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Sustainable Nutrient Management through Organic Manure, Biochar, and Inorganic Fertilizers in Rice (*Oryza sativa* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Biochar is produced through pyrolysis of waste plant materials. Application of Biochar to rice fields has yielded encouraging results regarding the enhancement of soil fertility and enhancing crop productivity. It helps in keeping nutrients in the soil and lowering nutrient leaching, which enhances nutrient availability for rice plants. Due to its porous structure, biochar promotes helpful microbial activity in the soil, which enhances nutrient cycling and overall soil health. The present study investigates the effects of organic manure, inorganic fertilizers and biochar on the yield attributes and yield of rice (*Oryza sativa* L.). The primary aim was to evaluate the comparative effectiveness of these soil amendments in improving rice production and their potential roles in sustainable agriculture. Organic manure, such as biochar and farmyard manure, was applied to enhance soil fertility, promoting beneficial soil microbial activity. Inorganic fertilizers, primarily nitrogen, phosphorus, and potassium (NPK), were used to supply essential nutrients directly, thus improving plant growth and development. Field trials were conducted at the agronomy research farm CSAUA&T, Kanpur, during kharif season 2023 and 2024, with the Rice crop subjected to different treatment combinations: Organic manure alone, Inorganic fertilizers alone, Biochar alone, and various integrated combinations of these amendments. The parameters assessed included plant height, number of tillers, dry matter accumulation, panicle length, number of grains panicle^{-1} and grain yield. The results showed that using both organic manure and inorganic fertilizers together significantly improved the growth parameters and yield attributes of rice, in comparison to using either treatment alone. Specifically, the synergistic effect of biochar with farmyard manure showed promising results in improving soil texture, increasing nutrient retention, and enhancing rice yield. The findings suggest that integrated soil management practices involving organic manure, inorganic fertilizers, and biochar could offer a sustainable alternative to conventional agricultural practices, fostering higher yields while mitigating environmental impacts. The improved performance under INM treatments validates the synergy of organic and inorganic inputs, making it a viable approach for achieving long-term productivity and ecological balance in rice-based cropping systems. Thus, adopting integrated strategies is essential for enhancing agricultural sustainability and resource-use efficiency.

Keywords: Organic manure; biochar; inorganic fertilizer; rice; sustainable agriculture.

1. INTRODUCTION

Organic manuring is becoming an increasingly significant part of environmentally healthy, long-term farming. Plant nutrients are replenished in agricultural soils primarily through inorganic, organic, and biofertilizers. Inorganic fertilizers are used indefinitely, causing a decline in soil chemical, physical, and biological qualities, as well as soil health. Chemical fertilizer's negative effects, combined with rising prices, have sparked a surge in interest in organic fertilizers as a nutritional source. The use of organic manure in conjunction with chemical fertilizers has the potential to improve soil fertility and crop output. Integrated plant nutrition systems, particularly using organic manure, could improve crop productivity in intensive cropping systems. Organic manure has lately been discovered to be an excellent source of plant nutrients in the soil. Farmyard manure (FYM) and inorganic N and P fertilizers were used together to improve chemical and physical qualities, which could lead to increased and sustainable rice production (Anisuzzaman et al., 2021). Rice (Oryza sativa L.) is a member of the grass family, Gramineae (Poaceae). As one of the three key food crops globally, it constitutes the staple diet for roughly half of the world's populace. Rice has been cultivated in India for a long time (Sangeetha et al., 2020). Rice serves as the principal food crop globally, providing the main dietary staple for roughly four billion individuals, approximately half of all people on Earth. Its agricultural activities span about 160 million hectares across different climatic zones, ranging from 44°N in North Korea to 35°S in Australia. Rice is cultivated in regions that vary greatly in elevation, from about 2.7 meters below sea level, such as Kuttanad in India's Kerala, to altitudes of 2,700 feet ASL in the foothills of the Himalayas. Rice is essential not just for agriculture; it holds a crucial role in the cultural and historical contexts of many Asian countries, as it is deeply intertwined with their traditions and heritage (NRRI-Bulletin, 2020). Application of organic manure has shown positive effects on rice yield by enhancing nutrient availability and promoting microbial activity. The use of organic manure raises the soil's organic matter content, which enhances its ability to retain water and nutrients (Ghorbani et al., 2023). Inorganic fertilizers, including Nitrogen (N), Phosphorus (P) and Potassium (K) varieties, offer nutrients that are immediately accessible to plants. Proper application of inorganic fertilizers has shown significant increases in rice yield, especially when nutrient deficiencies are addressed (Bhatt et al., 2019). Biochar is produced through pyrolysis of waste plant materials. Application of Biochar to rice fields has yielded encouraging results regarding the enhancement of soil fertility and crop productivity (Oladele et al., 2019). Biochar undergoes high-temperature pyrolysis or thermal cracking, resulting in high stability, resistance to decomposition, and the ability to persist in soil for extended periods, maintaining its effectiveness, biochar possesses abundant micropores and a high surface area, which endow it with excellent adsorption and storage capabilities, making it beneficial for adsorbing organic matter, nutrients, and water. Biochar application enhances acidic paddy soil by improving soil structure, regulating pH levels, supplying essential trace elements, increasing soil organic matter, and reducing nutrient loss (Liang et al., 2024). Biochar helps in keeping nutrients in the soil and lowering nutrient leaching, which enhances nutrient availability for rice plants. Due to its porous structure, biochar promotes helpful microbial activity in the soil, which enhances nutrient cycling and overall soil health. In the view of above facts, the present study aimed to explore evaluation of organic manure and biochar with inorganic fertilizer's on the growth and yield of rice (Oryza sativa L.). The impact of biochar on rice quality characteristics is limited, but its positive impact on soil fertility can indirectly contribute to improved grain quality (Hussain et al., 2017).

2. MATERIALS AND METHODS

This field experiment for two years was conducted at the Agronomy Research Farm in Nawabganj, part of the Department of Soil Science at Chandra Shekhar Azad University of Agriculture & Technology in Kanpur, during the Kharif season of 2023 and 2024. The soil of the experimental field is classified within the soil order of Inceptisols. It is sandy loam in texture and neutral to alkaline in soil reaction. The sixteen treatments were used with three replicates and each consisted of a T_1– Control (without fertilizer and manure) T_2 – 50 % RDF T_3 – 75 % RDF T_4 – 100 % RDF T_5 – 50 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc T_6 – 75 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc T_7 – 100 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc T_8 – 50 % RDF +5.0 tonnes ha^{-1} FYM + Biochar T_9 – 75 % RDF +5.0 tonnes ha^{-1} FYM + Biochar T_{10} – 100 % RDF +5.0 tonnes ha^{-1} FYM + Biochar T_{11} – 50 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc + Biochar T_{12} – 75 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc + Biochar T_{13} – 100 % RDF +5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc + Biochar T_{14} - 5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc T_{15} - 5.0 tonnes ha^{-1} FYM + Biochar T_{16} - 5.0 tonnes ha^{-1} FYM + 5.0 kg Zinc + Biochar, with Rice (27P37) crop having a plot size 4 x 5 m. Each treatment was replicated three times and organized using a Randomized Block Design (RBD). After thorough field preparation, initial soil samples were collected to analyze the initial soil properties. The available major nutrients in the initial soil sample were analyzed; N, P, K, Zn, OC, pH and EC. It is at the initial stage before start of experimentation had a pH of 8.09, EC 0.32 dSm^{-1}, CEC (Cmol (p+) kg^{-1}) 39.38 and 0.40% organic carbon. The experimental field had a low N status (203 kg ha^{-1}), medium available P (12.80 kg ha^{-1}), lower available K (195 kg ha^{-1}) and Zn (0.63 mg kg^{-1}). All treatments, including Biochar (5 t ha^{-1}) and FYM were assigned to the plots at random and uniformly mixed into the soil to a depth of 10 cm 15 days prior to transplanting the rice seedlings, after which submergence occurred. Prior to puddling, one-third of the nitrogen (from urea) was applied as a basal treatment, together with full doses of potash and phosphorus. This was mixed into the soil to a depth of 15 cm. The remaining nitrogen was supplied as a top-dressing in two applications of urea, during the tillering and panicle initiation stages. The trial utilized the rice variety 27P37, planted with a spacing of 20 × 10 cm. The crop was manually harvested from each plot once the grains had attained physiological maturity. When around 85% of the panicles contained about 85% ripened spikelets and the upper part of the spikelets had changed to a straw colour, harvesting was carried out with serrated-edge sickles. During the harvest, yields of straw and seed were noted. Plant samples were gathered for the chemical analysis of nitrogen, phosphorus, potassium, and zinc in both seed and straw samples. N was assessed by Alkaline Permanganate method (Subbiah and Asija, 1956), for the available P soil samples were taken using 0.5 M $NaHCO_3$ (pH = 8.5) as per Olsen et al. (1954) and the P content in the extracts was measured by vanado - molybdo phosphoric acid yellow colour method Jackson's method (1973). K that is available was determined by Flame photometer method (Toth & Prince, 1949) and Available Zn was determined by DTPA method (Lindsay & Norvell, 1978).

3. RESULTS AND DISCUSSION

Crop Growth Characters: The data presented in the Tables (1, 2, 3) that the analysis of crop growth parameters in rice across different treatments revealed significant variations, with treatment T_{13} (100 % RDF + 5 t ha^{-1} FYM + 5 kg Zn + Biochar) consistently outperforming other treatments. The highest plant height (115.32 cm in 2023 and 116.87 cm in 2024) and pooled basis is 116.09 cm, number of tillers (401.13 m^{-2} in 2023 and 404.45 m^{-2} in 2024 at 90 DAT) number of tillers pooled basis is 402.79 m^{-2} and dry matter accumulation (874.36 g m^{-2} in 2023 and 880.03 g m^{-2} in 2024) and pooled basis is 877.19 g m^{-2} were recorded under T_{13}. These findings indicate that integrated nutrient management combining organic, inorganic, and biochar inputs promotes superior vegetative growth in rice.

The observed increase in plant height and tiller number can be attributed to improved nutrient availability and soil health due to the synergistic effect of FYM, zinc and biochar (Singh et al., 2021). Organic amendments enhance microbial activity and nutrient cycling, while biochar improves soil structure, nutrient use efficiency and water retention (Yadav et al., 2020). Moreover, the substantial rise in dry matter accumulation under T_{13} suggests better photosynthetic efficiency and biomass partitioning, as supported by Kumar et al. (2019), who reported similar trends under integrated nutrient treatments. These results align with Patel et al. (2022), who emphasized that integrated use of nutrients not only sustains growth parameters but also ensures long-term soil productivity and crop resilience.

Yield and Yield attributes: The data presented in table 4 clearly reveal that the integrated application of organic (FYM), inorganic (RDF and zinc), and biochar significantly influenced all the yield attributes of the crop over the two year study (2023 and 2024). Panicle length, number of grains $panicle^{-1}$, test weight and effective tillers showed a consistent increasing trend with the progressive integration of nutrient management. The maximum panicle length (35.10 cm in 2023 and 35.34 cm in 2024) and pooled basis is 35.22 cm, number of grains per $panicle^{-1}$ (179 in 2023 and 182 in 2024) and pooled basis is 181.50, test weight (23.54 g in 2023 and 23.64 g in 2024) test weight on the pooled basis is 23.59 g and effective tillers (354 m^{-2} in 2023 and 358 m^{-2} in 2024) and pooled basis is 356 m^{-2} were recorded in treatment T_{13} (100 % RDF + 5 t ha^{-1} FYM + 5 kg Zn + biochar), which was significantly higher than the control (T_1).

This result demonstrates the beneficial role of combined nutrient sources in improving the reproductive growth of the crop. The two-year study period (2023 and 2024), corroborating findings by Yadav et al. (2020), who reported similar enhancements in yield components under integrated nutrient management. The application of RDF alone (T_4) improved the attributes over the control but was still inferior to treatments involving organic supplements and micronutrients. Among the integrated treatments, T_{12} and T_{11} (involving 75 % and 50 % RDF with FYM, Zn and biochar) also performed considerably well, indicating that even partial substitution of RDF with organic and micronutrient inputs can enhance grain formation and quality.

Biological Yield and Harvest Index: The data presented in the Table 5that the biological yield increased progressively with nutrient enrichment, reaching a maximum in treatment T_{13} (143.84 q ha^{-1} in 2023 and 144.64 q ha^{-1} in 2024) and pooled data is 144.24 q ha^{-1}, significantly outperforming the control T_1 (75.72 q ha^{-1} in 2023 and 76.22 q ha^{-1} in 2024) and pooled basis is 75.97 q ha^{-1}. This improvement can be attributed to the synergistic effect of inorganic and organic inputs, especially when enriched with biochar and micronutrients like zinc, which enhance plant growth and productivity. Similarly, treatments T_{12} and T_{10} also recorded high biological yields (140.95 and 136.12 q ha^{-1}, respectively), showing the beneficial role of integrated nutrient supply.

The harvest index (HI), which reflects the efficiency of biomass conversion to economic yield, ranged from 46.93 % in control to 48.79 % in T_{10}. While the HI did not vary as much as biological yield, the slight increase under integrated treatments indicates better partitioning of assimilates towards grain production, consistent with findings by Choudhary et al., 2016. The highest HI was observed in T_{13} (49.06 %), followed closely by T_{12}, T_{11}, and T_{09}, indicating positive contributions from organic amendments and biochar.

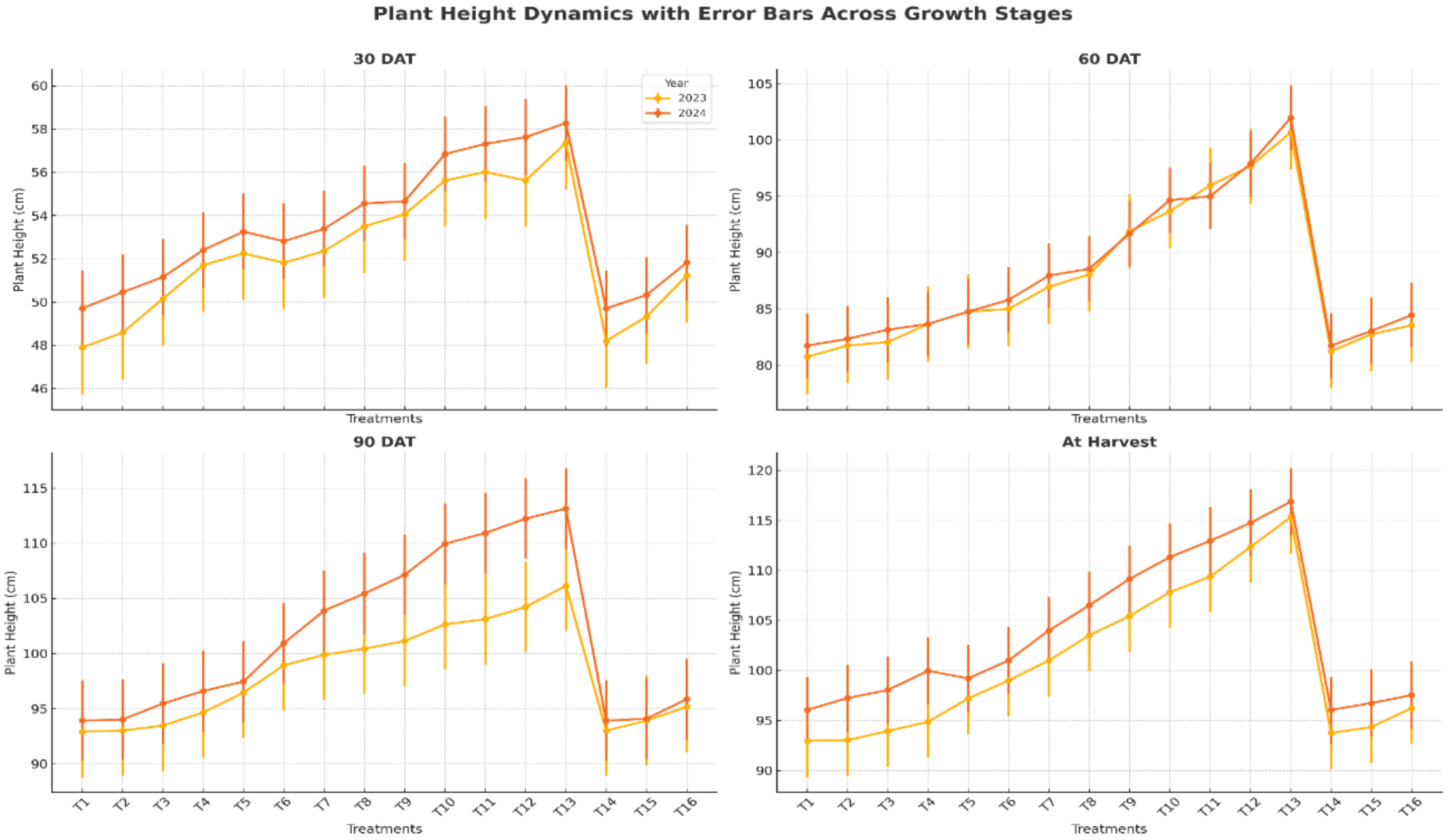

Fig. 1. Effect of organic manure, inorganic fertilizer and biochar on plant height (cm) at various growth stages of rice during 2023 and 2024

Table 1. Effect of organic manure, inorganic fertilizer and biochar on plant height (cm) at various growth stages of rice during 2023 and 2024

Treatments		Plant height (cm)											
		2023 30 DAT	2024 30 DAT	Mean	2023 60 DAT	2024 60 DAT	Mean	2023 90 DAT	2024 90 DAT	Mean	2023 At Harvest	2024 At Harvest	Mean
T_1	Control	47.90	49.70	48.8	80.74	81.74	81.24	92.92	93.92	93.42	92.96	96.06	94.51
T_2	50% RDF	48.5	50.4	49.5	81.7	82.3	82.0	93.0	94.0	93.5	93.0	97.2	95.1
T_3	75% RDF	50.15	51.15	50.65	82.05	83.15	82.60	93.47	95.47	94.47	93.95	98.05	96
T_4	100%RDF	51.70	52.40	52.05	83.66	83.66	83.66	94.66	96.60	95.63	94.87	99.97	97.42
T_5	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	52.25	53.25	52.75	84.76	84.76	84.76	96.46	97.46	96.96	97.21	99.21	98.21
T_6	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	51.81	52.81	52.31	85.00	85.80	85.40	98.93	100.93	99.93	99.01	101.01	100.01
T_7	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	52.35	53.38	52.86	86.96	87.96	87.46	99.88	103.88	101.88	101.00	104.00	102.5
T_8	50% RDF +5.0 tonnes ha-1 FYM + Biochar	53.50	54.56	54.03	88.06	88.56	88.31	100.43	105.43	102.93	103.51	106.51	105.01
T_9	75% RDF +5.0 tonnes ha-1 FYM + Biochar	54.05	54.65	54.35	91.89	91.69	91.79	101.13	107.13	104.13	105.44	109.14	107.29
T_{10}	100% RDF +5.0 tonnes ha-1 FYM + Biochar	55.62	56.84	56.23	93.68	94.66	94.17	102.64	109.94	106.29	107.83	111.33	109.58
T_{11}	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	56.01	57.31	56.66	95.98	95.00	95.49	103.11	110.91	107.01	109.37	112.95	111.16
T_{12}	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	55.62	57.62	56.62	97.68	97.89	97.78	104.21	112.21	108.21	112.34	114.74	113.54
T_{13}	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	57.35	58.27	57.81	100.68	101.98	101.33	106.13	113.13	109.63	115.32	116.87	116.09
T_{14}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc	48.20	49.70	48.95	81.24	81.74	81.49	93.02	93.92	93.47	93.76	96.06	94.91
T_{15}	5.0 tonnes ha-1 FYM + Biochar	49.32	50.32	49.82	82.74	83.04	82.89	93.92	94.09	94.00	94.34	96.74	95.54
T_{16}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	51.22	51.82	51.52	83.55	84.45	84.00	95.18	95.87	95.52	96.24	97.54	96.89
	C.D.	6.25	5.05	4.95	4.95	9.57	8.34	9.03	11.85	10.57	10.39	9.68	11.61
	S.Em	2.16	1.75	1.72	1.72	3.31	2.89	3.12	4.10	3.66	3.60	3.35	4.02
	C.V.	7.1%	5.6%	5.6%	5.6%	6.5%	5.7%	5.5%	7.0%	6.3%	6.1%	5.6%	6.8%

Table 2. Effect of organic manure, inorganic fertilizer and biochar on number of tillers (m^{-2}) at 30, 60, 90 DAT and at harvest of riceduring 2023 and 2024

Treatments		Number of tillers (m^{-2})											
		2023 30 DAT	2024 30 DAT	Mean	2023 60 DAT	2024 60 DAT	Mean	2023 90 DAT	2024 90 DAT	Mean	2023 At Harvest	2024 At Harvest	Mean
T_1	Control	180.43	181.63	181.03	256.37	258.07	257.22	264.78	266.88	265.83	252.43	255.43	253.93
T_2	50% RDF	184.65	186.45	185.55	260.14	262.32	261.23	269.72	271.52	270.62	257.32	259.22	258.27
T_3	75% RDF	188.07	190.17	189.12	274.03	276.03	275.03	283.21	285.21	284.21	273.47	276.07	274.77
T_4	100%RDF	191.23	193.23	192.23	292.63	294.62	293.62	299.01	301.21	300.11	291.84	293.24	292.54
T_5	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	189.60	191.90	190.75	278.82	280.72	279.77	298.11	300.21	299.16	276.61	278.71	277.66
T_6	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	196.67	198.47	197.57	301.18	303.28	302.23	311.12	312.12	311.62	299.31	301.81	300.56

Treatments		Number of tillers (m^{-2})											
		2023 30 DAT	2024 30 DAT	Mean	2023 60 DAT	2024 60 DAT	Mean	2023 90 DAT	2024 90 DAT	Mean	2023 At Harvest	2024 At Harvest	Mean
T_7	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	199.54	201.24	200.39	307.26	309.26	308.26	320.02	322.02	321.02	304.28	306.28	305.28
T_8	50% RDF +5.0 tonnes ha-1 FYM + Biochar	196.20	198.20	197.2	302.87	304.37	303.62	318.33	320.63	319.48	301.20	303.24	302.22
T_9	75% RDF +5.0 tonnes ha-1 FYM + Biochar	201.42	203.32	202.37	310.57	312.27	311.42	329.76	331.56	330.66	306.48	308.88	307.68
T_{10}	100% RDF +5.0 tonnes ha-1 FYM + Biochar	208.11	210.41	209.26	316.98	318.98	317.98	337.84	339.84	338.84	312.67	315.17	313.92
T_{11}	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	219.10	221.10	220.1	336.43	338.47	337.45	364.63	366.74	365.68	329.30	331.35	330.32
T_{12}	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	226.20	229.20	227.7	351.34	354.34	352.84	384.31	387.31	385.81	350.61	353.61	352.11
T_{13}	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	235.3	238.3	236.8	376.3	380.6	378.5	401.1	404.4	402.7	375.5	378.3	376.9
T_{14}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc	182.54	184.24	183.39	255.37	257.32	256.34	270.02	273.22	271.62	254.28	256.38	255.33
T_{15}	5.0 tonnes ha-1 FYM + Biochar	187.45	189.45	188.45	263.57	266.51	265.04	283.53	285.13	284.33	261.20	264.22	262.71
T_{16}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	192.12	195.12	193.62	273.66	273.66	273.66	285.34	288.34	286.84	271.13	272.46	271.79
	C.D.	17.03	18.33	18.73	36.27	26.66	27.90	27.10	28.18	30.65	32.08	36.47	29.38
	S.Em	5.90	6.35	6.49	15.56	9.23	9.66	9.38	9.76	10.61	11.11	12.63	10.17
	C.V.	5.1%	5.4%	5.6%	7.3%	5.3%	5.6%	5.1%	5.3%	5.8%	6.5%	7.3%	5.9%

Table 3. Effect of organic manure, inorganic fertilizer and biochar on dry matter accumulation (g m-2) at various growth stages of rice during 2023 and 2024

Treatments		Dry matter accumulation ($g\ m^{-2}$)											
		2023 30 DAT	2024 30 DAT	Mean	2023 60 DAT	2024 60 DAT	Mean	2023 90 DAT	2024 90 DAT	Mean	2023 At Harvest	2024 At Harvest	Mean
T_1	Control	243.29	245.29	244.29	341.56	344.50	343.03	458.34	462.34	460.34	668.02	675.02	671.52
T_2	50% RDF	256.23	258.23	257.23	359.06	361.26	360.16	467.65	470.21	468.93	674.06	679.06	676.56
T_3	75% RDF	260.67	262.07	261.37	364.75	367.25	366.00	478.51	482.51	480.51	683.53	689.13	686.33
T_4	100%RDF	268.47	270.57	269.52	379.52	382.12	380.82	501.47	505.07	503.27	703.27	709.37	706.32
T_5	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	266.79	268.79	267.79	376.70	379.30	378.00	490.34	494.24	492.29	701.29	707.00	704.14
T_6	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	274.24	276.93	275.58	386.63	389.60	388.11	523.34	527.32	525.33	738.08	744.21	741.14
T_7	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	287.96	289.35	288.65	428.27	431.62	429.94	608.76	612.26	610.51	789.56	795.01	792.28
T_8	50% RDF +5.0 tonnes ha-1 FYM + Biochar	276.34	278.04	277.19	400.80	403.20	402.00	601.60	604.50	603.05	761.66	767.05	764.35
T_9	75% RDF +5.0 tonnes ha-1 FYM + Biochar	293.70	295.36	294.53	448.23	451.33	449.78	622.62	624.22	623.42	821.42	826.02	823.72
T_{10}	100% RDF +5.0 tonnes ha-1 FYM + Biochar	300.36	302.21	301.28	416.67	419.23	417.95	648.33	652.13	670.5	856.21	862.01	859.11
T_{11}	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	294.69	296.28	295.48	403.62	406.12	404.87	646.70	650.10	648.4	845.59	851.50	848.54
T_{12}	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	310.58	312.58	311.58	456.56	459.64	458.10	639.49	643.40	641.44	857.12	863.36	860.24

Treatments		Dry matter accumulation (g m^{-2})											
		2023 30 DAT	2024 30 DAT	Mean	2023 60 DAT	2024 60 DAT	Mean	2023 90 DAT	2024 90 DAT	Mean	2023 At Harvest	2024 At Harvest	Mean
T_{13}	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	326.39	328.23	327.31	472.73	475.01	473.87	668.79	672.21	650.23	874.36	880.03	877.19
T_{14}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc	252.41	254.01	253.21	363.52	366.47	364.99	463.47	467.24	465.35	670.48	676.40	673.44
T_{15}	5.0 tonnes ha-1 FYM + Biochar	261.39	263.17	262.28	370.32	373.02	371.67	472.29	476.15	474.22	685.59	691.32	688.45
T_{16}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	264.57	266.02	265.29	379.63	382.24	380.93	478.65	482.15	480.4	696.18	701.06	698.62
	C.D.	28.49	30.76	20.59	35.50	43.26	37.37	49.56	58.45	53.31	70.61	73.70	82.11
	S.Em	9.87	10.65	9.24	12.29	14.98	12.94	17.16	20.24	18.46	24.45	25.52	28.43
	C.V.	6.1%	6.6%	5.7%	5.3%	6.4%	5.6%	5.4%	6.4%	5.8%	5.6%	5.8%	6.5%

Table 4. Effect of organic manure, inorganic fertilizer and Biochar on Yieldattributes of rice during 2023 and 2024

Treatments		Yield Attributes											
		Panicle length (cm)		Mean	Number of grains panicle^{-1}		Mean	Test weight (g)		Mean	Number of effective tillers (m^{-2})		Mean
		2023	2024		2023	2024		2023	2024		2023	2024	
T_1	Control	30.10	30.18	30.14	105	106	105.50	20.10	20.15	20.12	235	237	236
T_2	50% RDF	30.62	30.76	30.69	119	123	121.00	21.20	21.26	21.23	249	253	251
T_3	75% RDF	31.20	31.33	31.26	128	132	130.00	21.42	21.48	21.45	276	278	277
T_4	100%RDF	32.10	32.15	32.12	135	138	136.50	21.61	21.67	21.64	279	281	280
T_5	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	31.30	31.45	31.37	132	136	134.00	21.58	21.64	21.61	281	283	282
T_6	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	31.60	31.87	31.73	141	144	142.50	21.86	21.92	21.89	297	299	298
T_7	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	32.32	32.78	32.55	148	152	150.00	22.04	22.11	22.07	300	302	301
T_8	50% RDF +5.0 tonnes ha-1 FYM + Biochar	32.21	32.45	32.33	142	147	144.50	22.00	22.18	22.09	305	308	306.5
T_9	75% RDF +5.0 tonnes ha-1 FYM + Biochar	32.78	32.97	32.87	152	156	154.00	22.25	22.35	22.3	316	319	317.5
T_{10}	100% RDF +5.0 tonnes ha-1 FYM + Biochar	33.50	33.67	33.58	159	163	161.00	22.64	22.69	22.66	330	336	333
T_{11}	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	33.40	33.89	33.64	157	160	158.50	22.87	22.97	22.92	339	343	341
T_{12}	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	34.32	34.65	34.48	168	171	169.50	23.12	23.21	23.16	347	351	349
T_{13}	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	35.10	35.34	35.22	179	182	180.50	23.54	23.64	23.59	354	358	356
T_{14}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc	30.50	30.78	30.64	108	112	110.00	20.97	21.02	20.99	290	296	293
T_{15}	5.0 tonnes ha-1 FYM + Biochar	30.89	31.09	30.99	117	119	118.00	21.20	21.25	21.22	302	307	304.5
T_{16}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	31.54	31.86	31.70	126	128	127.00	21.88	21.98	21.93	311	316	313.5
	C.D.	3.56	4.73	3.63	14.95	12.28	14.67	2.73	2.05	2.34	43.63	31.33	37.55
	S.Em	1.23	1.64	1.26	5.18	4.46	6.88	0.96	0.71	0.81	15.11	10.85	13.00
	C.V.	6.6%	8.7%	6.7%	6.4%	5.4%	6.4%	7.6%	5.6%	6.4%	8.7%	6.1%	7.4%

Table 5. Effect of organic manure, inorganic fertilizer and biochar on yield studies of rice during 2023 and 2024

Treatments		Yield Studies											
		Grain yield (kg ha^{-1})		**Mean**	**Straw yield (kg ha^{-1})**		**Mean**	**Biological yield (kg ha^{-1})**		**Mean**	**Harvest Index (%)**		**Mean**
		2023	**2024**		**2023**	**2024**		**2023**	**2024**		**2023**	**2024**	
T_1	Control	3511	3598	3554	4012	4024	4018	7523	7622	7572	46.67	47.20	46.93
T_2	50% RDF	4575	4611	4593	5032	5108	5070	9607	9719	9663	47.62	47.44	47.53
T_3	75% RDF	5476	5506	5491	5898	6030	5964	11374	11536	11455	48.14	47.72	47.93
T_4	100%RDF	6256	6334	6295	6701	6835	6768	12957	13169	13063	48.28	48.09	48.18
T_5	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	5380	5453	5416	5828	5903	5865	11208	11356	11282	48.00	48.01	48.00
T_6	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	6212	6220	6216	6659	6750	6704	12871	12970	12920	48.26	48.11	48.18
T_7	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc	6327	6417	6372	6787	6854	6820	13114	13271	13192	48.19	48.35	48.27
T_8	50% RDF +5.0 tonnes ha-1 FYM + Biochar	5730	5810	5770	6151	6237	6194	11881	12047	11964	48.42	48.22	48.32
T_9	75% RDF +5.0 tonnes ha-1 FYM + Biochar	6483	6509	6496	6816	6920	6868	13299	13429	13364	48.74	48.46	48.60
T_{10}	100% RDF +5.0 tonnes ha-1 FYM + Biochar	6622	6662	6642	6920	7020	6970	13542	13682	13612	48.89	48.69	48.79
T_{11}	50% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	6184	6374	6279	6508	6698	6603	12692	13072	12777	48.72	48.76	48.74
T_{12}	75% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	6884	7044	6964	7210	7332	7271	14094	14376	14095	48.84	48.99	48.91
T_{13}	100% RDF +5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	7155	7235	7195	7429	7510	7469	14584	14745	14664	49.06	49.06	49.06
T_{14}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc	4423	4543	4483	4942	5068	5005	9365	9611	9488	47.22	47.26	47.24
T_{15}	5.0 tonnes ha-1 FYM + Biochar	4712	4856	4784	5240	5310	5275	9952	10166	10059	47.34	47.76	47.55
T_{16}	5.0 tonnes ha-1 FYM + 5.0 kg Zinc + Biochar	5287	5407	5347	5735	5805	5770	11022	11212	11117	47.96	48.22	48.09
	C.D.	5.79	5.67	6.22	5.29	6.35	6.51	10.23	11.32	11.81	6.10	6.34	6.14
	S.Em	2.00	1.96	2.15	1.83	2.20	2.25	3.54	3.92	4.09	2.11	2.20	2.13
	C.V.	6.1%	5.9%	6.5%	5.1%	6.1%	6.3%	5.2%	5.6%	5.9%	7.6%	7.9%	7.6%

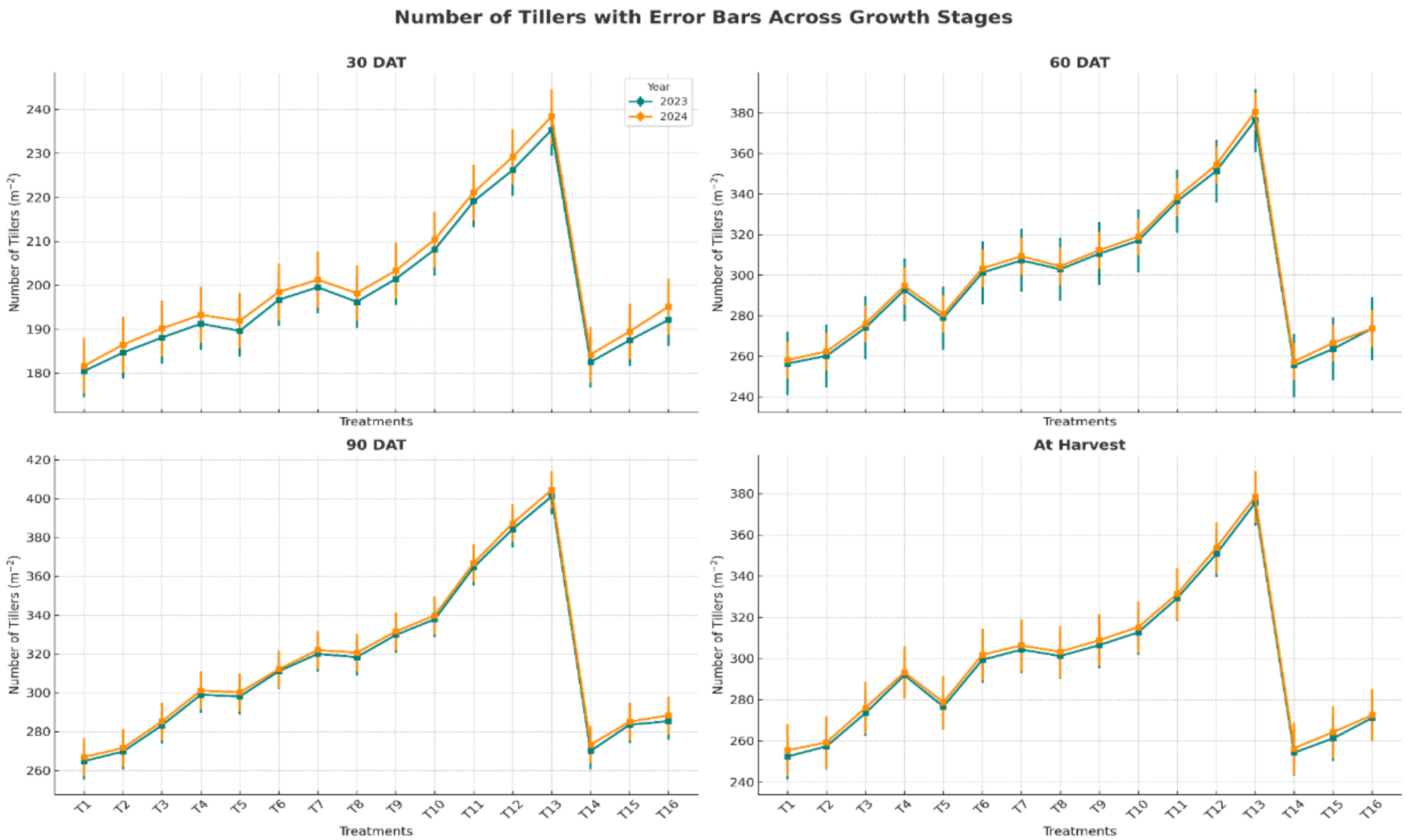

Fig. 2. Effect of organic manure, inorganic fertilizer and biochar on number of tillers (m-2) at 30, 60, 90 DAT and at harvest of riceduring 2023 and 2024

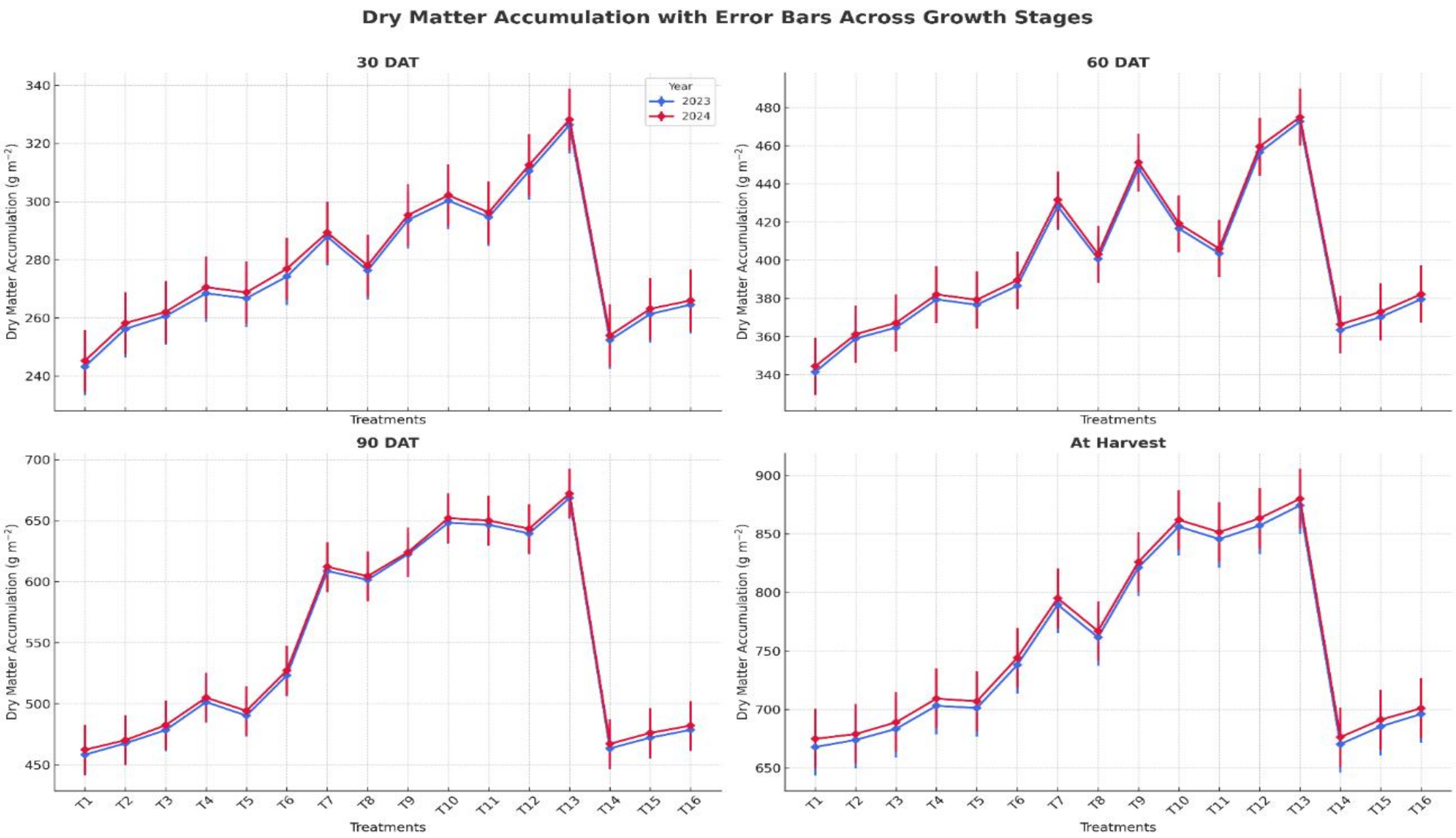

Fig. 3. Effect of organic manure, inorganic fertilizer and biochar on dry matter accumulation (g m-2) at various growth stages of rice during 2023 and 2024

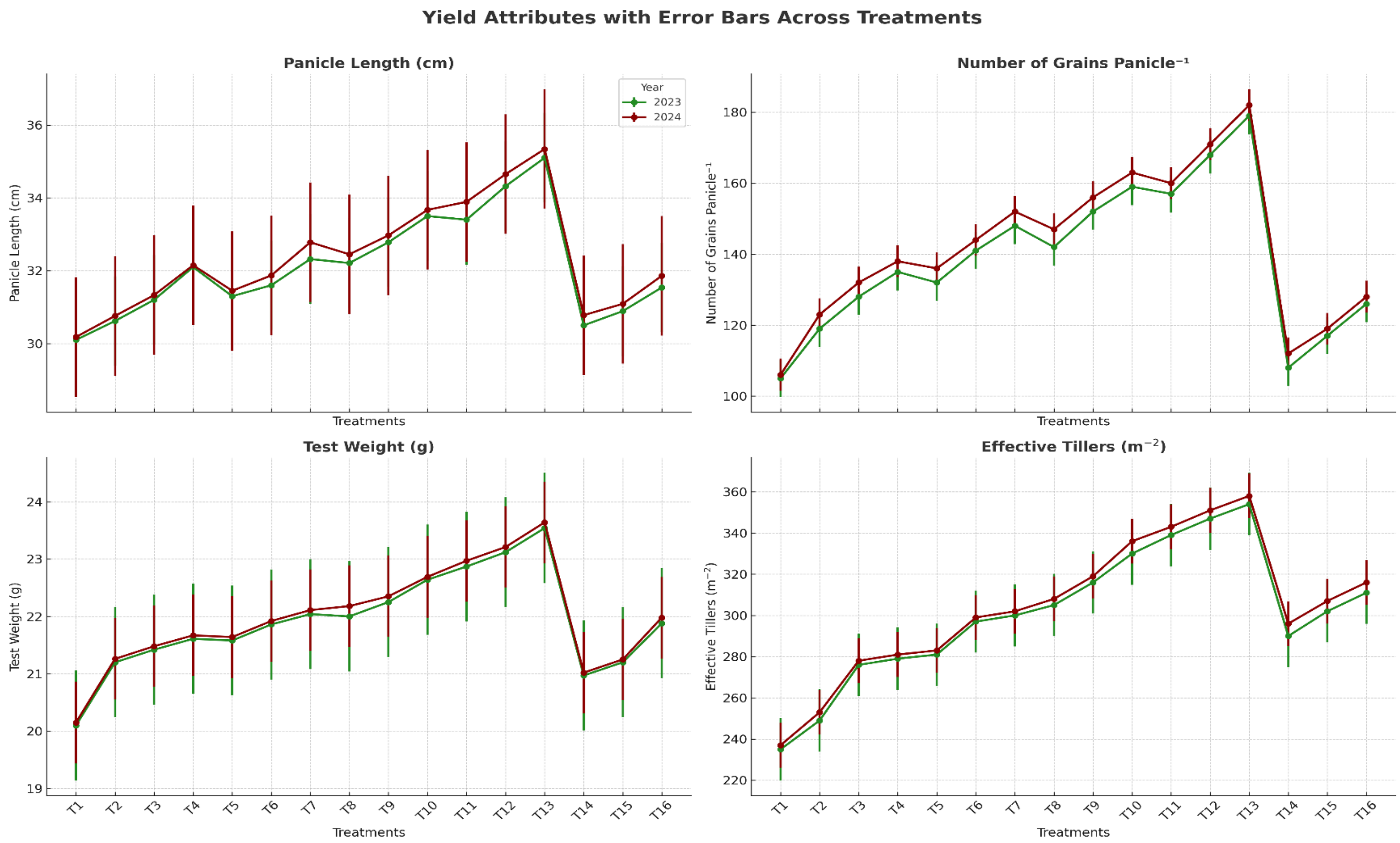

Fig. 4. Effect of organic manure, inorganic fertilizer and Biochar on Yieldattributes of rice during 2023 and 2024

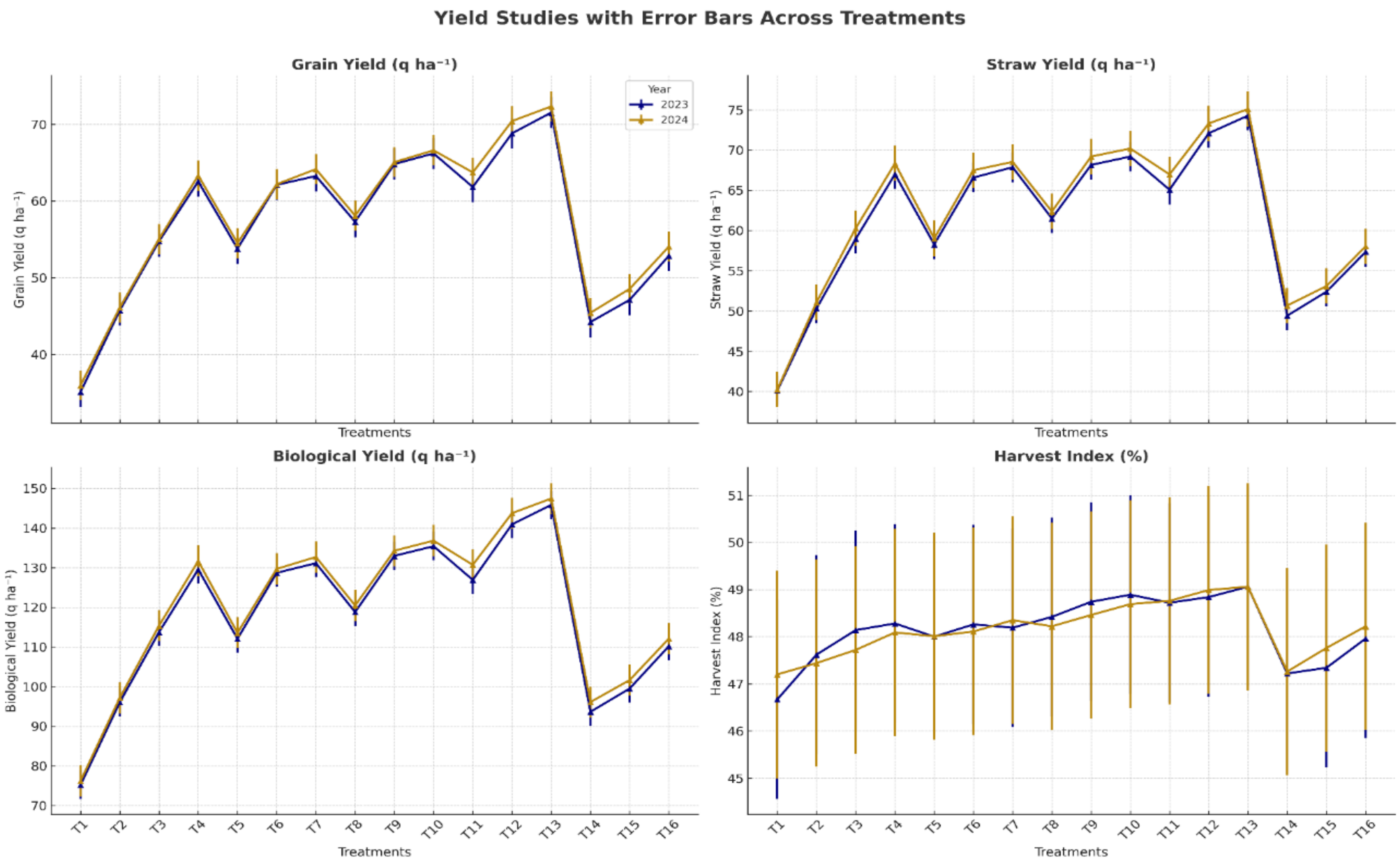

Fig. 5. Effect of organic manure, inorganic fertilizer and Biochar on Yield Studies of rice during 2023 and 2024

4. CONCLUSION

The present study clearly demonstrates that integrated nutrient management (INM), involving a combination of chemical fertilizers (RDF), farmyard manure (FYM), zinc, and biochar, significantly enhances crop performance. Among all treatments, the application of 100 % RDF + 5.0 tonnes ha^{-1} FYM + 5.0 kg ha^{-1} Zn + biochar (T_{13}) consistently recorded the highest values for key yield attributes such as panicle length, grain number, grain and test weight, biological yield (144.64 q ha^{-1}), and harvest index (48.35 %). These findings suggest that biochar, when combined with RDF, FYM and zinc, enhances nutrient use efficiency and boosts yield potential. The improved performance under INM treatments validates the synergy of organic and inorganic inputs, making it a viable approach for achieving long-term productivity and ecological balance in rice-based cropping systems. Thus, adopting integrated strategies is essential for enhancing agricultural sustainability and resource-use efficiency.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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