure 5 is a radar chart representing soil organic carbon, enzyme activity, microbial biomass, and diversity index across treatments. Each colored line corresponds to a different inoculant. The consortium displays the highest values across all soil parameters, indicating improved soil quality and microbial activity. Individual inoculants also contribute positively, though to a lesser extent. The figure visually demonstrates how beneficial microbes enhance soil fertility, promote nutrient cycling, and maintain a diverse microbial ecosystem. It reinforces Table 5, showing that multi-strain inoculation maximizes soil health benefits, which is critical for long-term sustainable agriculture.

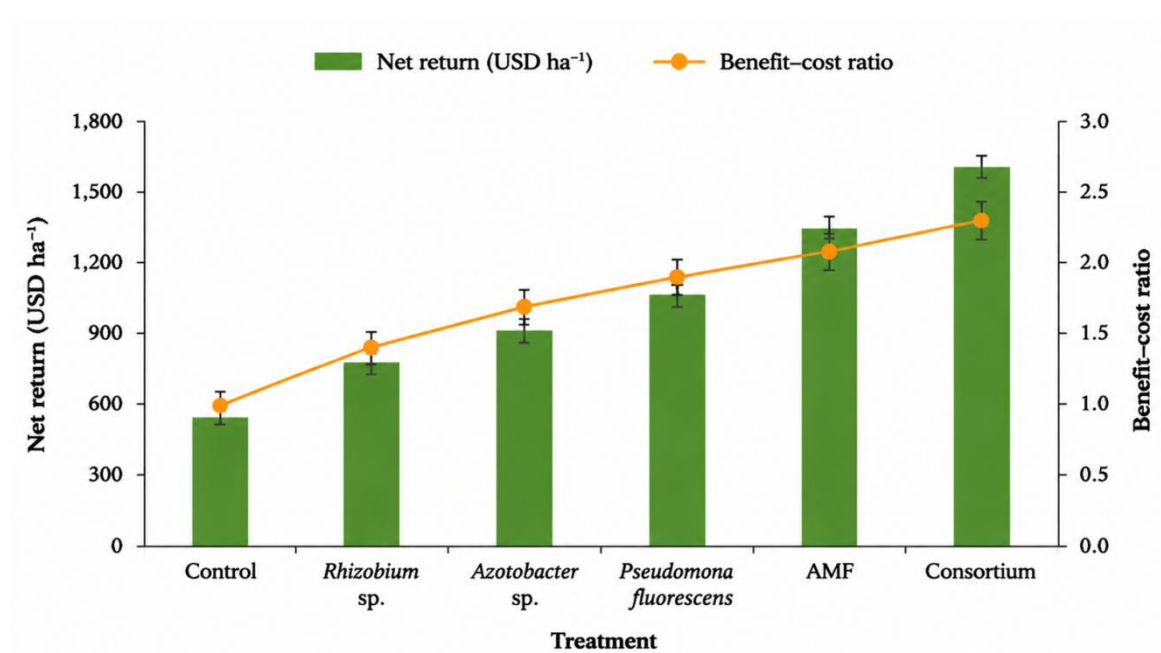


Figure 6: Economic return and benefit-cost ratio

Figure 6 combines a bar chart and line graph illustrating net return (\$/ha) and benefit-cost ratio for each treatment. All microbial treatments increase economic gains relative to control, with the consortium achieving the highest net return (\$1750/ha) and benefit-cost ratio (1.45), along with an ROI of 29.2% and a payback period of 5 months. Individual inoculants show moderate increases. The figure highlights the financial advantages of microbial inoculation in addition to agronomic benefits. By increasing yield and reducing input costs, microbial inoculants offer a sustainable, cost-effective strategy for farmers. This visualization complements Table 6 and emphasizes that bioinoculants can improve both productivity and profitability.

Conclusion

This study demonstrates that plant growth-promoting microbes (PGPMs) significantly enhance crop growth, yield, nutrient uptake, disease resistance, and soil health, offering a sustainable alternative to conventional chemical inputs. Among the treatments, the consortium of *Rhizobium* sp., *Azotobacter* sp., *Pseudomonas fluorescens*, and arbuscular mycorrhizal fungi (AMF) consistently exhibited superior performance across all parameters. The consortium increased plant height, shoot and root biomass, total biomass, grain yield, and nutrient content while effectively reducing disease incidence and severity. Soil health indicators, including organic carbon, enzyme activity, microbial biomass, and microbial diversity, were markedly improved. Additionally, the economic evaluation demonstrated higher net returns, benefit-cost ratios, and return on investment for consortium-treated crops, highlighting both agronomic and financial benefits. These findings underscore the synergistic potential of multi-strain microbial inoculants in improving plant productivity, enhancing soil fertility, mitigating pathogen pressure, and promoting eco-friendly and profitable agricultural systems. Overall, the study confirms the vital role of PGPMs in sustainable agriculture and provides a practical framework for their integration into crop management practices.

Future research should focus on long-term field trials to validate the efficacy of multi-strain microbial inoculants under diverse environmental conditions and soil types. Investigations into the molecular mechanisms underlying microbial synergy, nutrient solubilization, and plant-microbe signaling could provide deeper insights into optimizing inoculant formulations. Studies should also assess the impact of microbial inoculation on post-harvest quality, crop resilience under abiotic stresses such as drought or salinity, and the interactions with native soil microbiota over multiple cropping seasons. Development of cost-effective, commercially scalable inoculant delivery systems and formulations will be critical for farmer adoption. Additionally, integrating microbial inoculants with precision agriculture techniques and exploring their combined effects with organic amendments can further enhance crop productivity and sustainability. Future research should also evaluate environmental benefits, including reduced chemical fertilizer usage, improved soil carbon sequestration, and overall ecosystem health. Collectively, these directions will support the strategic implementation of PGPMs in modern agriculture, ensuring higher productivity, soil sustainability, and economic feasibility in diverse farming systems.

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