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Sustainable Intensification of Rice through Integrated Use of Organic Amendments, Biofertilizers, and Chemical Fertilizers in the Lower Gangetic Alluvial Zone

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the influence of various nutrient management approaches involving organic amendments, biofertilizer, and chemical fertilizers on soil health and plant health of rice under the lower Gangetic alluvial zone of West Bengal.
Study Design: A Randomized Block Design (RBD) was employed with six treatments and four replications.
Place and Duration of Study: The study was conducted at the Agricultural Experimental Farm, University of Calcutta, Baruipur, South 24 Parganas, West Bengal during the Rabi season of

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2024–25. Laboratory studies were undertaken in the Department of Agricultural chemistry and soil science and Department of Agronomy, University of Calcutta, Kolkata-700019.
Methodology: The rice variety MTU 1153 was transplanted at uniform spacing and managed according to standard agronomic practices. Organic manures and biofertilizers were incorporated into the soil before transplanting. The full dose of phosphorus and potassium along with half of the nitrogen was applied as basal, while the remaining nitrogen was top-dressed at 45 days after transplanting. Soil samples were collected from a depth of 0–15 cm and analyzed for soil physico-chemical parameters using standard analytical procedures during various growth stages of rice. Observations on growth attributes of rice were recorded at 30, 60 days after transplanting, and at harvest. Yield and yield attributes were measured from the net plot area and expressed in quintals per hectare. The data were subjected to analysis of variance at a five percent level of significance.
Results: Integrated treatments significantly enhanced soil CEC and OC, with T6 (organic amendments +Bio fertilizer+ 100% RDF) recording the highest values. Available nitrogen, phosphorus, and potassium were consistently higher in integrated nutrient treatments compared to sole chemical fertilizers, reflecting improved nutrient retention and slow mineralization from organic sources. Significant variations ($p < 0.05$) were observed among treatments for growth and yield parameters. The highest plant height (107 cm), Crop growth rate (24.76 g m^{-2} day^{-1}), and dry matter accumulation (1266.74 g m^{-2}) were recorded at harvest under integrated nutrient management which involved organic amendments, biofertilizer and chemical fertilizer (T5 and T6). Grain yield increased significantly from 3.20 t ha^{-1} in control to 5.36 t ha^{-1} in the treatment(T6), while straw yield rose from 5.37 t ha^{-1} to 7.24 t ha^{-1}. ANOVA confirmed treatment effects were significant ($p < 0.05$) for all major growth and yield traits.
Conclusion: These findings highlight the potential of INM as a sustainable strategy for intensive rice cultivation in Gangetic alluvial soils. Although short-term effects on soil physico-chemical properties were observed, substantial improvements require repeated application over multiple seasons.

Keywords: Bio-fertilizer; INM; physio-chemical property; rice productivity; sustainability.

1. INTRODUCTION

The growing global population and its increasing demand for food have placed tremendous pressure on agricultural systems, leading to excessive exploitation of natural resources and degradation of soil health. Ensuring food and nutritional security through sustainable agricultural practices has thus become one of the most critical challenges, particularly in developing nations like India. After the era of green revolution (1960's), the widespread use of chemical fertilizers has significantly boosted agricultural productivity; however, their indiscriminate and imbalanced application has resulted in nutrient depletion, soil degradation, and environmental pollution. The dependence on inorganic fertilizers alone has disrupted soil microbial balance, reduced soil organic matter, and adversely affected soil structure and fertility.

Recent estimates indicate that the fertilizer industry in India has achieved substantial growth, with its market value reaching approximately Rs. 887 billion. Projections suggest a continued upward trend, with an anticipated compound annual growth rate (CAGR) of about 5.5% by the year 2026 (International Fertilizer Association, 2020). This steady expansion reflects the rising demand for fertilizers driven by the country's intensive agricultural practices and the growing need to sustain crop productivity under increasing population pressure.

India, being the world's third-largest producer and consumer of chemical fertilizers, faces a widening nutrient gap as nutrient removal by crops exceeds replenishment through fertilizer application (Kirtikumar et al., 2021). Continuous reliance on NPK-based formulations has caused deterioration in soil physico-chemical properties, leading to reduced nutrient-use efficiency and increased greenhouse gas emissions. Hence, sustainable management of soil fertility is imperative to restore and maintain soil productivity while minimizing environmental impact (Samantaray, 2021).

Integrated Nutrient Management (INM) offers a holistic approach by combining chemical fertilizers with organic manures, crop residues, and biofertilizers to ensure balanced nutrient supply and improved soil health. The synergistic use of these nutrient sources enhances soil structure, microbial activity, and nutrient availability, thereby improving crop growth and yield sustainably.

West Bengal is a predominantly agrarian state where rice constitutes the principal staple food and occupies a central role in the state's agricultural economy. The agro-climatic conditions, characterized by high rainfall, humid subtropical climate, and fertile alluvial soils, are highly conducive to rice cultivation. Owing to its extensive rice-growing area and substantial contribution to national rice output, the state is often referred to as the "Rice Bowl of India."

According to the Indian Council of Agricultural Research (ICAR), rice cultivation in West Bengal covers approximately 5.8 million hectares of the total cultivated area. Data from the Ministry of Agriculture and Farmers Welfare (2023–24) indicate that the state produced about 15.69 million tonnes of rice, contributing nearly 11.4% to the total national production. In terms of area under cultivation, West Bengal ranks second, while in production it stands third among all Indian states. These figures highlight the state's pivotal role in ensuring national food security (West Bengal | ICAR) and sustaining the livelihood of millions of farming household's dependent on rice-based cropping systems.

Rice, a major staple crop in India, demands substantial nutrient inputs for optimal growth. However, conventional fertilizer-based practices often fail to maintain long-term soil fertility. Therefore, adopting diversified nutrient management approaches is essential for sustaining rice productivity while improving soil physico-chemical characteristics.

2. MATERIALS AND METHODS

A field experiment was carried out during the *Rabi* season of 2024–2025 at the Agricultural Experimental Farm of Calcutta University, Baruipur, South 24 Parganas, West Bengal. The experimental site is geographically situated at 22°22′ N latitude and 88°26′ E longitude with an elevation of 128.93 m above mean sea level. The soils of the region come under lower Gangetic alluvial zone, developed from alluvial deposits of the river Ganga, are dominated by illite, quartz, and feldspar minerals.

The experiment consisted of six treatment combinations laid out in a Randomized Block Design (RBD) with four replications. The rice variety MTU1153 was selected for the study. Nutrient applications were made as per the respective treatment specifications. Treatment details are T1: Control, T2: 50% RDF(NPK) , T3:100% RDF(NPK) , T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK) , T6: T4 + 100% RDF(NPK) , where RDF denotes the recommended dose of fertilizer (120:60:40 kg ha^{-1} of $N:P_2O_5:K_2O$). A mixture of organic and bio-based materials was applied to the soil (T4, T5 and T6). On a weight basis, for every 100 kg of soil, 0.1 kg of *Azotobacter* and 1 kg each of vermicompost, poultry litter, oil cake, and farmyard manure were used. The materials were mixed thoroughly and applied 10–15 days before transplanting, followed by incorporation into the top 15 cm soil layer to ensure uniform blending and to enhance soil fertility and microbial activity. The entire dosage of Phosphorus and Potassium was applied at the time of final land preparation while Nitrogen was applied in 2 equal splits at the time of final land preparation and 45 DAT. The N, P and K fertilizers were applied in the form of urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (MOP) (60% K_2O) respectively.

All agronomic practices and other plant protection measures were followed as and when required.

Soil samples were collected from each treatment plot, air-dried, gently crushed with a wooden roller, and sieved through a 2 mm mesh. The processed samples were analyzed for key chemical properties using standard procedures: organic carbon by the method of Walkley and Black (1934); available nitrogen following Subbiah and Asija (1956); available phosphorus using 0.5 M $NaHCO_3$ (pH 8.5) extract as per Olsen et al. (1954); exchangeable potassium with 1 N ammonium acetate.

Growth attributes such as plant height (cm), number of tillers m^{-2}, Crop Growth Rate (g m^{-2} day^{-1}) and dry matter accumulation (g m^{-2}) were recorded from five tagged plants in each plot, and the mean values were computed. Grain yield from the net plot area was recorded after proper cleaning and drying, expressed in grams, and subsequently converted to tonnes per hectare using appropriate conversion factors. Straw yield was estimated by recording the weight of stem and chaff after threshing and similarly expressed on a hectare basis.

Data were statistically analysed using the standard procedure for RBD as suggested by

Gomez and Gomez (1984), with treatment means compared at 5% level of significance.

3. RESULTS AND DISCUSSION

3.1 Effect on Physio Chemical Properties

The data presented in Table 1 depict the temporal variations in soil reaction, electrical conductivity (EC), cation exchange capacity (CEC) and organic carbon (OC) under different nutrient management practices. Soil pH remained nearly neutral throughout the crop growth stages, and the differences among treatments were statistically non-significant. The negligible variation in pH may be attributed to the inherent buffering capacity of the Gangetic alluvial soil, which resists abrupt changes in soil reaction even under contrasting nutrient management conditions. Electrical conductivity values also remained within a safe range (0.23–0.37 dS m^{-1}) and did not vary significantly among treatments, suggesting that none of the applied inputs contributed to soil salinity. The slight reduction in EC towards harvest might be ascribed to uptake of soluble salts by plants and leaching losses.

In contrast, CEC and OC exhibited noticeable improvement under the organic and integrated nutrient management treatments. The highest CEC (24.88 cmol (p^+) kg^{-1}) was recorded under T6 (0.1 % Azotobacter + 1 % vermicompost + 1 % poultry litter + 1 % oil cake + 1 % FYM + 100 % RDF), followed by T4 and T5, while the control (T1) maintained the lowest value (21.06 cmol (p^+) kg^{-1}). The increase in CEC under organic and integrated treatments may be attributed to the enhancement of humus content and formation of negatively charged colloids through decomposition of organic manures, which improved nutrient-retention capacity. Similar improvements in CEC due to organic matter addition have been reported by Coêlho et al. (2023), who emphasized the strong association between soil organic carbon and cation exchange sites.

A pronounced improvement in soil organic carbon was observed in treatments involving organics and integrated nutrient management. The maximum OC (0.57 %) was recorded under T4, followed by T6 (0.54 %) and T5 (0.53 %), whereas the lowest (1.07 %) occurred in the control. The increase in OC under these treatments could be due to the direct addition of carbonaceous materials from organic manures and enhanced microbial activity stimulated by *Azotobacter* inoculation.

The present findings are well supported by earlier research that demonstrated similar improvements in soil chemical properties under integrated nutrient management systems. Bhatt et al. (2023) reported that the combined application of organic manures and inorganic fertilizers enhanced soil organic carbon and nutrient-retention capacity in long-term rice–wheat systems due to the synergistic contribution of humic substances and mineral nutrients. Likewise, Rahman et al. (2021) observed that integrated nutrient application significantly improved soil aggregation, cation exchange capacity, and total nitrogen by stimulating microbial activity and continuous nutrient cycling. The convergence of these reports with the present study clearly indicates that the integration of organic and inorganic nutrient sources promotes balanced nutrient supply, enhances soil colloidal charge, and maintains soil health in Gangetic alluvial ecosystems.

3.2 Effect on Available Macro Nutrients

The data in Table 2 depict the dynamic changes in soil available nitrogen (N), phosphorus (P), and potassium (K) as influenced by various nutrient management treatments during different growth stages of rice. A gradual decline in the available nutrient content was observed from the initial stage to harvest across all treatments, indicating nutrient uptake and utilization by the crop. However, the magnitude of reduction varied significantly among treatments, reflecting the differential effects of integrated nutrient management practices.

Soil available nitrogen showed a consistent decreasing trend from the initial stage to harvest. The lowest nitrogen content at harvest (150.31 kg ha^{-1}) was recorded under the control (T1), whereas the highest residual nitrogen (191.77 kg ha^{-1}) was observed with the combined application of organic manures, biofertilizer, and 100% RDF (T6). Treatments receiving integrated sources of nutrients (T4, T5, and T6) maintained higher available N throughout the growth period compared to chemical fertilizer alone (T2 and T3), which may be attributed to the continuous mineralization of organic matter and improved microbial activity enhancing N availability (Kharlukhi et al., 2024). The trend clearly indicates that integration of organic and inorganic sources enhanced soil N status sustainably.

Table 1. Effect of various nutrient management approaches on physio chemical properties of soil during different growth stages of rice

Treatments	PH				EC (dS m⁻¹)				CEC (cmol (p⁺) kg⁻¹))				OC (%)			
	Initial	30 DAT	60 DAT	at Harvest	Initial	30 DAT	60 DAT	at Harvest	Initial	30 DAT	60 DAT	at Harvest	Initial	30 DAT	60 DAT	at Harvest
T1	6.83	6.85	6.82	6.79	0.27	0.25	0.24	0.23	21.83	21.35	21.15	21.06	0.40	0.30	0.24	0.26
T2	7.07	7.10	7.07	7.06	0.28	0.29	0.29	0.23	21.68	21.89	22.30	23.41	0.33	0.37	0.31	0.36
T3	7.06	7.11	7.08	7.04	0.31	0.30	0.29	0.24	21.83	22.11	22.60	22.43	0.49	0.47	0.44	0.48
T4	7.17	7.21	7.18	7.10	0.37	0.33	0.29	0.23	21.81	23.13	24.02	24.70	0.48	0.50	0.54	0.57
T5	7.13	7.12	7.11	7.10	0.32	0.30	0.32	0.26	21.59	23.06	23.67	24.68	0.47	0.50	0.52	0.53
T6	7.15	7.18	7.17	7.06	0.35	0.32	0.33	0.28	21.53	23.81	24.15	24.88	0.46	0.53	0.51	0.54
SEm(±)	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.23	0.26	0.22	0.24	0.02	0.01	0.02	0.02
CD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.76	0.65	0.69	NS	NS	NS	NS

T1: Control, T2: 50% RDF(NPK), T3:100% RDF(NPK), T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK), T6: T4 + 100% RDF(NPK)

Table 2. Effect of various nutrient management approaches on Available macro nutrient of soil during different growth stages of rice

Treatments	Available Nitrogen (kg ha⁻¹)				Available Phosphorous (kg ha⁻¹)				Available Potassium (kg ha⁻¹)			
	Initial	30 DAT	60 DAT	at Harvest	Initial	30 DAT	60 DAT	at Harvest	Initial	30 DAT	60 DAT	at Harvest
T1	170.94	158.08	158.00	150.31	16.58	13.47	12.10	11.59	263.48	262.32	257.42	231.88
T2	172.36	175.41	157.70	164.70	16.85	14.85	13.79	12.93	265.66	257.07	260.09	263.29
T3	175.26	140.27	145.45	169.79	16.09	15.45	14.66	13.94	260.53	237.29	259.56	265.22
T4	171.50	162.11	177.29	178.10	16.90	14.78	13.30	16.09	267.80	250.61	257.39	261.91
T5	173.03	161.77	171.95	180.85	16.04	15.80	15.01	16.33	264.96	252.23	259.60	273.85
T6	179.09	171.60	186.27	191.77	16.62	15.98	16.51	17.01	265.47	253.51	262.36	275.37
SEm(±)	7.81	3.77	3.48	3.96	1.47	0.79	0.69	0.61	8.16	4.74	2.92	4.13
CD (0.05)	NS	11.04	10.17	11.59	NS	NS	2.03	1.77	NS	13.87	8.54	12.07

T1: Control, T2: 50% RDF(NPK), T3:100% RDF(NPK), T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK), T6: T4 + 100% RDF(NPK)

Available phosphorus also followed a similar declining pattern during crop growth, mainly due to plant uptake and fixation in soil colloids. The lowest P content (11.59 kg ha^{-1}) at harvest was found in the control (T1), while the highest (17.01 kg ha^{-1}) was recorded under T6. The integrated treatments (T5 and T6) exhibited significantly higher available P throughout the growth stages, suggesting the beneficial role of organic amendments and Azotobacter in solubilizing native phosphorus and reducing fixation losses. Organic manures might have released organic acids during decomposition, which helped in maintaining P availability in the rhizosphere.

Available potassium also decreased gradually with crop growth but remained higher under integrated nutrient treatments. The lowest K content at harvest (231.88 kg ha^{-1}) was found under control (T1), whereas the highest (275.37 kg ha^{-1}) was recorded with the combined use of biofertilizer, organics, and 100% RDF (T6). The enhanced K status under these treatments could be ascribed to the slow mineralization of organic sources and improved cation exchange capacity, leading to better retention and release of K to plants. The integrated application thus helped maintain a favorable nutrient balance even at the end of the crop cycle.

The observed increase in available soil potassium with the application of organic manures may be attributed to reduced potassium fixation and the gradual release of K resulting from interactions between organic matter and clay minerals, in addition to the direct contribution of potassium from the organic amendments. These results are in agreement with Kumar et al. (2014), who reported that organic inputs can enhance soil K availability. Similarly, the incorporation of farmyard manure (FYM) along with N, P, and K fertilizers has been shown to improve soil organic carbon content, which in turn promotes higher availability of essential nutrients such as nitrogen, phosphorus, and potassium, as demonstrated by Gawde et al. (2017).

Overall, the integrated treatments (particularly T6) consistently maintained higher available macronutrient levels throughout the growth period, emphasizing the positive effect of combining organic manures, biofertilizers, and recommended fertilizer doses on sustaining soil fertility and nutrient availability. This improvement is likely due to synergistic interactions among nutrient sources that enhance microbial activity, nutrient mineralization, and soil structure. In contrast, the control and the treatments receiving only chemical fertilizers (T_1–T_3) showed comparatively lower nutrient availability, which might be due to rapid nutrient exhaustion, leaching losses, and limited microbial activity. The sole use of mineral fertilizers often accelerates nutrient depletion and leads to deterioration of soil health over time, whereas integration with organic manures enhances nutrient use efficiency and soil productivity in a sustainable manner.

3.3 Effect on Growth Attributes of Rice

The data on the growth attributes as affected by integrated nutrient management have been summarized in Table 3. An interception of the data revealed that plant height, dry matter accumulation (DMA), and crop growth rate (CGR) were markedly influenced by the applied treatments throughout the crop growth period. A progressive increase in plant height was observed from 30 to 90 DAT across all treatments, with the tallest plants recorded under T6 at all growth stages (54.98 cm at 30 DAT, 69.00 cm at 60 DAT, and 107.50 cm at harvest). This treatment remained statistically superior over the others, followed by T5 and T3, while the minimum plant height was obtained in T1 (84.50 cm at harvest). The enhanced plant height under T6 may be attributed to improved nutrient availability and physiological activity that favoured rapid cell elongation and sustained vegetative growth.

A similar trend was noted in Dry matter accumulation (DMA) and crop growth rate (CGR), where a consistent increase with crop age was recorded under all treatments. T6 recorded the highest DMA (213.16, 638.21, 1218.38 g m^{-2} at 30, 60 DAT, and harvest) and CGR (14.17 and 19.34 g m^{-2} day^{-1}), followed by T5, while T1 showed the lowest values. The superior performance of T6 is attributed to efficient photosynthate assimilation, enhanced nutrient uptake, and improved physiological activity, which together supported greater biomass production and sustained growth during critical developmental stages.

This clearly demonstrates the positive impact of balanced and integrated nutrient management practices on the growth performance and physiological efficiency of the crop, leading to enhanced productivity potential.

Table 3. Effect of various nutrient management approaches on Growth attributes of rice during different growth stages

Treatments	Plant height (cm)			DMA (g m^{-2})			CGR (g m^{-2} day^{-1})	
	30 DAT	60 DAT	At Harvest	30 DAT	60 DAT	At Harvest	30-60 DAT	60-90 DAT
T1	41.08	54.08	84.50	110.52	358.23	625.67	8.26	8.91
T2	49.71	64.86	94.86	181.05	472.05	994.79	9.70	17.42
T3	50.60	65.30	96.18	186.10	487.26	1004.49	10.04	17.24
T4	46.76	58.71	90.41	129.31	395.61	753.71	8.88	11.94
T5	52.55	67.37	98.69	198.89	523.89	1266.74	10.83	24.76
T6	54.98	69.00	107.50	213.16	638.21	1218.38	14.17	19.34
SEm(±)	2.14	1.55	2.03	8.69	19.94	39.29	0.56	1.53
CD (0.05)	6.27	4.55	5.95	25.44	58.35	114.94	1.64	4.47

T1: Control, T2: 50% RDF(NPK), T3:100% RDF(NPK), T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK), T6: T4 + 100% RDF(NPK)

Table 4. Effect of various nutrient management approaches on yield attributes of rice during different growth stages

Treatments	Effective tillers (m^{-2})	Panicle length (cm)	Filled grains ($pancle^{-1}$)	Test Weight (g)
T1	181.08	20.82	91.68	19.66
T2	186.44	21.87	89.51	21.37
T3	200.22	23.16	98.75	21.42
T4	193.62	22.88	101.33	20.66
T5	224.56	24.68	96.78	22.18
T6	238.09	23.35	98.71	21.14
SEm (±)	10.96	0.43	2.23	0.67
CD (0.05)	32.06	1.25	6.52	NS

T1: Control, T2: 50% RDF(NPK), T3:100% RDF(NPK), T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK), T6: T4 + 100% RDF(NPK)

The findings are in accordance with Nureti et al. (2024), who reported that the combined application of organic and inorganic sources ensures a continuous flow of essential nutrients, fostering robust root development and stimulating metabolic functions. This promotes the synthesis of key biomolecules such as carbohydrates, amino acids, and proteins, which collectively enhance cell division, elongation, and tissue differentiation. The present findings, therefore, corroborate these earlier studies, underscoring that an integrated nutrient management approach effectively sustains growth, biomass accumulation, and overall productivity of rice under diverse environmental conditions.

3.4 Effect on Yield Attributes of Rice

The scrutiny of data from Table 4 clearly reveals that there was a significant impact of different nutrient management on yield attributing characters. A consistent improvement in all yield attributes was observed with the integration of organic and inorganic sources of nutrients over the control.

The number of effective tillers m^{-2} varied significantly among the treatments, ranging from 181.08 in T1 (control) to 238.09 in T6. The maximum number of effective tillers was recorded under T6 (0.1% Azotobacter + 1% Vermicompost + 1% Poultry Litter + 1% Oil Cake + 1% FYM + 100% RDF), which was statistically superior to all other treatments. This was closely followed by T5 (224.56 tillers m^2), whereas the minimum value was obtained in the control plot. The increase in effective tillers under integrated nutrient management may be attributed to improved nutrient supply, better soil structure, and enhanced microbial activity, which facilitated robust tiller initiation and survival.

Panicle length was also favourably influenced by the treatments, with T5 recording the longest panicle (24.68 cm), followed by T6 (23.35 cm) and T3 (23.16 cm), while the shortest panicles were observed under T1 (20.82 cm). The enhancement in panicle length due to integrated nutrient sources could be attributed to balanced nutrient availability and hormonal stimulation caused by *Azotobacter* and organic manures, which promoted reproductive growth and spikelet development.

The number of filled grains panicle^{-1} exhibited significant variation among the treatments, ranging from 89.51 in T2 to 101.33 in T4. The maximum number of filled grains (101.33) recorded in T4 was statistically at par with T6 (98.71) and T3 (98.75). The increase in filled grains may be attributed to efficient nutrient translocation, better photosynthate partitioning, and improved pollen viability due to favourable physiological conditions induced by organic and biofertilizer combinations.

The test weight did not differ significantly among the treatments, though the highest value (22.18 g) was recorded under T5, followed by T3 (21.42 g), while the lowest (19.66 g) was obtained under T1. The non-significant variation in test weight indicates that grain size and density are less affected by nutrient sources, as these are more genetically governed traits.

The present results are in close conformity with Singh et al*.* (2018), who observed that the integration of organic manures with inorganic fertilizers markedly enhanced the yield-attributing characters of rice. The improvement may be ascribed to the continuous and balanced nutrient supply achieved through integrated nutrient management (INM). Organic manures, being rich in humic substances and beneficial microorganisms, gradually release nutrients through microbial mineralization, whereas inorganic fertilizers provide nutrients immediately after application. This complementary effect ensures a steady nutrient supply throughout the crop growth period, particularly during the grain-filling phase, thereby enhancing the development of productive tillers and filled grains. Similarly, Senthamizhkumaran et al*.* (2021) reported that the combined application of organic and inorganic nitrogen sources enhances nutrient use efficiency and supports continuous nutrient uptake, leading to improved reproductive development and higher grain yield in rice. The contribution of vermicompost and farm yard manure, due to its gradual nutrient release and improvement of soil physical and biological properties, further aids in sustained nutrient supply and better utilization by plants. Neti et al*.* (2022) also emphasized that organic manures provide nutrients in a slow-release form, thereby maintaining soil fertility and promoting higher yield attributes and productivity across the growth stages of rice.

3.5 Effect on Yield of Rice

The perusal of data (Table 5) indicated a significant improvement in all yield parameters with integrated nutrient management (INM) and recommended doses of fertilizers compared to the control. Among the treatments, T6 (0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure + 100% RDF) recorded the highest grain yield (5.36 t ha^{-1}) and straw yield (7.24 t ha^{-1}). This indicates that partial substitution of chemical fertilizers with organic sources along with biofertilizers could achieve yield levels comparable to full RDF application.

Treatment T3 (100% RDF) significantly improved grain yield (5.11 t ha^{-1}) and straw yield (6.72 t ha^{-1}) over control (T1), confirming the beneficial effect of balanced fertilization. The T4 treatment, which included only organic amendments and biofertilizer, enhanced yields over the control but was slightly lower than treatments combining organic sources with chemical fertilizers (T5 and T6).

The observed increase in grain and straw yield in plots receiving chemical fertilizers combined with organic manures may be attributed to enhanced colonization by arbuscular mycorrhizal fungi (AMF), improved activity of beneficial soil microbes, and elevated soil enzyme activity. These processes facilitate efficient nutrient mobilization, ensuring balanced and timely availability of nutrients throughout the crop growth period, which promotes the development of yield-contributing traits and ultimately results in higher economic yield. In support of these findings, Hoseinzade et al. (2016) reported that microbial inoculation, when applied alongside chemical and biological fertilizers, significantly improved nutrient uptake and rice growth, leading to enhanced grain yield. Similarly, Sekiya et al. (2025) demonstrated that the application of organic fertilizers positively influenced soil microbial communities, enhanced nitrogen

Table 5. Effect of various nutrient management approaches on yield of rice during different growth stages

Treatments	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
T1	3.20	5.37
T2	4.41	6.27
T3	5.11	6.72
T4	3.65	5.76
T5	4.77	6.45
T6	5.36	7.24
SEm(±)	0.28	0.27
CD (0.05)	0.81	0.80

T1: Control, T2: 50% RDF(NPK), T3:100% RDF(NPK), T4: 0.1% Azotobacter + 1% Vermi Compost + 1% Poultry Litter + 1% Oil Cake + 1% Farm Yard Manure, T5: T4 + 50% RDF(NPK), T6: T4 + 100% RDF(NPK)

mineralization, and increased rice productivity by improving fertilizer use efficiency. These studies corroborate the present results, confirming that integrated nutrient management combining organic, inorganic, and biofertilizer sources is highly effective in enhancing rice yield under Gangetic alluvial soils.

4. CONCLUSION

Integrated nutrient management combining organic amendments, biofertilizer, and chemical fertilizers significantly enhanced rice growth, yield, and nutrient availability in lower Gangetic alluvial soils. Partial substitution of chemical fertilizers with organics and azotobacter achieved yields comparable to full recommended doses, highlighting the potential of INM for sustainable rice cultivation. Although short-term effects on soil physico-chemical properties were observed, substantial improvements require repeated application over multiple seasons. Adoption of INM can optimize productivity while maintaining soil health, offering a practical strategy for sustainable rice production in West Bengal.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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