



RESEARCH ARTICLE

Evaluation of the effect of organic manure, inorganic fertilisers and bio-inoculants on plant growth of rice (*Oryza sativa* L.)

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Abstract

The declining productivity of rice and deterioration of soil health associated with conventional rice cultivation necessitate the adoption of sustainable nutrient management strategies. Field experiments were conducted during the Kharif seasons of 2021–22 and 2022–23 at the Students' Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, to evaluate the effects of organic manure, inorganic fertilisers and bio-inoculants on the growth of rice (*Oryza sativa* L.). The experiment comprised 18 treatment combinations arranged in a randomised block design with 3 replications, involving different combinations of inorganic fertilisers, organic manures and biofertilisers. The results indicated that among the various growth parameters, the maximum plant height (99.15 cm and 99.85 cm), number of tillers (409.4 m⁻² and 412.25 m⁻²), dry matter accumulation (760.48 g m⁻² and 764.34 g m⁻²) and leaf area index (4.32 and 4.37) were recorded during 2021–22 and 2022–23, respectively, under treatment T₁₇ (100 % NPK + 5 t ha⁻¹ FYM + *Azolla* 300 kg ha⁻¹ + S 30 kg ha⁻¹ + Zn 5 kg ha⁻¹). These findings highlight the synergistic effects of integrating organic and inorganic nutrient sources along with bio-inoculants. This integrated approach enhances crop performance, improves soil sustainability and ensures better economic returns, making it a promising strategy for modern rice farming systems.

Keywords: bio-inoculants; growth parameters; inorganic fertilisers; integrated nutrient management; organic manure; rice; yield

Introduction

Rice is the major staple food for more than half of the world's population, with the majority of consumers in Asia, Sub-Saharan Africa and South America. Although rice can be grown in many parts of the world, its specific cultivation requirements limit its distribution to certain regions (1). Rice is the primary source of food in Asia, where more than 85 % of global rice production occurs. In India, rice ranks second among food grains in terms of both production and area under cultivation, contributing over 40 % to the country's annual food grain output.

In general, nutrient-responsive rice varieties exhibit low productivity with wide variability depending largely on the availability of nutrients in the soil. The major challenge for agricultural scientists, researchers and climatologists is to develop strategies to improve rice productivity (2). Intensive rice production has adversely affected the environment and exerted pressure on natural resources, resulting in problems such as increased soil salinity and alkalinity, waterlogging, surface water pollution, groundwater depletion and health risks due to excessive use of agrochemicals and pesticides (3). It also contributes to increased methane emissions (4). This has led to growing interest among

farmers, scientists and policymakers in integrated nutrient management (INM) for rice and other crops (5). The INM optimises the provision of nutrients to crops through the combined use of organic manures, inorganic fertilisers and beneficial microorganisms such as bio-inoculants. This approach not only sustains crop yields but also improves soil fertility and ecological balance over time (6).

Natural organic matter, such as compost, poultry manure and farmyard manure (FYM), improves soil structure, enhances microbial biomass and contribute to stable carbon sequestration (7). However, chemical fertilisers remain essential to meet the initial nutrient requirements of high-yielding rice genotypes. Nevertheless, exclusive dependence on synthetic inputs is both economically and environmentally unsustainable (8). Nitrogen plays a crucial role in plant nutrition, significantly influencing growth and physiological characteristics. It affects light penetration, photosynthetically active radiation, light utilisation efficiency, and the distribution of dry matter in plants. The allocation of dry matter to reproductive organs is associated with the number, capability and functionality of physiological sinks (9–11). Imbalanced nitrogen application results in nutrient losses through leaching and volatilisation, thereby reducing fertiliser use efficiency. These losses can be minimised by the combined application of inorganic and organic inputs (12).

Recently, bio-inoculants are gaining attention as an eco-friendly supplement for nutrient management (13). Some microbial inoculants, such as *Azospirillum* and *Azotobacter*, are known to fix atmospheric nitrogen, while phosphate-solubilizing bacteria increase phosphorus availability and enhance root growth through the secretion of plant growth hormones (14). Farmyard manure acts as a soil conditioner, improving the physical, chemical and biological properties of soil and by enhancing microbial life in the soil. This results in vigorous root system development, improved nutrient acquisition, enhanced grain yield, and better quality (15). These inoculants, especially when used along with organic and inorganic fertilisers, improve nutrient uptake and overall plant performance in rice ecosystems (16). From an economic perspective, cost-effectiveness becomes central in nutrient management strategies. While organic materials and bio-inoculants may seem costly due to higher handling requirements, they reduce long-term fertiliser input needs and provide more stable yields over time. Numerous field studies have demonstrated that integrated nutrient management practices not only improve crop performance but also enhance the cost-benefit ratio by reducing dependence on expensive chemically synthesised inputs (17). There is limited region-specific information on integrated nutrient management across diverse agro-climatic zones, where variations exist in soil characteristics, rainfall patterns, and management practices, and their studies are often restricted to individual components. Therefore, studies assessing the agronomic and economic impact of integrated nutrient application in rice under

real farming conditions are needed. This research was developed to address this gap by evaluating the effects of organic manure, chemical fertilisers, and bio-inoculants applied individually or in combination on rice crops. The results aim to provide practical insights for developing balanced nutrient management strategies in rice-based cropping systems.

Materials and Methods

Experimental Site

The experiment was carried out at the Students' Instructional Farm C.S. Azad University of Agriculture and Technology, Kanpur Nagar (Uttar Pradesh), India, during the kharif seasons of 2021–22 and 2022–23. Geographically, Kanpur district is situated between latitudes 25.26° and 26.58° N and longitudes 79.31° and 80.34° E, at an altitude of 124 m above mean sea level. It lies in the central Gangetic plains of Uttar Pradesh and is characterised by alluvial soil. The region experiences a subtropical climate with hot, dry summers and cold winters. The average annual rainfall is about 800 mm, most of which is received during the rainy season from early July to the end of September, with occasional winter showers.

Experimental treatment details

The initial physical and chemical parameters of the experimental site are presented in Table 1. The experiment was carried out in a randomised block design. The gross plot area of each plot was 13.2 m² (4.4 m × 3.0 m). The study comprised 18 treatment combinations using the rice variety PB-1509 (Table 2). The experimental field was ploughed twice using a tractor-drawn cultivator, followed by levelling. Subsequently, two puddling operations were carried out using a rotavator in 10 cm of standing water. The nursery was sown on June 25, 2022 and June 28, 2023, with a seed rate of 30 kg ha⁻¹. In both years, two seedlings per hill were transplanted on July 14 and July 26, respectively, maintaining a spacing of 20 cm × 10 cm. Fertilisers were applied as per the treatment details. The crop reached maturity at 130 days after transplanting and was harvested accordingly. Transplanting was carried out in accordance with the experimental design.

Procedure for collecting and estimating growth characteristics

Plant height (cm)

Plant height was recorded at 30, 60 and 90 days after transplanting (DAT) and at harvest, based on the average of five randomly selected hills. The height of the plants was measured from the base of the stem touching the ground level to the tip of the uppermost leaf.

Number of tillers (m⁻²)

The total number of tillers per m² at 30, 60 and 90 DAT and at harvest was determined by randomly placing a 50 cm × 50 cm (0.25 m²) quadrat randomly at three different locations within each plot.

Table 1. Physico-chemical characteristics of the experimental field

Characteristics	Value	Method of determination
pH (1:2.5)	7.9	Method No. 21, USDA Handbook No. 60 (18)
EC (dS m ⁻¹)	0.3	Method No. 21, USDA Handbook No. 60 (19)
Organic carbon (g kg ⁻¹)	4.5	Walkely and Black method (20)
Available N (kg ha ⁻¹)	210	Alkaline permanganate method (21)
Available P (kg ha ⁻¹)	12.8	Olsen's method (22)
Available K (kg ha ⁻¹)	198	Hanway and Heidel (23)
Available DTPA-Zn (kg ha ⁻¹)	0.55	Lindsay and Norvell (24)

Table 2. Details of treatment combinations

Symbol	Treatment combinations
T ₁	Control
T ₂	100 % NPK
T ₃	50 % NPK + 5 t ha ⁻¹ FYM
T ₄	75 % NPK + 5 t ha ⁻¹ FYM
T ₅	100 % NPK + 5 t ha ⁻¹ FYM
T ₆	50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹)
T ₇	75 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹)
T ₈	100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹)
T ₉	50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹)
T ₁₀	75 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹)
T ₁₁	100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹)
T ₁₂	50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₃	75 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₄	100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₅	50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₆	75 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₇	100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)
T ₁₈	5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zinc (5 kg ha ⁻¹)

FYM: farmyard manure; NPK: nitrogen, phosphorus and potassium; *Azolla* applied at 300 kg ha⁻¹; sulfur applied at 30 kg ha⁻¹; zinc applied at 5 kg ha⁻¹.

Dry matter accumulation (g m⁻²)

Dry matter accumulation was determined at 30, 60 and 90 DAT and at harvest by randomly sampling five plants from each plot. The plant shoots were trimmed carefully at ground level, placed in paper bags and sun-dried for approximately two days. Subsequently, the samples were oven-dried at 65–70 °C until a constant weight was achieved. The dry matter was expressed as g m⁻².

Leaf area index

Leaf area index (LAI) was determined at 30, 60 and 90 DAT. An automatic leaf area meter was used to measure the leaf surface area (cm²) after separating the green leaves. The leaves were categorised into three groups based on size: small, medium and large. From each group, five representative leaves were selected and their surface area was measured. The total leaf area was calculated by multiplying the average area of five leaves by the number of leaves in each group. The leaf area index was obtained by dividing the total leaf area by the corresponding ground area. The LAI was computed using the following formula:

$$\text{LAI} = \text{Leaf area (cm}^2\text{)} / \text{Ground area (cm}^2\text{)}$$

Where:

L - Leaf area (cm²)

A - Ground area (cm²)

Statistical analysis

The data collected during the field experiment were subjected to analysis of variance (ANOVA) for data analysis in a randomised block design (20), using the OPSTAT online software. All graphs were prepared using Microsoft Excel and the results were expressed as mean ± standard error (SE).

Results

Effect on growth characters

Effect on plant height

The summarized data on periodic observations of plant height at 30, 60, 90 and 120 DAT during the 2021–22 and 2022–23 growing seasons are shown in Table 3 and Fig. 1 respectively. The pooled data revealed significant variations in plant height across treatments and growth stages, indicating the influence of treatments on

vegetative growth in rice. Across both years, plant height ranged from 46.16–99.15 cm in 2021–22 and 44.74–99.85 cm in 2022–23. The maximum plant height was consistently recorded under treatment T17 (100 % recommended NPK + 5 t ha⁻¹ FYM + 300 kg ha⁻¹ *Azolla* + 30 kg ha⁻¹ sulfur + 5 kg ha⁻¹ zinc). Specifically, T17 recorded a peak height of 99.15 cm in the first year and 99.85 cm in the second year, indicating a stable and sustained improvement in plant height due to the synergistic effect of organic, inorganic and bio-inoculant inputs. In contrast, the minimum plant heights were recorded in the control treatment (T1), which received no external nutrient inputs. Treatment T1 exhibited plant heights of 46.16 cm in 2021–22 and 44.74 cm in 2022–23, highlighting the importance of balanced nutrient supply for optimal rice growth. A progressive increase in plant height was observed across successive growth stages in all treatments, with a sharper increase from 60 to 90 DAT, indicating that this period is critical for vegetative development. The year-wise comparison revealed slightly higher growth performance in 2022–23, which may be attributed to improved soil conditions and the residual effects of organic amendments on soil fertility.

Effect on number of tillers (m⁻²)

The data on the number of tillers per m² are presented in Table 4 and Fig. 2, respectively. Observations were recorded at 30, 60, 90 and 120 DAT and at the harvesting stage during the two consecutive cropping seasons (2021–22 and 2022–23). On a pooled basis, the number of tillers ranged from 170.34 to 396.47 tillers m⁻² in 2021–22 and 172.52 to 412.25 tillers m⁻² in 2022–23. A progressive increase in tillering was observed with the advancement of crop growth under integrated nutrient management treatments. The highest number of tillers was consistently recorded under treatment T17 (100 % NPK + 5 t ha⁻¹ FYM + 300 kg ha⁻¹ *Azolla* + 30 kg ha⁻¹ sulfur + 5 kg ha⁻¹ zinc), registering 409.84 tillers m⁻² in 2021–22 and 412.25 tillers m⁻² in 2022–23. The superior performance of this treatment may be attributed to the combined effect of balanced macronutrient supply, organic matter enrichment, enhanced microbial activity from *Azolla* and micronutrient supplementation (S and Zn), all of which synergistically improved soil health, root proliferation and vegetative growth, thereby increasing tillering capacity. In contrast, the lowest tiller counts were recorded in the control treatment (T1), which recorded 170.34 tillers m⁻² in 2021–22 and 172.52 tillers m⁻² in 2022–23, indicating the critical role of nutrient inputs in supporting tiller development. Treatments involving partial NPK combined with FYM

Table 3. Effect of organic manure, inorganic fertilizer and bio-inoculants on plant height at various growth stages of rice during 2021–22 and 2022–23

Treatments	Plant height (cm)				Plant height (cm)				Pooled mean at harvest (cm)
	2021–22				2022–23				
	30 DAT	60 DAT	90 DAT	At Harvest	30 DAT	60 DAT	90 DAT	At Harvest	
T1 Control	46.16	56.47	71.92	72.11	44.74	57.63	73.13	73.29	72.70 ^g
T2 100 % NPK	50.81	65.05	84.47	84.59	52.23	66.57	85.87	86.13	85.36 ^f
T3 50 % NPK + FYM	51.40	67.29	86.93	87.04	52.80	68.81	88.24	88.46	87.75 ^e
T4 75 % NPK + FYM	51.62	67.66	87.66	87.81	53.11	69.15	88.97	89.14	88.48 ^e
T5 100 % NPK + FYM	51.70	68.16	88.46	88.61	53.38	69.68	89.66	90.07	89.34 ^d
T6 50 % NPK + FYM + <i>Azolla</i>	51.98	69.96	89.81	89.94	53.75	71.46	91.10	91.25	90.60 ^d
T7 75 % NPK + FYM + <i>Azolla</i>	52.38	73.68	92.21	92.34	57.01	75.44	93.83	94.12	93.23 ^c
T8 100 % NPK + FYM + <i>Azolla</i> + S	53.29	75.46	94.13	94.39	58.40	77.07	95.42	95.79	95.09 ^b
T9 50 % NPK + FYM + <i>Azolla</i> + S	52.29	71.06	90.38	90.51	54.90	72.63	91.69	91.93	91.22 ^{cd}
T10 75 % NPK + FYM + <i>Azolla</i> + S	52.61	73.94	92.84	92.97	57.02	76.08	94.04	94.43	93.70 ^c
T11 100 % NPK + FYM + <i>Azolla</i> + S	53.34	77.12	96.35	96.93	58.89	78.68	97.76	98.02	97.48 ^{ab}
T12 50 % NPK + FYM + <i>Azolla</i> + Zn	52.35	73.23	91.13	91.32	55.05	74.73	92.42	92.73	92.03 ^c
T13 75 % NPK + FYM + <i>Azolla</i> + Zn	52.62	74.78	93.16	93.31	57.41	76.28	94.47	94.78	94.05 ^c
T14 100 % NPK + FYM + <i>Azolla</i> + Zn	53.50	78.34	97.13	97.83	59.09	79.87	98.44	98.73	98.28 ^{ab}
T15 50 % NPK + FYM + <i>Azolla</i> + S + Zn	52.35	73.39	91.83	92.02	55.47	74.90	93.13	93.47	92.75 ^c
T16 75 % NPK + FYM + <i>Azolla</i> + S + Zn	53.02	74.98	93.33	93.49	57.75	76.58	94.69	95.01	94.25 ^c
T17 100 % NPK + FYM + <i>Azolla</i> + S + Zn	54.02	79.33	98.26	99.15	59.87	80.93	99.57	99.85	99.50 ^a
T18 FYM + <i>Azolla</i> + S + Zn	49.58	62.74	81.02	81.17	50.56	64.14	82.27	82.46	81.82 ^f

CD (P : 0.05): 2021–22: 30 DAT: NS; 60 DAT: 12.78; 90 DAT: 14.92; at harvest: 14.90. 2022–23: 30 DAT : NS; 60 DAT : 11.28; 90 DAT: 14.91; at harvest : 14.82. SEm (±): 1.87–5.02. CV (%): 5.01–6.79. Values are means of replicates. Treatment means were separated using the least significant difference (LSD) test at p: 0.05 following ANOVA. Means with the same superscript letter(s) in the pooled column do not differ significantly. DAT: Days after transplanting; NS: non-significant.

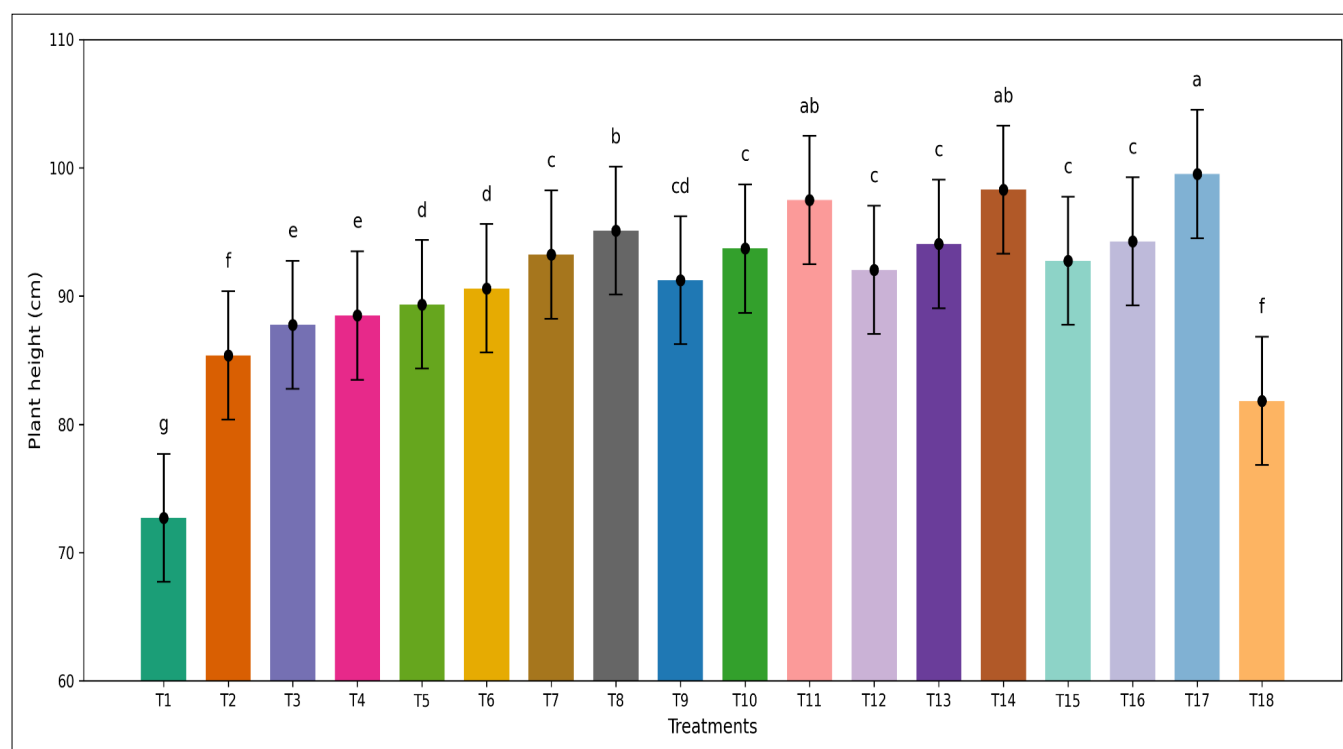
**Fig. 1.** Effect of organic manure, inorganic fertilizer and bio-inoculants on plant height at different growth stages of rice during 2021–22 and 2022–23.

Table 4. Effect of organic manure, inorganic fertilizer and bio-inoculants on number of tillers at various growth stages of rice during 2021–22 and 2022–23

Treatments	Number of tillers (m ⁻²)				Number of tillers (m ⁻²)				Pooled mean at harvest (m ⁻²)
	2021–22				2022–23				
	30 DAT	60 DAT	90 DAT	Harvest	30 DAT	60 DAT	90 DAT	Harvest	
T1 Control	170.34	208.37	240.91	229.65	172.52	210.76	243.32	232.06	230.86 ^g
T2 100 % NPK	177.77	269.03	288.21	278.47	179.94	271.42	290.62	280.88	279.68 ^f
T3 50 % NPK + FYM	178.13	286.63	299.51	288.84	180.30	289.02	301.92	291.25	290.05 ^e
T4 75 % NPK + FYM	180.90	291.82	304.11	295.61	183.07	294.21	306.52	298.02	296.82 ^e
T5 100 % NPK + FYM	181.66	301.18	318.11	302.51	183.83	303.57	320.59	304.92	303.72 ^d
T6 50 % NPK + FYM + <i>Azolla</i>	184.54	309.77	326.02	309.28	186.71	312.16	328.43	311.69	310.49 ^d
T7 75 % NPK + FYM + <i>Azolla</i>	189.41	316.51	346.84	337.47	191.58	318.90	349.25	339.88	338.68 ^c
T8 100 % NPK + FYM + <i>Azolla</i> + S	194.54	336.89	379.82	364.28	196.71	339.28	382.23	366.69	365.49 ^b
T9 50 % NPK + FYM + <i>Azolla</i> + S	186.12	310.66	331.76	322.18	188.29	313.05	334.17	324.59	323.39 ^{cd}
T10 75 % NPK + FYM + <i>Azolla</i> + S	189.60	318.82	353.11	340.61	191.77	321.21	355.52	343.02	341.82 ^c
T11 100 % NPK + FYM + <i>Azolla</i> + S	195.90	344.87	388.73	371.80	198.07	347.26	391.14	374.21	373.01 ^{ab}
T12 50 % NPK + FYM + <i>Azolla</i> + Zn	188.90	314.37	337.33	325.80	191.07	316.76	339.74	328.21	327.01 ^c
T13 75 % NPK + FYM + <i>Azolla</i> + Zn	191.90	319.46	357.13	345.90	194.07	321.85	359.50	348.31	347.11 ^c
T14 100 % NPK + FYM + <i>Azolla</i> + Zn	197.12	353.76	396.56	384.18	199.29	356.15	398.97	386.59	385.39 ^{ab}
T15 50 % NPK + FYM + <i>Azolla</i> + S + Zn	189.01	314.86	343.02	333.80	191.18	317.25	345.43	336.21	335.01 ^c
T16 75 % NPK + FYM + <i>Azolla</i> + S + Zn	193.06	329.18	366.18	355.51	195.23	331.57	368.59	357.92	356.72 ^c
T17 100 % NPK + FYM + <i>Azolla</i> + S + Zn	199.91	366.51	396.47	409.40	202.08	368.90	398.88	412.25	410.83 ^a
T18 FYM + <i>Azolla</i> + S + Zn	175.34	243.77	268.72	257.02	177.51	246.90	271.13	259.43	258.23 ^f

CD (P: 0.05): 2021–22: 30 DAT: NS; 60 DAT: 44.55; 90 DAT: 52.00; at harvest: 50.35. 2022–23: 30 DAT: NS; 60 DAT: 47.86; 90 DAT: 52.12; at harvest: 49.73. SEM ($\pm$): 7.19–17.54. CV (%): 4.69–6.69. Values are means of replicates. Treatment means were separated using the least significant difference (LSD) test at p: 0.05 following ANOVA. Means followed by the same superscript letter(s) in the pooled column do not differ significantly. DAT: Days after transplanting; NS: non-significant.

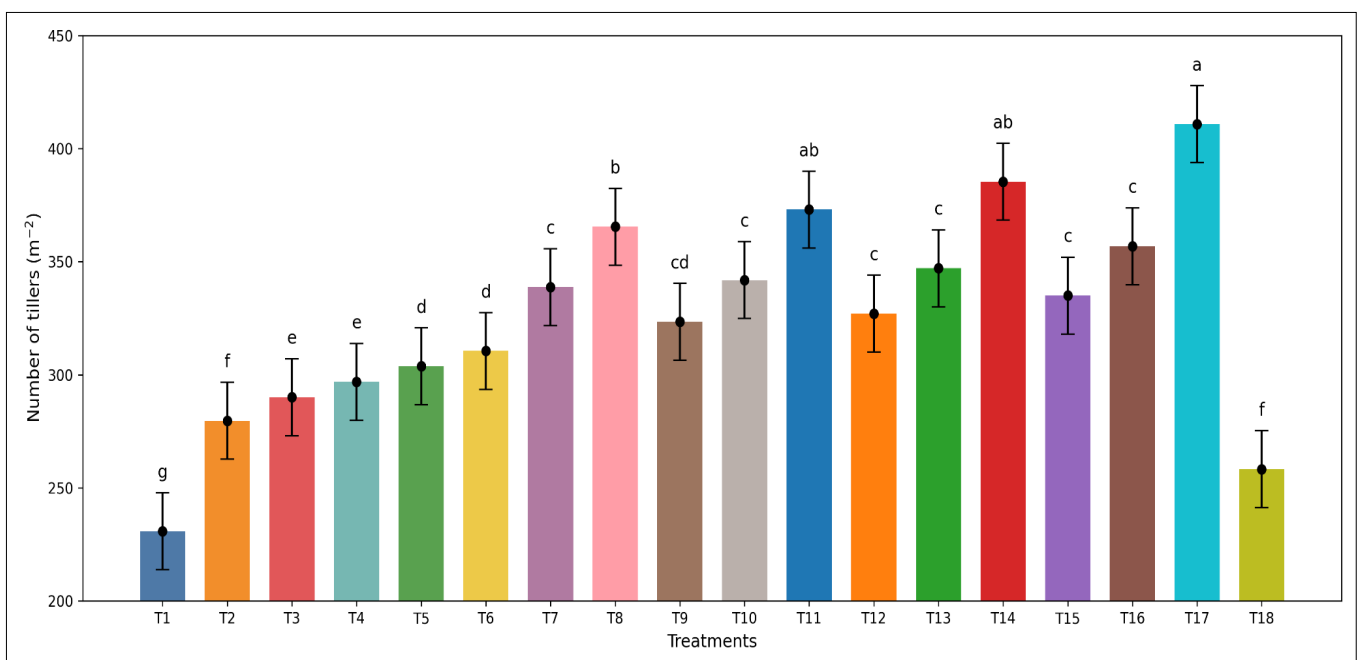


Fig. 2. Effect of organic manure, inorganic fertiliser and bio-inoculants on number of tillers (m⁻²) at different growth stages of rice during 2021–22 and 2022–23.

and *Azolla* (e.g., T6, T9 and T12) resulted in moderate tiller production, whereas treatments combining all five components (NPK, FYM, *Azolla*, S and Zn), such as T14, T15 and T16, showed significantly enhanced tiller formation compared to their respective lower-tier treatments. Notably, T18 (FYM + *Azolla* + S + Zn) without chemical NPK also showed a considerable increase over the control, indicating the potential of organic and biological inputs in enhancing tillering.

Effect on dry matter accumulation (g m⁻²)

The data on dry matter accumulation (DMA) are presented in Table 5 and Fig. 3, respectively. Measurements were recorded at 30, 60 and 90 DAT and at the harvesting stage during both years of the study (2021–22 and 2022–23). On a pooled basis, dry matter accumulation ranged from 220.29 to 760.48 g m⁻² in 2021–22 and 221.89 to 764.34 g m⁻² in 2022–23, indicating a gradual and significant increase with crop growth. Among all treatments, the highest DMA was recorded under T17 (100 % NPK + 5 t ha⁻¹ FYM + *Azolla* at 300 kg ha⁻¹ + Sulfur at 30 kg ha⁻¹ + Zinc at 5 kg ha⁻¹), recording 760.48 g m⁻² in 2021–22 and 764.34 g m⁻² in 2022–23. This enhanced performance may be attributed to synergistic effects of integrated nutrient application. In contrast, the lowest DMA was recorded in the control treatment (T1) which recorded 220.29 g m⁻² in 2021–22 and 221.89 g m⁻² in 2022–23, demonstrating the significant positive influence of nutrient supplementation on biomass production. Intermediate treatments such as T5, T8, T14 and T16 also exhibited considerable improvements in dry matter accumulation over the control and lower-input

treatments. The increasing trend in biomass was more pronounced in treatments combining multiple nutrient sources, particularly organic, microbial and micronutrient components. Overall, the results underscore that T17 was the most effective treatment for enhancing dry matter accumulation, indicating its potential for improving the growth and productivity of rice through a holistic nutrient strategy.

Effect on leaf area index

The data related to LAI, presented in Table 6 and Fig. 4, were recorded at 30, 60 and 90 DAT during both years of the study (2021–22 and 2022–23). The LAI values increased progressively with crop growth stages and were found to be significantly influenced by the different nutrient management treatments. On a pooled basis, the LAI ranged from 1.36 to 4.32 in 2021–22 and 1.38 to 4.37 in 2022–23. The highest LAI was observed under the treatment T17 (100 % NPK + 5 t ha⁻¹ FYM + *Azolla* at 300 kg ha⁻¹ + Sulfur at 30 kg ha⁻¹ + Zinc at 5 kg ha⁻¹), recording values of 4.32 in 2021–22 and 4.37 in 2022–23. This superior performance may be attributed to the synergistic effect of combined nutrient sources. In contrast, the lowest LAI values were recorded in the control treatment (T1), with values of 1.36 in 2021–22 and 1.38 in 2022–23, indicating restricted vegetative growth due to the absence of external nutrient inputs. Treatments such as T5, T8, T14 and T16, which included combinations of organic, inorganic and biofertilizer components, also showed notable improvements in LAI compared to treatments with single nutrient sources. Overall, the results highlight that T17 was the most effective treatment in improving LAI during both years of the study.

Table 5. Effect of organic manure, inorganic fertiliser and bio-inoculants on dry matter accumulation at various growth stages of rice during 2021–22 and 2022–23

Treatments	Dry matter accumulation (g m ⁻²)				Dry matter accumulation (g m ⁻²)				Pooled mean at harvest (g m ⁻²)
	2021-22				2022-23				
	30 DAT	60 DAT	90 DAT	Harvest	30 DAT	60 DAT	90 DAT	Harvest	
T1 Control	220.29	321.56	402.54	598.47	221.89	323.06	406.24	602.27	600.37 ^g
T2 100 % NPK	224.58	340.50	459.52	670.56	225.18	341.96	461.42	672.76	671.66 ^f
T3 50 % NPK + FYM	228.39	354.75	488.36	688.36	229.33	357.05	489.36	690.06	689.21 ^e
T4 75 % NPK + FYM	230.47	356.56	501.47	705.48	231.47	358.47	504.97	709.43	707.46 ^e
T5 100 % NPK + FYM	230.58	356.75	526.29	722.59	232.18	358.75	528.19	724.63	723.61 ^d
T6 50 % NPK + FYM + <i>Azolla</i>	231.39	363.52	539.52	738.18	232.99	365.02	543.02	740.38	739.28 ^d
T7 75 % NPK + FYM + <i>Azolla</i>	234.24	380.62	543.65	752.59	235.04	382.04	546.69	754.56	753.58 ^c
T8 100 % NPK + FYM + <i>Azolla</i> + S	237.96	390.57	568.76	758.36	238.90	392.07	571.76	761.36	759.86 ^b
T9 50 % NPK + FYM + <i>Azolla</i> + S	232.47	363.52	541.29	741.49	233.44	365.02	543.20	743.36	742.43 ^{cd}
T10 75 % NPK + FYM + <i>Azolla</i> + S	234.24	380.80	543.65	755.19	235.23	382.23	546.96	757.08	756.14 ^c
T11 100 % NPK + FYM + <i>Azolla</i> + S	237.96	390.57	568.76	759.34	238.96	392.57	573.76	762.34	760.84 ^b
T12 50 % NPK + FYM + <i>Azolla</i> + Zn	232.79	370.79	541.60	741.66	233.74	372.29	545.55	753.50	747.58 ^c
T13 75 % NPK + FYM + <i>Azolla</i> + Zn	234.69	381.63	546.47	756.18	235.59	383.13	547.75	757.15	756.67 ^c
T14 100 % NPK + FYM + <i>Azolla</i> + Zn	238.75	398.23	582.62	759.34	239.75	399.73	584.02	763.43	761.39 ^b
T15 50 % NPK + FYM + <i>Azolla</i> + S + Zn	232.79	370.79	542.36	750.56	233.79	372.29	546.62	754.47	752.52 ^c
T16 75 % NPK + FYM + <i>Azolla</i> + S + Zn	235.56	381.63	546.75	756.58	236.56	383.13	548.47	761.13	758.86 ^c
T17 100 % NPK + FYM + <i>Azolla</i> + S + Zn	240.36	404.67	598.79	760.48	243.31	406.31	602.79	764.34	762.41 ^a
T18 FYM + <i>Azolla</i> + S + Zn	222.56	331.85	441.69	649.36	224.52	334.31	445.73	657.83	653.60 ^f

CD (p: 0.05): 2021–22: 30 DAT: NS; 60 DAT: 57.13; 90 DAT: 80.06; at harvest: 106.02. 2022–23: 30 DAT: NS; 60 DAT: 53.57; 90 DAT: 80.31; at harvest: 107.12. SEm (±): 8.43–36.01. CV (%): 4.67–6.92. Values are means of replicates. Treatment means were separated using the least significant difference (LSD) test at p: 0.05 following ANOVA. Means followed by the same superscript letter(s) in the pooled column do not differ significantly. DAT: Days after transplanting; NS: non-significant.

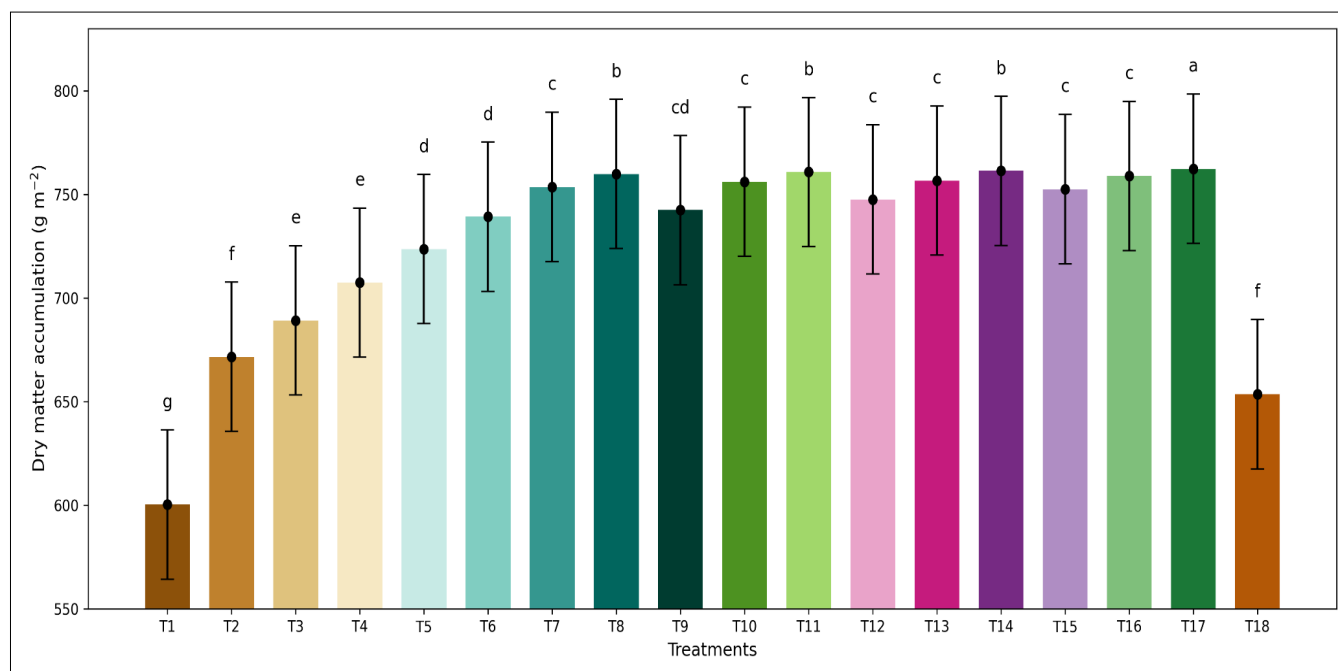


Fig. 3. Effect of organic manure, inorganic fertiliser and bio-inoculants on dry matter accumulation (g m^{-2}) at different growth stages of rice during 2021–22 and 2022–23.

Table 6. Effect of organic manure, inorganic fertiliser and bio-inoculants on leaf area index (LAI) at various growth stages of rice during 2021–22 and 2022–23

Treatments	Leaf area index (LAI)						Pooled mean at 90 DAT (LAI)
	2021–22			2022–23			
	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT	
T1 Control	1.36	2.45	2.72	1.38	2.56	2.73	2.73 ^f
T2 100 % NPK	1.41	2.98	2.99	1.42	2.99	3.00	3.00 ^e
T3 50 % NPK + 5 t ha ⁻¹ FYM	1.43	3.09	3.14	1.44	3.15	3.18	3.16 ^d
T4 75 % NPK + 5 t ha ⁻¹ FYM	1.46	3.15	3.29	1.46	3.15	3.30	3.30 ^d
T5 100 % NPK + 5 t ha ⁻¹ FYM	1.46	3.15	3.33	1.47	3.27	3.34	3.34 ^c
T6 50 %NPK + 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹)	1.46	3.25	3.35	1.47	3.30	3.35	3.35 ^c
T7 75 % NPK + 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹)	1.49	3.45	3.78	1.49	3.48	3.71	3.75 ^b
T8 100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹)	1.53	3.83	3.92	1.54	3.89	3.98	3.95 ^b
T9 50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹)	1.47	3.27	3.42	1.48	3.35	3.44	3.43 ^c
T10 75 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹)	1.51	3.64	3.83	1.52	3.69	3.84	3.84 ^b
T11 100 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹)	1.54	3.84	4.10	1.54	3.89	4.13	4.12 ^{ab}
T12 50 % NPK + 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.48	3.34	3.52	1.49	3.36	3.64	3.58 ^c
T13 75 % NPK+ 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.53	3.78	3.84	1.53	3.86	3.89	3.87 ^b
T14 100 % NPK+ 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.55	3.96	4.22	1.55	3.98	4.24	4.23 ^{ab}
T15 50 % NPK+ 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.49	3.44	3.64	1.49	3.47	3.69	3.67 ^c
T16 75 % NPK+ 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹) + Sulfur (30 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.53	3.81	3.87	1.53	3.87	3.90	3.89 ^b
T17 100 % NPK+ 5 t ha ⁻¹ FYM+ <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.56	4.13	4.32	1.56	4.17	4.37	4.35 ^a
T18 5 t ha ⁻¹ FYM + <i>Azolla</i> (300 kg ha ⁻¹) + S (30 kg ha ⁻¹) + Zn (5 kg ha ⁻¹)	1.37	2.87	2.87	1.39	2.84	2.92	2.90 ^e
CD	NS	0.50	0.52	NS	0.51	0.53	
SEm (±)	0.05	0.17	0.17	0.05	0.17	0.18	
CV	6.25	4.79	4.81	6.17	4.80	4.82	

CD ($p = 0.05$): 2021–22: 30 DAT: NS; 60 DAT: 0.50; 90 DAT: 0.52. 2022–23: 30 DAT: NS; 60 DAT: 0.51; 90 DAT: 0.53. SEm ($\pm$): 0.05–0.18. CV (%): 4.79–6.25. Values are means of replicates. Treatment means were separated using the least significant difference (LSD) test at $p = 0.05$ following ANOVA. Means followed by the same superscript letter(s) in the pooled column do not differ significantly. DAT: Days after transplanting; NS: non-significant.

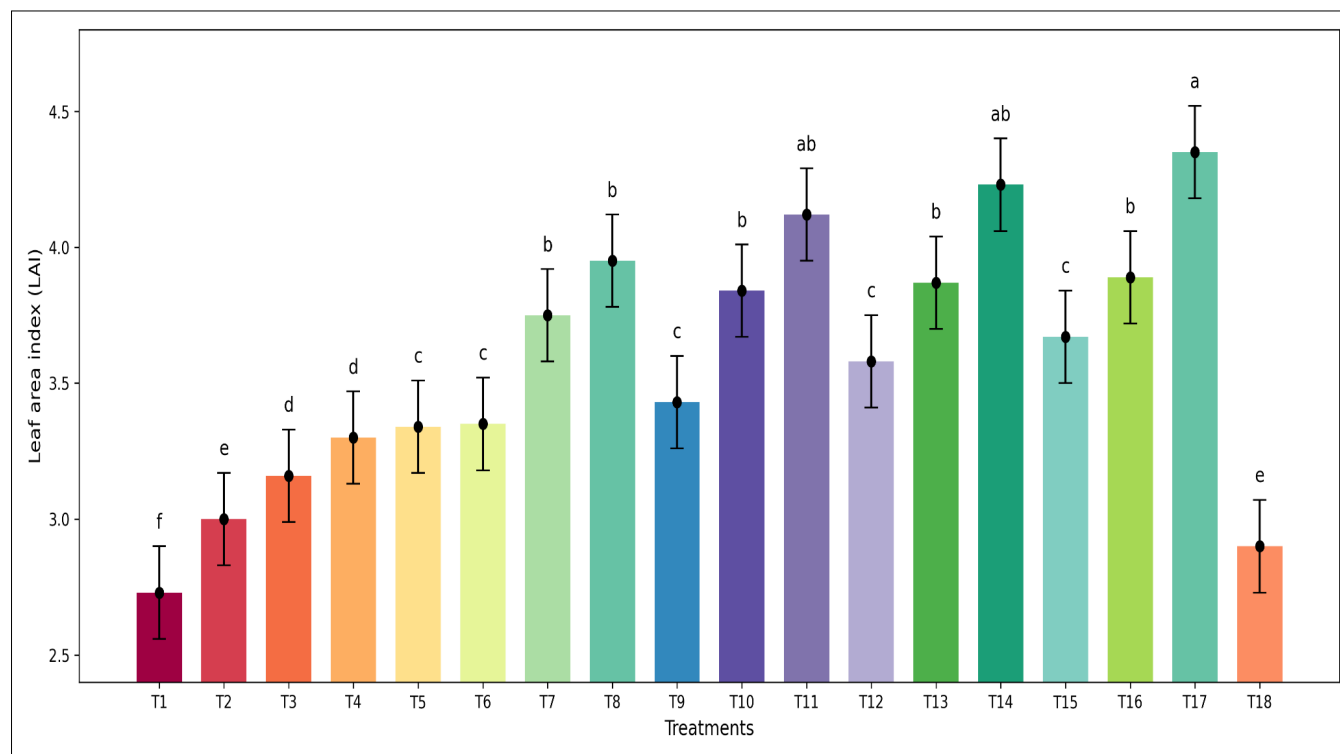


Fig. 4. Effect of organic manure, inorganic fertiliser and bio-inoculants on leaf area index (LAI) at different growth stages of rice during 2021–22 and 2022–23.

Discussion

The study revealed a significant effect of integrated nutrient management (INM) on rice growth attributes over two consecutive years (2021–22 and 2022–23). Among all treatments, T17 (100 % NPK + 5 t ha⁻¹ FYM + 300 kg ha⁻¹ *Azolla* + 30 kg ha⁻¹ Sulphur + 5 kg ha⁻¹ Zinc) consistently recorded the tallest plants, reaching 99.85 cm in 2022–23. This improved height resulted from the combined benefits of balanced macronutrients and essential micronutrients, particularly Zinc and Sulphur, which play key roles in enzyme activation and chlorophyll synthesis (21). Additionally, the contribution of FYM and *Azolla* likely enhanced soil structure and microbial activity, thereby improving root growth and nutrient absorption (22). The control treatment (T1) consistently showed the shortest plants, emphasising the importance of adequate nutrient supplementation for optimal development. A similar pattern was observed in tiller number, with T17 producing the highest count (412.25 m⁻² in 2022–23). Tillering is influenced by nitrogen levels and carbohydrate distribution in plants. The presence of *Azolla*, a nitrogen-fixing organism, along with FYM, may have ensured a consistent nitrogen supply during key growth stages, enhancing tiller production (23). Micronutrient addition may have also improved hormonal balance and cell division, contributing to greater tillering. Dry matter accumulation, a key indicator of photosynthetic performance and biomass production, was also highest in T17, with values of 760.48 and 764.34 g m⁻² in 2021–22 and 2022–23, respectively. This improvement may be attributed to the synergistic effects of organic and inorganic nutrient sources, which aligned nutrient release with plant demand throughout the crop cycle (24). The incorporation of FYM and *Azolla* improved microbial turnover, while Sulphur and Zinc supported protein and enzyme synthesis, thereby enhancing overall biomass (25). Leaf area index, which reflects canopy expansion and light interception, reached its peak under T17 (4.37 in 2022–23). This improvement may be attributed to enhanced nutrient availability, promoting healthy leaf growth and delayed senescence. Improved soil

moisture retention and aeration due to organic additions supported vigorous leaf development (26). In contrast, nutrient-deficient conditions in the control resulted in restricted leaf growth and lower LAI values. These results align with earlier findings indicating that integrated nutrient management strategies combining fast-acting chemical fertilizers with organic and bio-inoculant sources outperform the application of individual nutrient inputs (27).

Conclusion

The study concludes that an integrated approach to nutrient management significantly enhances the growth performance of rice. The combination of 100 % recommended dose of NPK with organic manure (FYM), bio-inoculants (*Azolla*) and critical micronutrients (sulphur and zinc) not only improved plant height, number of tillers, dry matter accumulation and leaf area index, but also promoted balanced and sustained plant growth across both years of the study. Among the treatments, T17 (100 % NPK + 5 t ha⁻¹ FYM + 300 kg ha⁻¹ *Azolla* + 30 kg ha⁻¹ S + 5 kg ha⁻¹ Zn) consistently recorded the most favourable results across all growth parameters, indicating the strong synergistic effect of combined nutrient sources. These inputs act complementarily with chemical fertilisers to meet the immediate nutrient needs of the crop, while organic manures and *Azolla* improve soil health and ensure sustained nutrient release over time. Micronutrients further enhance metabolic processes essential for crop growth and development. In light of these findings, integrated nutrient management emerges as a sustainable and economically viable strategy for improving rice productivity. It offers a practical solution for farmers aiming to reduce dependence on chemical fertilisers, improve input efficiency and promote environmentally responsible farming practices. Future research should focus on developing location-specific INM models under diverse agro-climatic conditions and evaluating their long-term impacts on soil health, yield stability and profitability.

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Authors' contributions

ASY, KS and SY conceived and designed the study, conducted the experiments and performed data analysis and data curation. SS¹ and D supervised the work, developed the methodology and critically reviewed the manuscript. AKY, JM, VS, SS², KP, JC, SC and DKM prepared the original draft and carried out revision and editing of the manuscript. All authors read and approved the final manuscript [SS¹ stands for Sanjeev Sharma and SS² stands for Satyabrata Sarangi].

Compliance with ethical standards

Conflict of interest: The authors declare that there is no conflict of interest.

Ethical issues: None

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