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Microbiome-Assisted Crop Production Improves Nutrient Cycling and Reduces Fertilizer Dependency

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Abstract
The increasing concern over soil degradation and environmental impacts associated with excessive use of chemical fertilizers has led to growing interest in biologically driven nutrient management approaches. In this context, a field experiment was conducted during the Kharif season at the Agriculture Research Farm, Salema, Dhalai, Tripura, to evaluate the role of microbiome assisted crop production in paddy cultivation. The study was carried out using a Randomized Block Design with ten treatments involving different combinations of recommended fertilizer doses and microbial inoculants, including Azotobacter, phosphate-solubilizing bacteria (PSB), and arbuscular mycorrhizal fungi (AMF). The results revealed that the integration of microbial consortia with reduced fertilizer levels significantly improved soil organic carbon, available nitrogen, phosphorus, and potassium compared to control treatments. The treatment receiving 75% recommended fertilizer dose along with microbial consortium recorded the highest grain yield (5.3 t ha^{-1}), while 50% fertilizer combined with consortium produced comparable yield (5.1 t ha^{-1}), indicating substantial scope for reducing chemical fertilizer inputs. Enhanced microbial biomass carbon, dehydrogenase activity, and soil respiration further confirmed improved soil biological activity and nutrient cycling. The findings suggest that microbiome-assisted nutrient management can effectively sustain crop productivity while reducing fertilizer dependency and improving soil health. This approach offers a promising pathway for sustainable and environmentally sound agricultural practices, particularly in regions with fragile soil ecosystems.

Keywords: *Microbiome-assisted agriculture; Biofertilizers; Nutrient cycling; Paddy (Oryza sativa); Soil health; Fertilizer reduction; Sustainable agriculture.*

Highlights

- Microbial consortium significantly improved soil organic carbon and nutrient availability in paddy fields.
- Integration of biofertilizers with reduced fertilizer levels maintained or enhanced crop yield.
- Up to 50% reduction in chemical fertilizer was possible without significant yield loss.
- Enhanced microbial activity indicated improved soil health and nutrient cycling under field conditions.

1. Introduction

Agricultural intensification over the past few decades has largely depended on the extensive use of chemical fertilizers to achieve higher crop productivity. Although this approach has contributed significantly to global food security, it has also led to several unintended consequences, including soil degradation, nutrient imbalance, decline in soil biological activity, and environmental pollution (Tilman et al., 2011; Savci, 2012). These issues are of particular concern in regions with fragile ecosystems, where continuous fertilizer use without adequate biological inputs can accelerate the deterioration of soil health.

Soil is not merely a physical medium for plant growth but a dynamic living system inhabited by diverse microbial communities. These microorganisms play a central role in regulating key biogeochemical processes such as nitrogen fixation, phosphorus solubilization, and organic matter decomposition (Berg et al., 2017). Beneficial microbes, including Azotobacter, Rhizobium, and phosphate-solubilizing bacteria, are known to enhance nutrient availability through natural biological processes, thereby improving nutrient use efficiency in crops (Vessey, 2003; Richardson and Simpson, 2011). Similarly, arbuscular mycorrhizal fungi (AMF) establish symbiotic associations with plant roots and facilitate the uptake of relatively immobile nutrients, particularly phosphorus (Smith and Read, 2008).

In recent years, there has been increasing interest in utilizing soil microbiomes as a sustainable alternative to conventional fertilizer-based systems. The concept of microbiome-assisted crop production involves the application of beneficial microbial consortia to support plant growth, improve soil fertility, and enhance nutrient cycling (Singh et al., 2020). Such approaches not only reduce reliance on synthetic inputs but also contribute to maintaining ecological balance. Previous studies have indicated that integrating biofertilizers with reduced chemical fertilizer doses can sustain crop yields while improving soil biological properties (Adesemoye et al., 2009; Bender et al., 2016).

The importance of microbial processes in nutrient cycling is well established. Biological nitrogen fixation can significantly supplement plant nitrogen requirements, reducing dependence on synthetic fertilizers (Galloway et al., 2008). Likewise, phosphate-solubilizing nutrient losses and enhancing sustainability in agricultural systems (Lal, 2015). Additionally, microbial activity contributes to soil organic carbon accumulation and structural stability, which are essential for long-term soil productivity (Banerjee et al., 2019).

Despite these advantages, the field-level performance of microbial inoculants often varies depending on soil type, climatic conditions, and crop management practices. Therefore, region-specific studies are necessary to evaluate their effectiveness under local agro-ecological conditions. This is particularly relevant for northeastern India, where high rainfall and acidic soils influence nutrient dynamics and microbial activity.

In this context, the present study was undertaken to assess the effect of microbiome-assisted nutrient management on soil properties, crop growth, and yield of paddy under field conditions. The study also aimed to evaluate the extent to which chemical fertilizer inputs can be reduced through the use of microbial consortia without compromising crop productivity.

2. Materials and Methods

2.1 Study Location and Site Description

The field experiment was carried out during the Kharif season at the Agriculture Research Farm, Salema, located in Dhalai district of Tripura, India. The area falls under a humid subtropical climate with high rainfall, most of which is received during the monsoon months (June to September). During the cropping period, the temperature generally ranged between 24°C and 32°C, which is favourable for paddy cultivation. The soil of the experimental field was sandy loam in texture with a moderately acidic reaction. Before initiating the experiment, composite soil samples were collected and analyzed to determine baseline fertility status following standard laboratory procedures (Jackson, 1973). The soil was found to be medium in available nutrients.

2.2 Experimental Design and Treatment Details

The experiment was laid out in a Randomized Block Design (RBD) with ten treatments and three replications. Each experimental plot measured 4 m × 5 m, and sufficient space was maintained between plots to avoid lateral movement of nutrients and microbial inoculants. The treatments consisted of different combinations of recommended fertilizer dose (RDF) and microbial inoculants, including Azotobacter, phosphate-solubilizing bacteria (PSB), and arbuscular mycorrhizal fungi (AMF). The treatment structure was designed to evaluate both individual and combined effects of microbial inputs under reduced fertilizer levels, along with appropriate control treatments.

The treatments were as follows:

- T1: 100% Recommended Dose of Fertilizer (RDF) (Control)
- T2: 75% RDF + Azotobacter
- T3: 75% RDF + Phosphate-Solubilizing Bacteria (PSB)
- T4: 75% RDF + AMF (Glomus spp.)
- T5: 75% RDF + Microbial Consortium (Azotobacter + PSB + AMF)
- T6: 50% RDF + Azotobacter
- T7: 50% RDF + PSB
- T8: 50% RDF + AMF
- T9: 50% RDF + Microbial Consortium
- T10: Absolute Control (no fertilizer, no microbial inoculation)

Carrier-based Azotobacter and PSB were each applied at the rate of 2.0 kg ha^{-1}. These were mixed with well-decomposed farmyard manure (FYM) and uniformly broadcast in the respective plots before transplanting. The AMF inoculum (Glomus spp.) was applied at 10.0 kg ha^{-1} directly in the root zone at the time of transplanting. In treatments involving microbial consortium, all inoculants were applied together at the same individual rates. The recommended fertilizer dose for paddy was applied as per regional recommendations. Fertilizers were applied in split doses following standard agronomic practices.

2.3 Crop Establishment and Management Practices

The test crop used in the study was paddy (Oryza sativa L.). Healthy seedlings, approximately 25–30 days old, were transplanted in the field maintaining a spacing of 20 cm × 15 cm. All intercultural operations such as irrigation, weeding, and plant protection measures were carried out uniformly across treatments to minimize variability. Care was taken to ensure that no additional inputs interfered with the treatment effects.

2.4 Soil Sampling and Laboratory Analysis

Soil samples were collected from a depth of 0–15 cm at two stages: before transplanting and after crop harvest. The samples were air-dried, processed, and passed through a 2 mm sieve prior to analysis.

The following parameters were analyzed using standard procedures:

- Soil pH was determined using a glass electrode pH meter (Jackson, 1973)
- Organic carbon content was estimated by Walkley and Black's method (Walkley and Black, 1934)
- Available nitrogen was determined by alkaline permanganate method (Subbiah and Asija, 1956)
- Available phosphorus was estimated using Olsen's extraction method (Olsen et al.,1954)
- Available potassium was determined using a flame photometer (Jackson, 1973)

2.5 Plant Growth and Yield Observations

Observations on plant growth and yield parameters were recorded from randomly selected plants within each plot.

The parameters included:

- Plant height at maturity
- Number of tillers per hill
- Panicle length
- Number of grains per panicle

At harvest, grain and straw yields were recorded from the net plot area and converted to yield per hectare.

2.6 Assessment of Soil Microbial Activity

To understand the biological changes in the soil, selected parameters of microbial activity were measured. Soil microbial biomass carbon (MBC) was determined using the fumigation-extraction method (Vance et al., 1987). Dehydrogenase activity (DHA), which reflects overall microbial activity, was estimated following the method described by Casida et al.(1964). Soil respiration was measured based on the evolution of CO2 as described by Anderson (1982).

These indicators were used to assess the functional activity of soil microorganisms under different treatments.

2.7 Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for Randomized Block Design as outlined by Gomez and Gomez (1984). The significance of treatment effects was tested at the 5% level of probability. Wherever significant differences were observed, treatment means were compared using the Least Significant Difference (LSD) test.

2.8 Ethical and Quality Considerations

The experiment was conducted following standard agronomic practices and research protocols. All microbial inoculants used in the study were non-pathogenic and suitable for agricultural application. Care was taken during data collection and analysis to ensure accuracy and consistency. The study does not involve any ethical issues related to human or animal subjects.

3. Results

3.1 Soil Chemical Properties

The application of microbial inoculants showed noticeable changes in soil properties after harvest. In general, treatments receiving microbial inputs performed better than the control. The improvement was more pronounced when microbial consortium was applied along with reduced fertilizer levels.

Observation: Among the treatments, T5 (75% RDF + microbial consortium) recorded the highest values for organic carbon and available nutrients. This was followed by T9 (50% RDF + consortium). The absolute control (T10) consistently showed the lowest values. The differences between T5 and control were statistically significant for all parameters, indicating a clear improvement in soil fertility due to microbial application.

3.2 Plant Growth Parameters

Growth attributes of paddy were influenced by the different treatments. Plants in plots receiving microbial inoculants appeared more vigorous compared to those under control conditions.

Observation: The tallest plants and highest number of tillers were recorded in T5, followed closely by T9. The control treatment (T1) showed comparatively lower values, while the absolute control (T10) recorded the minimum. The differences observed were statistically significant, particularly for tiller number and plant height.

3.3 Yield and Yield Attributes:

Yield performance of paddy varied across treatments depending on the level of fertilizer and microbial inputs.

Observation: The highest grain yield was recorded in T5 (5.3 t/ha), which was significantly higher than the control. Treatment T9 also performed well and produced yield comparable to T5. The absolute control recorded the lowest yield. The results indicate that reduced fertilizer levels, when combined with microbial inoculants, can sustain yield effectively.

3.4 Soil Microbial Activity

Microbial activity in soil was influenced considerably by the application of bio-inoculants.

Observation: Higher microbial biomass and enzyme activity were observed in treatments receiving microbial inoculants. T5 recorded the highest values, followed by T9. The absolute control showed the lowest microbial activity. The differences were statistically significant, suggesting that microbial inoculation enhanced biological processes in the soil.

4. Discussion

The results obtained from the present study indicate that the use of microbial inoculants, particularly in combination, had a clear influence on soil properties, crop growth, and yield of paddy. The improvements observed were not limited to a single parameter but were reflected across soil fertility, plant performance, and biological activity, suggesting a broader effect of microbiome-based interventions.

An increase in soil organic carbon was observed in treatments receiving microbial inputs, especially where consortium was applied. This may be attributed to enhanced microbial activity leading to better decomposition of organic matter and stabilization of carbon in soil. Similar observations have been reported by Lal (2015), who emphasized the role of soil microorganisms in carbon sequestration and maintenance of soil structure. Under field conditions, such gradual improvements are important for sustaining productivity over time.

The availability of nitrogen was comparatively higher in treated plots, which can be linked to the activity of nitrogen-fixing organisms such as Azotobacter. Biological nitrogen fixation contributes to the pool of plant-available nitrogen and reduces dependence on external inputs. Earlier studies have also pointed out that plant growth-promoting rhizobacteria can improve nitrogen uptake efficiency and overall crop performance (Vessey, 2003). The trend observed in the present study supports this understanding.

Similarly, higher phosphorus availability in PSB and consortium treatments indicates the role of microorganisms in mobilizing otherwise unavailable nutrients. The release of organic acids by phosphate-solubilizing bacteria is known to convert insoluble phosphorus into forms accessible to plants (Sharma et al., 2013). In addition, the presence of arbuscular mycorrhizal fungi likely contributed to improved nutrient uptake by extending the effective root surface area (Smith and Read, 2008). The combined effect of these microbial groups appears to have resulted in better nutrient use efficiency.

The improvement in plant growth parameters, such as plant height and tiller number, may be associated with better nutrient availability as well as the production of growth-promoting substances by soil microbes. Microbial synthesis of compounds like auxins and other phytohormones has been reported to stimulate root growth and plant development (Adesemoye et al., 2009). In the present study, the overall plant

Table 1. Effect of Treatments on Soil Chemical Properties (Post-Harvest)

Treatments	**Organic Carbon (%)**	**Available N (kg/ha)**	**Available P (kg/ha)**	**Available K (kg/ha)**
T_1	0.58	235	21	185
T_2	0.62	245	24	190
T_3	0.63	242	26	188
T_4	0.64	240	25	187
T_5	0.70	265	30	198
T_6	0.60	230	22	182
T_7	0.61	228	24	180
T_8	0.62	226	23	179
T_9	0.68	255	28	195
T_10	0.50	200	18	170
SEm (±)	0.02	5.2	1.3	3.5
CD (p=0.05)	0.05	15.1	3.8	10.2

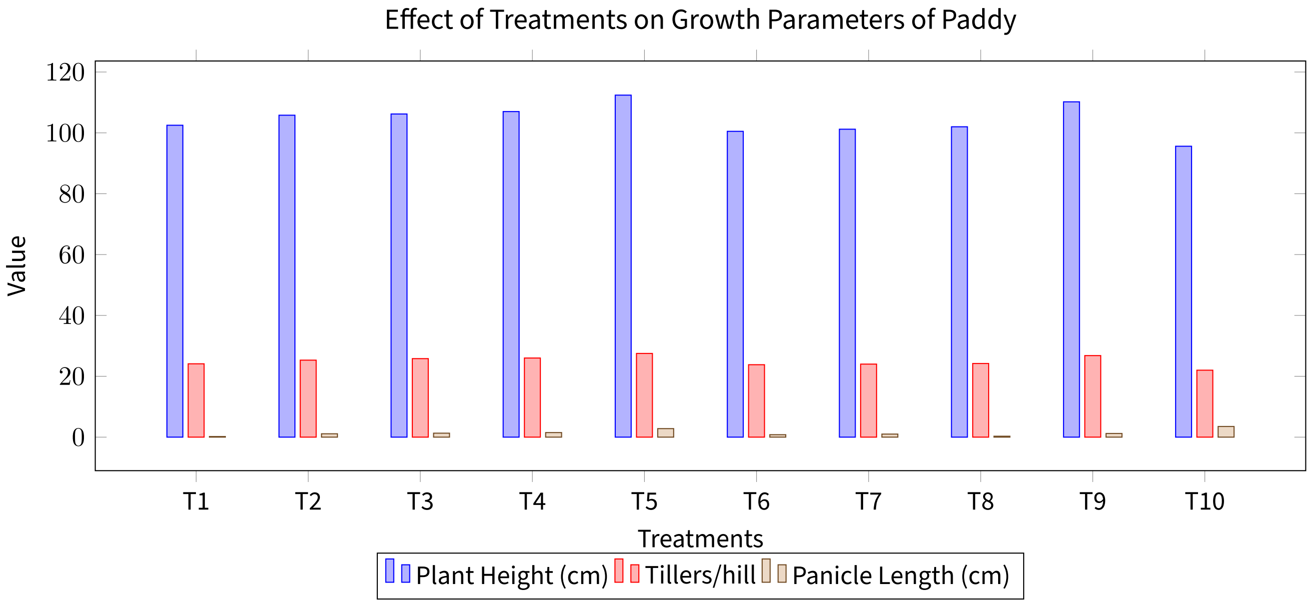

Figure 1. Effect of Treatments on Growth Parameters of Paddy

vigour observed in consortium treatments supports this possibility.

Yield performance followed a similar trend, with the highest yield recorded in the treatment receiving 75% RDF along with microbial consortium. It is noteworthy that even at 50% fertilizer level, when combined with microbial inoculants, the yield remained comparable to higher input treatments. This suggests that a part of the chemical fertilizer requirement can be substituted by biological inputs without adversely affecting productivity. Similar findings have been reported by Bender et al. (2016), who highlighted the importance of soil microbial diversity in maintaining crop yields under reduced input conditions.

The increase in microbial biomass carbon, dehydrogenase activity, and soil respiration observed in this study further indicates that microbial processes were more active in treated soils. These parameters are often used as indicators of soil biological health and reflect the intensity of microbial-mediated transformations (Casida et al., 1964). Higher values in consortium treatments suggest a more active and functional soil microbial system.

From an environmental perspective, reducing fertilizer input without yield loss is an important outcome. Excessive fertilizer use is often associated with nutrient losses, water contamination, and greenhouse gas emissions (Tilman et al., 2011). The results of the present study indicate that microbiome-assisted approaches

Table 2. Effect of Treatments on Growth Parameters of Paddy

Treatments	**Plant Height (cm)**	**Tillers/hill)**	**Panicle Length (cm)**
T$_1$	102.5	10.2	24.1
T$_2$	105.8	11	25.3
T$_3$	106.2	11.3	25.8
T$_4$	107.0	11.5	26.0
T$_5$	112.4	12.8	27.5
T$_6$	100.5	9.8	23.8
T$_7$	101.2	10.0	24.0
T$_8$	102.0	10.3	24.2
T$_9$	110.2	12.0	26.8
T$_1$0	95.6	8.5	22.0
SEm (±)	1.8	0.4	0.6
CD (p=0.05)	5.2	1.2	1.7

Table 3. Effect of Treatments on Soil Chemical Properties Effect of Treatments on Yield of Paddy

Treatments	**Grains/Panicle**	**Grain Yield (t/ha)**	**Straw Yield (t/ha)**
T$_1$	120	4.6	5.8
T$_2$	128	4.8	6.0
T$_3$	130	4.9	6.1
T$_4$	132	5.0	6.2
T$_5$	145	5.3	6.6
T$_6$	118	4.4	5.6
T$_7$	120	4.3	5.5
T$_8$	122	4.4	5.6
T$_9$	140	5.1	6.4
T$_1$0	105	3.8	5.0
SEm (±)	4.5	0.12	0.15
CD (p=0.05)	13.0	0.35	0.44

can contribute to minimizing such risks while maintaining productivity.

Overall, the findings support the view that integrating microbial inoculants with reduced fertilizer doses can be an effective strategy for improving soil fertility and sustaining crop yield under field conditions. However, it may be noted that responses to microbial inoculants can vary depending on local soil and climatic conditions, and therefore, location-specific evaluation remains important.

5. Conclusion

Based on the results of the present investigation, it can be concluded that microbiome- assisted nutrient management has considerable potential in improving soil health and sustaining paddy productivity. The use of microbial consortia, comprising nitrogen-fixing, phosphate-solubilizing, and mycorrhizal organisms, contributed to better nutrient availability, enhanced microbial activity, and improved crop performance under field conditions.

Among the different treatments, the combination of 75% recommended fertilizer dose with microbial consortium consistently performed better in terms of soil

Table 4. Effect of Treatments on Soil Microbial Activity

Treatments	MBC (µg/g soil)	DHA (µg TPF/g soil/day)	Soil Respiration (mg CO_2/kg/day)
T_1	280	32	45
T_2	310	36	50
T_3	315	38	52
T_4	320	39	53
T_5	360	45	60
T_6	275	30	43
T_7	270	29	42
T_8	278	31	44
T_9	345	42	58
T_10	250	25	38
SEm (±)	8.5	1.5	2.8
CD (p=0.05)	24.5	4.3	8.1

properties, growth parameters, and yield. At the same time, the treatment with 50% fertilizer combined with microbial inoculants produced yield levels comparable to higher fertilizer inputs, indicating that chemical fertilizer use can be reduced to a significant extent without affecting productivity.

The observed increase in microbial activity and soil organic carbon also suggests long-term benefits for soil sustainability. Such improvements are particularly relevant for regions with high rainfall and acidic soils, where maintaining soil health is essential for stable agricultural production.

In practical terms, the integration of microbial inputs with reduced fertilizer application offers a feasible approach for improving nutrient use efficiency, lowering input costs, and minimizing environmental risks. The results of this study highlight the importance of biological processes in soil and their role in supporting sustainable agriculture.

Further studies over multiple seasons and locations may help to refine these findings and support wider adoption of microbiome-based practices in crop production systems.

6. Authors Contribution

All authors wrote, reviewed and approved this manuscript for publication.

7. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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