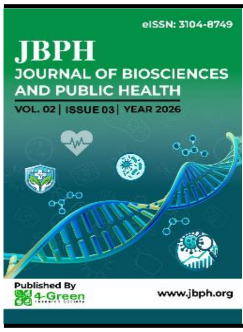

J. Biosci. Public Health **2026; 2(3):238-250**

Journal of Biosciences and Public Health

Open access

DOI: https://doi.org/10.5455/JBPH.2026.10

Published by: www.4greenresearch.org

Original Article

Bio-Organic Fertilizer as a Sustainable Substitute for Inorganic Nitrogen and Phosphorus Fertilizers Improves Rice Yield in Coastal Area of Bangladesh

Md. Rokibuzzaman[1,2], Md. Jahidul Islam[1], Md. Bashir Ahmed[1], Sibdas Ghosh[3], Md. Azizul Haque[2,*]

[1] Fertilizer division, Advanced Chemical Industries PLC (ACI), Dhaka, Bangladesh

[2]Department of Biochemistry and Molecular Biology, Faculty of agriculture, Hajee Mohammad Danesh Science and Technology University, Dinajpur 5200, Bangladesh

[3]Albany College of Pharmacy and Health Sciences, 106 New Scotland Avenue, Albany, Newyork 12208, United States of America

Article information
Received: February 03, 2026
Accepted: April 29, 2026
Published: May12, 2026

***Corresponding author:**
Dr. Md. Azizul Haque, E-mail: helalbmb2016@hstu.ac.bd

Keywords: Bio-organic fertilizer, Soil biodiversity, Soil microbial activity, Phosphorus-free fertilization, Sustainable agriculture, cost effective cultivation, Soil fertility

Cite this article: Rokibuzzaman M et al. Bio-Organic Fertilizer as a Sustainable Substitute for Inorganic Nitrogen and Phosphorus Fertilizers Improves Rice Yield in Coastal Area of Bangladesh. J Biosci Public Health.2026;2(3):238-250. doi:10.5455/JBPH.2026.10

ABSTRACT

Calcareous soils in coastal lowland regions are typically deficient in nitrogen (N) and available phosphorus (P). Moreover, these agro-ecosystems are regularly affected by tidal activities. Therefore, this study evaluated the effect of bio-organic fertilizer application without inorganic phosphorus and with a 30% reduction in nitrogen on the yield and yield attributes of rice in a coastal area of Bangladesh. A field experiment was conducted during the Rabi season using a randomized complete block design (RCBD) with five treatments and three replications. Each plot measured 20 m^2 with a spacing of 20 cm × 20 cm. The treatments included: T1 = 100% chemical fertilizer (control); T2 = 70% N without inorganic P + recommended fertilizers; T3 = 70% N without inorganic P + K and S + bio-organic fertilizer at 500 kg ha^{-1}; T4 = similar to T3 with bio-organic fertilizer at 750 kg ha^{-1}; and T5 = similar to T3 with bio-organic fertilizer at 1000 kg ha^{-1}. Results demonstrated that bio-organic fertilizer significantly improved growth and yield attributes. Treatment T4 produced the highest effective yield (6.66 MT ha^{-1}), representing an 11.09% increase over the control. Although T5 showed the highest numerical yield, T4 was identified as the optimal treatment due to its comparable productivity at a lower input cost and the highest benefit-cost ratio. The findings suggest that integrating bio-organic fertilizer at 750 kg ha^{-1} can effectively replace inorganic phosphorus and reduce nitrogen use by 30% without compromising yield. This strategy improves soil biological activity and supports sustainable nutrient management. Overall, the approach offers a cost-effective and environmental solution for rice cultivation in Bangladesh and similar agroecological systems.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is the most critical staple food crop globally, providing the primary caloric intake for more than half of the world's population [1, 2]. To maintain global food security for a growing population, rice yields must increase by approximately 40% by 2030 [3]. Currently, stable production relies heavily on the application of essential macronutrients, particularly nitrogen (N) and phosphorus (P), which are the primary limiting factors for crop growth in over 50% of the world's cultivable soils [4, 5].

While chemical fertilizers have historically driven productivity gains, their use is characterized by significant inefficiency; it is estimated that only about 20% of applied N and P is actually absorbed by the rice plant [5]. The remaining nutrients are lost to the environment, leading to severe ecological consequences such as the eutrophication of water bodies, soil degradation, and increased greenhouse gas emissions [6, 7]. Notably, flooded rice systems are a major source of atmospheric methane, accounting for roughly 50% of global cropland emissions [8]. Furthermore, excessive chemical inputs can suppress beneficial soil microorganisms and essential pollinators, further compromising the long-term resilience of agricultural ecosystems by contaminating aquatic environments [7, 9].

In response to these challenges, bio-organic fertilizers and plant growth-promoting bacteria have emerged as sustainable alternatives. These biological inputs enhance nutrient cycling through mechanisms such as biological nitrogen fixation, phosphate solubilization, and the production of phytohormones like auxins and gibberellins [10-15]. In particular, the application of BoF can improve soil organic carbon by 6% to 13% compared to synthetic treatments and significantly increase microbial biomass carbon [16, 17].

The integration of specific PGPB strains, such as *Bacillus* and *Paenibacillus* spp., has demonstrated the potential to maintain high yields while reducing synthetic fertilizer requirements. For instance, recent field trials have shown that bio-organic formulations can supplement at least 30% of nitrogen requirements and potentially eliminate the need for triple superphosphate entirely [17]; her studies suggest that probiotic bacteria like *Paraburkholderia* and *Delftia* can reduce the overall chemical fertilizer requirement by up to 50% without sacrificing yield [18]. Although several studies have demonstrated the benefits of plant growth-promoting bacteria and bio-organic fertilizers in rice cultivation, limited information is available regarding the complete replacement of inorganic phosphorus combined with reduced nitrogen input under coastal agroecosystems of Bangladesh [17, 19].

This study was therefore conducted to evaluate whether a bio-organic fertilizer developed from locally isolated PGPB can maintain or enhance rice productivity while eliminating inorganic P fertilizer and reducing N application by 30%. We hypothesized that an appropriately dosed BoF would compensate for the reduced chemical inputs through improved nutrient mobilization and plant growth promotion, offering a sustainable and economically viable strategy for rice cultivation in resource-constrained coastal environments.

2. MATERIALS AND METHODS

2.1. Experimental site and climate

The field experiment was conducted randomly selected Mirjagonj, Patuakhali, located in the southern coastal region of Bangladesh as a part of a pilot test. The experimental site belongs to the Ganges Tidal Floodplain under Agro-Ecological Zone (**AEZ**) 13. The area is characterized by medium- to high-elevation land with predominantly clay loam soils. These calcareous soils are generally deficient in nitrogen (N) and available phosphorus (P). The site is also influenced by regular tidal activities typical of lowland coastal ecosystems.

AEZ 13 is considered suitable for rice cultivation under the humid tropical monsoon climate of Bangladesh, which is characterized by high annual rainfall, warm temperatures, and distinct wet and dry seasons. The relative humidity in the region generally ranges from 70% to 84%. These environmental conditions are favorable for rice cultivation during both the rainfed Aman and irrigated Boro seasons.

2.2. Formulation of bio-organic fertilizer

The bio-organic fertilizer was developed and supplied by the Soil Microbiology Laboratory, Bangladesh Rice Research Institute (BRRI), Gazipur. It was a solid formulation with approximately 15–20% moisture content and a maximum particle size of 2 mm. The fertilizer consisted of 79.5% biodegradable kitchen and vegetable waste collected from local markets, 15% rice husk biochar (chita-dhan), and 5% rock phosphate. A consortium of locally isolated, effective plant growth-promoting bacteria (0.5–1% w/w) was incorporated during composting. The bacterial strains included *Bacillus mycoides, Bacillus subtilis, Bacillus pumilus*, *Bacillus cereus*, *Proteus* sp., *Paenibacillus polymyxa,* and other *Paenibacillus* spp. These strains are known for nitrogen fixation, phosphate solubilization, and indole-3-acetic acid (IAA) production. The bacterial inoculum was multiplied in molasses-based broth before mixing with the organic substrate, following the method described earlier [17].

In this study, the final product contained 250 g kg^{-1} organic carbon, 10.4 g kg^{-1} total N, and 10.4 g kg^{-1} total P, along with appreciable amounts of potassium, sulfur, and zinc. It had a neutral pH (7.2) and low heavy metal content, ensuring environmental safety. The phosphorus supplied by the bio-organic fertilizer (at 500–1000 kg ha^{-1}) was sufficient to fully substitute the recommended inorganic triple superphosphate (TSP) dose for one rice crop.

2.3. Experimental design and crop management

A field experiment was laid out in a randomized complete block design (RCBD) with five treatments and three replications. Individual plot size was 5 m × 4 m (20 m^2). Thirty-five-day-old seedlings of a suitable rice variety were transplanted in March 2023. Standard crop management practices were followed. Weeds were removed manually at 30 and 60 days after transplanting (DAT). Supplemental irrigation was provided as needed to maintain appropriate soil moisture, particularly during dry periods.

2.4. Fertilizer application

Fertilizer rates were based on the Fertilizer Recommendation Guide (FRG, 2012) of Bangladesh. The recommended doses for the control treatment were: urea 300 kg ha^{-1} (adjusted to N basis), triple superphosphate (TSP) 120 kg ha^{-1}, muriate of potash (MoP) 180 kg ha^{-1}, gypsum 65 kg ha^{-1}, and mono-zinc sulfate 7.5 kg ha^{-1}.

The treatments were as follows:

T1 (Control): 100% recommended chemical fertilizers (full N, P, K, S, and Zn).

T2: 70% recommended N + 0% inorganic P + 100% K, S, and Zn.

T3: 70% recommended N + 0% inorganic P + 100% K, S, and Zn + bio-organic fertilizer @ 500 kg ha^{-1}.

T4: 70% recommended N + 0% inorganic P + 100% K, S, and Zn + bio-organic fertilizer @ 750 kg ha^{-1}.

T5: 70% recommended N + 0% inorganic P + 100% K, S, and Zn + bio-organic fertilizer @ 1000 kg ha^{-1}.

All basal fertilizers (except urea) and the bio-organic fertilizer were applied during final land preparation. Urea was top-dressed in three equal splits at basal, active tillering, and panicle initiation stages. Inorganic TSP was omitted in T2-T5 and replaced by the bio-organic fertilizer, which supplied an additional 5.2, 7.8, and 10.4 kg P ha^{-1} in T3, T4, and T5, respectively. Full recommended doses of K and S were applied uniformly across all treatments.

2.5. Data collection and analysis

Data on growth and productivity were recorded at vegetative and reproductive stages. Panicle length (cm), 1000-seed weight (gm), and grain yield were determined by standard procedure. Observations were recorded from five randomly selected plants per plot. Yield attributes were recovered after harvesting time. The harvested crop was dried and threshed manually by plot. All agronomic practices were kept uniform for all treatments. Grain yields were recorded from 10 m^2 of each plot and converted to MT ha^{-1}. Data were analyzed statistically. In each column, means followed by common letter(s) do not differ significantly at the 5% level by DMRT.

3. RESULTS

3.1. Growth attributes of rice by bio-organic fertilizer application

Growth attributes, such as plant shoot length (cm), shoot fresh weight (g), root fresh weight (g), and number of effective tillers, were significantly influenced at both the vegetative and reproductive stages as a result of applying different doses of bio-organic fertilizer (**Tables 1** and **2**).

At the vegetative stage, the tallest plant (66.333 cm) was observed in the T4 treatment, which was significantly taller than the control plant but was not statistically different from the T5 treatment.

A significant effect of treatments on shoot fresh weight was observed at 40 DAT. The highest fresh shoot weight (61.667 g) was observed in the T4 treatment, which was statistically similar to T5 but significantly different from T1 and T2. The highest root fresh weight was observed in the vegetative stage at T4 (19.26 g). This observation is similar to our previous report where the highest shoot and root dry weights in plants were treated with beneficial bacteria [14, 15]. Additionally, the highest number of effective tillers and the highest 100-grain weight significantly increased rice grain yield by 35% compared to the control treatment [15].

Table 1. Effects of growth attributes by Bio-organic fertilizer application on rice at 40 DAT.

Treatments	At 40 DAT			
	Shoot length (cm)	Shoot fresh weight (gm)	Root fresh weight (gm)	Number of effective tillers
T1 (Control)	60.667 AB	37.400 BC	13.833 BC	17.833 B
T2	56.667 C	23.867 C	10.300 C	10.167 C
T3	64.333 B	45.233 B	16.733 B	20.333 AB
T4	66.333 A	61.600 A	19.267 A	22.667 A
T5	65.667 A	59.267 A	18.433 A	21.967 A
P	0.0240	0.0005	0.0915	0.0000
CV (%)	4.28	19.46	24.03	4.84

At the reproductive stage, plant shoot length increased gradually with bio-organic fertilizer application compared to the control, with the tallest plant (99.333 cm) in T4, which was statistically similar to T5.

The shoot fresh weight of rice was significantly influenced by the treatment. The highest shoot fresh weight was observed in the T4 treatment (107.73 g), which was not statistically different from that in the T5 treatment. The root fresh weight of rice applied with bio-organic fertilizer tends to be higher than that of the control. The highest root fresh weight was observed at the reproductive stage from T4 (23.833 gm). This might be due to the use of bio-organic fertilizer and the soil, which becomes available to the plant.

It was reported that *Bacillus* sp. significantly increased plant height, root length, shoot dry weight, root dry weight, and grain yield by up to 11% compared with the control [20]. Similarly, a significant difference in the total number of effective tillers was observed at 40 and 60 DAT across all treatments (**Tables 1** and **2**).

Table 2. Effects of growth attributes by Bio-organic fertilizer application on rice at 60 DAT.

Treatments	At 60 DAT			
	Shoot length (cm)	**Shoot fresh weight (gm)**	**Root fresh weight (gm)**	**Number of effective tillers**
T_1 (Control)	86.333 B	90.40 BC	22.133 AB	16.000 BC
T_2	73.333 C	71.93 C	15.100 C	14.667 C
T_3	93.667 AB	98.50 B	21.300 AB	17.333 BC
T_4	99.333 A	107.73 A	23.833 A	20.333 A
T_5	98.333 A	105.53 A	22.633 A	19.333 A
P	0.0198	0.0093	0.1944	0.0492
CV (%)	2.69	12.08	18.99	10.75

At the vegetative stage, the maximum number of effective tillers was observed in the T4 treatment (22.667), while T5 yielded results that were statistically similar and non-significant. During the reproductive stage, both T4 and T5 also showed results that were statistically similar and non-significant.

3.2. Yield and yield attribution of rice by bio-organic fertilizer application

The different dosages of treatment affected most yield components, such as panicle length (cm), number of grains per panicle, 1000-grain weight (g/m), and grain yield (MT ha^{-1}), as well as the bio-organic fertilizer. The top panicle length was found from T4 (26.833 cm). There is a statistically similar result shown from T3 and T5 treatments.

Table 3. Effects of Yields attributes of rice by Bio organic fertilizer application at harvesting stage.

Treatments	At harvesting stage				
	Panicle Length (cm)	Number of Grain/ Panicle	1000 grain weight (gm)	Yield (MT ha^{-1})	Yield increases over control (%)
T_1 (Control)	21.400 B	149.67 B	13.533 AB	5.9907 AB	0.00%
T_2	21.333 B	137.67 C	12.933 B	5.5870 B	-6.72%
T_3	25.533 A	156.40 AB	14.000 A	6.491 AB	8.36%
T_4	26.833 A	161.33 A	14.267 A	6.6550 A	11.09%
T_5	26.800 A	158.67 A	14.133 A	6.8223 A	13.88%
P	0.4195	0.0143	0.0264	0.0694	
CV (%)	2.92	4.98	6.41	7.67	

The number of grains per panicle was significantly higher, with the maximum from T2 (161.33). On the other hand, a maximum grain weight of 1000 (14.267 gm) was recorded in T4, which is statistically equivalent to all treatments except T1 and T2, however numerically higher than the control treatment.

Rice grain yield showed numerical improvement with bio-organic fertilizer treatment. (822 MT ha^{-1}) and (6.655 MT ha^{-1}) were recorded in treatments T4 and T5, respectively, which were numerically higher than the control and T2 (**Table 3**), but not significantly different at the 5% level. Treatment T1 showed less yield due to the recommended chemical fertilizer application compared to the treated plots, and T2 showed minimum yield due to the absence of inorganic phosphorus fertilizer, which was 5.9907 MT ha^{-1} and 5.5870 MT ha^{-1}, respectively. Yield increases over control (%) was significantly influenced by the application of bio-organic fertilizer. Treatment T4 numerically increased (11.09%) and treatment T5 (13.88%) over control T1.

Improved plant growth and phosphate uptake have been reported in many crop species following bacterial inoculation. For example, *Pseudomonas aeruginosa* in rice [21], *Bacillus sp.* in maize [22], and *B. amyloliquefaciens* in wheat, maize, and cotton [23] have shown benefits. Panhwar et al. (2011) showed that inoculating rice *with the Bacillus sp.* PSB9 isolate enhances P uptake, plant biomass, plant height, and root morphology compared to the control [24].

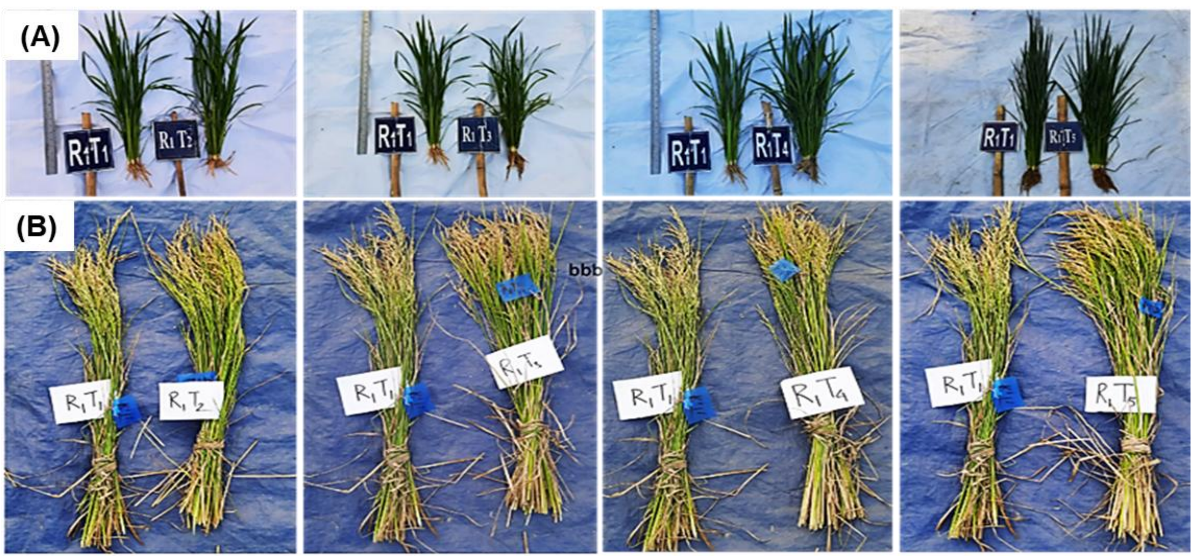

Figure 1. Comparative growth performance of rice plants under different fertilizer treatments; **(A)** at 40 DAT and, **(B)** at harvesting stage. Here in inset leveling, R1 means replication whereas T1 to T5 stand for treatment.

Figure 1 illustrates the comparative growth performance of rice plants under different fertilizer regimes at 40 days after transplanting (DAT) (A) and at the harvesting stage (B). Visual assessment revealed clear treatment effects, with plants receiving 70% N + bio-organic fertilizer (particularly T4 at 750 kg ha^{-1} and T5 at 1000 kg ha^{-1}) exhibiting superior vigor, taller stature, and more robust tillering compared to the full chemical fertilizer control (T1) and the P-deficient treatment without bio-organic fertilizer (T2).

At 40 DAT, the most vigorous growth was consistently observed in T4, followed closely by T5. By harvest, this trend was maintained, with T4 and T5 plants showing markedly enhanced overall biomass, panicle development, and canopy uniformity relative to T1 and T2. These observations corroborate the quantitative data on shoot length, fresh weights, and effective tiller number, highlighting the effectiveness of bio-organic fertilizer in sustaining and enhancing rice growth when inorganic phosphorus is omitted and nitrogen is reduced by 30%.

3.3. Economic analysis

An economic analysis was performed to evaluate the profitability of replacing inorganic phosphorus fertilizer and reducing nitrogen input by 30% through the integration of bio-organic fertilizer. Only the variable costs associated with fertilizers (chemical and bio-organic), fertilizer application, and additional labor for product application were considered, while all other production costs were assumed constant across treatments. Gross returns were calculated based on paddy and straw yields using prevailing market prices (paddy: Tk. 28.75 kg^{-1}; straw: Tk. 5.00 kg^{-1}). The benefit-cost ratio (BCR) was computed as gross return divided by total variable cost (TVC).

The results of the economic analysis are presented in **Table 4**. Application of bio-organic fertilizer substantially increased gross returns compared to the control (T1), ranging from Tk. 217,616 ha^{-1} in T3 to Tk. 229,141 ha^{-1} in T5. Treatment T5 recorded the highest net return (Tk. 197,029 ha^{-1}), followed closely by T4 and T3. However, the highest BCR (7.98) was achieved in T3, followed by T4 (6.87). Although T5 produced the highest numerical grain yield, its higher input cost resulted in the lowest BCR (6.13) among the bio-organic treatments.

Table 4. Benefit-cost ratio (BCR) analysis of rice production under different fertilizer treatments.

Treatment	Yield (MT ha^{-1})	Straw Yield (MT ha^{-1})	Gross Return (Tk. ha^{-1})	*TVC (Tk. ha^{-1})	Net Return (Tk. ha^{-1})	BCR
T1	5.99	6.5	204,733	18,915	185,817	10.83
T2	5.59	6.0	190,626	15,513	175,113	12.29
T3	6.49	6.2	217,616	24,213	193,413	7.98
T4	6.66	6.4	223,331	28,363	194,968	6.87
T5	6.82	6.6	229,141	32,113	197,029	6.13

***TVC** = Total variable cost (costs of chemical fertilizers, bio-organic fertilizer, application labor, and additional labor for bio-organic fertilizer). Labor wage: Tk. 400 man-day^{-1}. Two additional man-days ha^{-1} for fertilizer application; four man-days ha^{-1} per ton of bio-organic fertilizer. Fertilizer prices (Tk. kg^{-1}): Urea = 27.00, TSP = 27.00, MoP = 20.00, gypsum = 30.00, and $ZnSO_4$ = 180.00. Paddy price = 28.75 Tk. kg^{-1}; Straw price = Tk. 5.00 kg^{-1}. Yields are rounded for presentation; original values were used for calculations.

Among the treatments, T4 (750 kg ha^{-1} bio-organic fertilizer) provided the best balance between yield performance and economic return. Although T3 recorded the highest BCR, T4 produced a significantly higher grain yield (numerically 11.09% above the control) that was statistically comparable to T5, while maintaining a favorable BCR and lower input requirement than T5. This treatment demonstrated that nitrogen application can be reduced by 30% and inorganic phosphorus can be completely eliminated without yield penalty when supplemented with an appropriate dose of bio-organic fertilizer. The improved economic performance is attributed to enhanced nutrient use efficiency and the substitution of costly chemical inputs with bio-organic fertilizer.

Based on yield response, input optimization, and economic profitability, the application of 750 kg/ha bio-organic fertilizer (T4) is recommended as the optimal dose for sustainable and cost-effective rice production in the coastal region of Bangladesh.

4. DISCUSSION

The present study demonstrates that bio-organic fertilizer enriched with a consortium of plant growth–promoting bacteria (PGPB) can significantly enhance soil fertility and crop productivity. The formulation used in this study incorporated well-characterized bacterial genera such as *Bacillus*, *Proteus*, and *Paenibacillus*, which are widely recognized for their multifunctional roles in plant growth promotion, including nutrient mobilization, phytohormone production, and stress mitigation. Species such as *Bacillus subtilis*, *Bacillus pumilus*, *Bacillus cereus*, and *Paenibacillus polymyxa* have been extensively reported to improve plant growth through phosphate solubilization, nitrogen cycling, and the secretion of growth-promoting metabolites [17, 25]. The inclusion of *Proteus* spp. further contributes to nitrogen transformation and rhizosphere competence, enhancing nutrient availability in soil systems.

The effectiveness of such microbial consortia is often attributed to synergistic interactions among the constituent strains, leading to enhanced metabolic diversity and functional redundancy. These interactions promote improved root colonization, biofilm formation, and resilience under environmental stress conditions. In particular, *Bacillus* spp. are known for their ability to produce endospores, enabling survival under adverse environmental conditions and ensuring long-term persistence in soil ecosystems [26]. Similarly, *Paenibacillus* spp. contribute to nitrogen fixation and the production of antimicrobial compounds, which can suppress soil-borne pathogens and indirectly enhance plant health [27].

Recent advances in microbial genomics have further expanded our understanding of plant-associated endophytes and their potential application as next-generation biofertilizers. Genomic investigations into rice-associated bacterial endophytes have identified several novel strains with significant plant growth–promoting potential. Notably, isolates such as *Enterobacter* sp. (HSTU-ASn37, HSTU-Sny2), *Acinetobacter* sp. (HSTU-ASn38, HSTU-ASn41), *Morganella* sp. (HSTU-ASny43), *Pantoea* sp. (HSTU-Sny4), *Klebsiella* sp. (HSTU-Sny67), *Kosakonia* sp. (HSTU-ASn39), and *Citrobacter* sp. (HSTU-ABk15) have been reported to harbor diverse genetic determinants linked to nutrient acquisition and plant growth promotion [13, 14].

Among these, *Citrobacter* sp. HSTU-ABk15 exhibits a particularly comprehensive functional profile, encoding genes associated with biological nitrogen fixation (e.g., *nif*, *isc* clusters), phosphate solubilization (*pho*, *pst* systems), and indole-3-acetic acid (IAA) biosynthesis via tryptophan-dependent (*trp*) pathways. These traits collectively contribute to enhanced root architecture, increased nutrient uptake, and improved plant biomass accumulation [28]. Similarly, *Serratia* sp. strain

HSTU-ABk35 and *Acinetobacter* sp. HSTU-ASm16 demonstrate significant versatility, possessing genes involved in siderophore biosynthesis (e.g., enterobactin pathways), ammonia assimilation (*gltB*), and phosphate metabolism (*phoU*, *ppx*), alongside key determinants for rhizosphere colonization such as chemotaxis proteins (*cheB*) and biofilm formation mechanisms [29, 30].

Importantly, all these three strains, such as *Citrobacter* sp. HSTU-ABk15 and *Acinetobacter* sp. HSTU-Asm16 encode 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity (*dcyD*), which plays a crucial role in lowering plant ethylene levels under stress conditions. This mechanism is widely recognized as a key factor in enhancing plant tolerance to abiotic stresses such as drought, salinity, and nutrient deficiency [31]. The presence of such stress-regulating genes highlights the adaptive advantage of these endophytes in sustainable agricultural systems.

The integration of these genomically characterized endophytes with traditional biofertilizer consortia represents a promising strategy for developing next-generation bio-organic inputs. By combining classical PGPB such as *Bacillus* and *Paenibacillus* with newly identified endophytic strains possessing advanced metabolic capabilities, it is possible to create highly efficient and resilient biofertilizer formulations. Such formulations can simultaneously enhance nutrient use efficiency, stimulate plant growth, and reduce dependence on synthetic fertilizers, thereby contributing to environmentally sustainable agriculture.

The strategic integration of bio-organic fertilizer not only sustains rice yield under reduced chemical fertilizer regimes but also offers a practical pathway toward improving soil biological health and reducing the environmental footprint of rice production. Long-term multi-location trials are warranted to assess residual effects on soil fertility, microbial community dynamics, and yield stability across seasons and agroecological zones.

5. CONCLUSION

In this study, the application of 750 kg/ha of bio-organic fertilizer without inorganic phosphorus and 30% reduced nitrogen fertilizer resulted in the highest yield and cost-effectiveness for rice plants. Also enrich soil biodiversity and save 100% of inorganic phosphorus and 30% of nitrogen. In the present study, crop growth and yield responses were evaluated; however, changes in soil organic carbon and post-harvest fertility were not directly measured. The treatment T4 was sufficient to increase growth, yield, and yield attributes of the rice crop, producing the top yield of 6.6550 MT ha^{-1}, which was 11.09% numerically higher than the control plot (T1). Although T5 produced the highest numerical grain yield, T4 was considered the optimum treatment because it achieved a yield comparable to T5 with a lower bio-organic fertilizer dose and the highest benefit–cost ratio. Although T3 had the highest BCR, T4 was considered the optimal treatment due to its higher yield and acceptable economic return. Previous studies report that nitrogen application can be reduced by up to 70% without hampering crop yield. So, it can be concluded that the application of bio-organic fertilizer might be recommended to achieve the maximum rice yield with the least chemical fertilizers, especially nitrogenous and phosphorus fertilizers. The improved plant performance under bio-organic fertilizer treatments may be attributed to enhanced nutrient mineralization, microbial activity, and improved root development, which collectively enhance nutrient uptake efficiency. These findings highlight the potential of integrated nutrient management strategies to enhance productivity while reducing environmental impact. It would help sustain and cost-effectively produce rice in Bangladesh. Future research should focus on multi-location validation and long-term soil health impacts to further confirm the sustainability of reduced-input systems.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of all co-authors to the conceptualization, analysis, and preparation of this study. The authors also note that limited AI-assisted tools (about 13%) were used primarily for language editing and creating diagram, in accordance with the journal's editorial policy (≤15%).

FUNDING SOURCES

This research received no external funding.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICS STATEMENT

This study did not involve any experiments on human participants or animals; therefore, formal written informed consent was not required by the Institutional Review Board. All figures in this study were created; therefore, no permission for reuse is required for any figure presented herein.

REFERENCES

1. Harwindah, Rosbarnawan F, Wati R, Yahumri, Hidayat T, Ishak A, Fauzi E, Rahman T, Rosmanah S, Alfayanti, Afrizon, Rohiat S. Recommendations for rice fertilizing based on soil nutrient status. In: CRC Press eBooks. Informa; 2024:196. doi:10.1201/9781003468943-31
2. Kvakić M, Pellerin S, Ciais P, Achat DL, Augusto L, Denoroy P, Gerber J, Goll DS, Mollier A, Mueller ND, Wang X, Ringeval B. Quantifying the limitation to world cereal production due to soil phosphorus status. Glob Biogeochem Cycles. 2018;32(1):143-157. doi:10.1002/2017GB005754
3. Wang W, Sardans J, Wang C, Tong C, Ji Q, Peñuelas J. Effects of fertilization on porewater nutrients, greenhouse-gas and rice productivity in a subtropical paddy field. Exp Agric. 2019;55(3):395-410. doi:10.1017/S0014479718000078
4. Huang S, Zhao C, Zhang Y, Wang C. Nitrogen use efficiency in rice. In: InTech eBooks. IntechOpen; 2018. doi:10.5772/intechopen.69052
5. Takehisa H, Sato Y. Transcriptome-based approaches for clarification of nutritional responses and improvement of crop production. Breed Sci. 2021;71(1):76-88. doi:10.1270/jsbbs.20098
6. Kundu P, Mallick UK. Modeling the analysis for the exploitation of fertilizers and pesticides on rice production in Bangladesh. Org Farming. 2024;10(1):13-24. doi:10.56578/of100102

7. Saha S, Paul D, Poudel TR, Basunia NM, Hasan T, Hasan M, Li B, Reza R, Haque AR, Hanif MA, Sarker M, Roberts NJ, Khoso MA, Wu H, Shen H. Biofertilizer science and practice for agriculture and forestry: A review. J Appl Biol Biotechnol. 2023. doi:10.7324/jabb.2023.148741
8. White M, Heros E, Graterol E, Chirinda N, Pittelkow CM. Balancing economic and environmental performance for small-scale rice farmers in Peru. Front Sustain Food Syst. 2020;4:564418. doi:10.3389/fsufs.2020.564418
9. Afrin L, Roy S, Rahman A, Binduraz B, Afroz MS, Mahmud JA, et al. Mitigating pesticide runoff in paddy agroecosystems through endophytic bacteria: A pathway toward aquatic biodiversity restoration. Journal of Bioscience and Public Health. 2026;2(2):152–174. https://doi.org/10.5455/JBPH.2026.06
10. Amaya YMQ, Beltrán-Medina JI, Hoyos-Cartagena JÁ, Carvajal JEC, Quijano EB. Selection of sowing date and biofertilization as alternatives to improve the yield and profitability of the F68 rice variety. Agronomía Colombiana. 2020;38(1):61–69. https://doi.org/10.15446/agron.colomb.v38n1.79803
11. Santos FL, Silva FB da, Sá ELS de, Vian AL, Muniz AW, Santos RN. Inoculation and co-inoculation of growth-promoting rhizobacteria in irrigated rice plants. Revista Brasileira de Ciências Agrárias. 2019;14(3):1–8. https://doi.org/10.5039/agraria.v14i3a5665
12. Kaur T, Devi R, Negi R, Kumar S, Singh S, Rustagi S, Shreaz S, Rai AK, Kour D, Yadav AN. Microbial consortium with multifunctional attributes for the plant growth of eggplant (Solanum melongena L.). Folia Microbiologica. 2024;69(6):1255–1266. https://doi.org/10.1007/s12223-024-01168-x
13. Haque MA, Simo, Prodhan MY, Ghosh S, Hossain MS, Rahman A, Haque MA. Enhanced rice plant (BRRI-28) growth at lower doses of urea caused by diazinon-mineralizing endophytic bacterial consortia and exploration of relevant regulatory genes in Klebsiella sp. strain HSTU-F2D4R. Archives of Microbiology. 2023;205(6):231. https://doi.org/10.1007/s00203-023-03564-3
14. Haque MA, Hossain MS, Ahmad I, Akbor MA, Rahman A, Manir MS, Cho KM. Unveiling chlorpyrifos-mineralizing and tomato plant growth-promoting activities of Enterobacter sp. strain HSTU-ASh6 using biochemical tests, field experiments, genomics, and in silico analyses. Frontiers in Microbiology. 2022; 13:1060554. https://doi.org/10.3389/fmicb.2022.1060554
15. Prodhan MY, Rahman MB, Rahman A, Akbor MA, Ghosh S, Nahar MNEN, Simo, Shamsuzzoha M, Cho KM, Haque MA. Characterization of growth-promoting activities of consortia of chlorpyrifos-mineralizing endophytic bacteria naturally harboring in rice plants—A potential bio-stimulant to develop safe and sustainable agriculture. Microorganisms. 2023;11(7):1821. https://doi.org/10.3390/microorganisms11071821
16. Meng T, Liu J. Effects of bio-organic fertilizers on soil organic carbon components and biomass of shamrock. *Bangladesh Journal of Botany*. 2021;50(Special Issue):911–918. https://doi.org/10.3329/bjb.v50i5.56444
17. Wang X, Sun M, Tian L, Yang M, Gao Q, Wang L, Yan H, Yang L, Hou X, Liu P, Zhang L. Microbial fertilizers modulate tobacco growth and development through reshaping soil microbiome and metabolome. Microbiology Spectrum. 2025;13(7):e02605-24. https://doi.org/10.1128/spectrum.02605-24
18. Islam T, Fatema, Hoque MN, Gupta DR, Mahmud NU, Sakif TI, Sharpe AG. Improvement of growth, yield and associated bacteriome of rice by the application of probiotic Paraburkholderia and Delftia. Front Microbiol. 2023; 14:1212505. doi:10.3389/fmicb.2023.1212505
19. Chaudhary AK, Sah PK, Paudel S, Timsina A. Effects of Azolla incorporation timing on growth and yield performance of spring rice (Oryza sativa L.). Turk J Agric Food Sci Technol. 2025; 13:2420-2428. doi: 10.24925/turjaf.v13is1.2420-2428.7990
20. Etesami H, Jeong BR, Glick BR. Potential use of Bacillus spp. as an effective biostimulant against abiotic stresses in crops—A review. Curr Res Biotechnol. 2023; 5:100128. doi: 10.1016/j.crbiot.2023.100128
21. Singh RK, Malik N, Singh S. Improved nutrient use efficiency increases plant growth of rice with the use of IAA-overproducing strains of endophytic Burkholderia cepacia strain RRE25. Microb Ecol. 2013;66(2):375-384. doi:10.1007/s00248-013-0231-2
22. Ferioun M, Zouitane I, Bouhraoua S, Belahcen D, Srhiouar N, Louahlia S, El Ghachtouli N. PGPR consortia promote soil quality and functioning in barley rhizosphere under different levels of drought stress. Ecol Front. 2025;45(2):444-454. doi: 10.1016/j.ecofro.2024.12.001

23. Egamberdiyeva D, Juraeva D, Poberejskaya S, et al. Improvement of wheat and cotton growth by phosphate-solubilizing bacteria. In: Proceedings of the 26th Southern Conservation Tillage Conference for Sustainable Agriculture; 2003; Raleigh, NC, USA.
24. Panhwar QA, Othman R, Zaharah AR, Sariah M, Naher UA. Contribution of phosphate-solubilizing bacteria in phosphorus bioavailability and growth enhancement of aerobic rice. Span J Agric Res. 2011;9(3):810-820.
25. Tariq H, Subramanian S, Geitmann A, Smith DL. Bacillus and Paenibacillus as plant growth-promoting bacteria in soybean and cannabis. Front Plant Sci. 2025; 16:1529859. doi:10.3389/fpls.2025.1529859
26. Nicholson WL, Munakata N, Horneck G, Melosh HJ, Setlow P. Resistance of Bacillus endospores to extreme terrestrial and extraterrestrial environments. Microbiol Mol Biol Rev. 2000;64(3):548-572. doi:10.1128/MMBR.64.3.548-572.2000
27. Dobrzyński J, Naziębło A. Paenibacillus as a biocontrol agent for fungal phytopathogens: Is P. polymyxa the only one worth attention? Microb Ecol. 2024;87(1):134. doi:10.1007/s00248-024-02450-8
28. Roy S, Sultana MT, Rahman A, Hossain MS, Binduraz B, Hanna T, Abir MAI, Rahman M, Abdullah-Al-Mamun M, Roy MK, Cho KM, Haque MA. Genomic and in silico characterization of Acinetobacter sp. strain HSTU-Asm16 with plant growth-promoting traits and diazinon biodegradation potential. J Biosci Public Health. 2026;2(1):68-95. doi:10.5455/JBPH.2026.02122
29. Hossain MS, Alam S, Wmburry L, Rahman A, Binduraz B, Roy S, Sultana MT, Ghosh S, Haque MA. Decoding genome, phylogenetic insights, plant-beneficial genetic repertoire, and in silico pesticide biodegradation pathways of endophytic strain Serratia sp. HSTU-ABk35. J Biosci Public Health. 2026;2(1):30-54. doi:10.5455/JBPH.2025.20
30. Glick BR. Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiol Res. 2014;169(1):30-39. doi: 10.1016/j.micres.2013.09.009
31. Ferreira JP, Vidal MS, Baldani JI. Exploring ACC deaminase-producing bacteria for drought stress mitigation in Brachiaria. Front Plant Sci. 2025; 16:1607697. doi:10.3389/fpls.2025.1607697