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RESEARCH ARTICLE

Effect of organic manure, inorganic fertilisers and biochar on quality characteristics, nutrient content and uptake of rice (*Oryza sativa* L.)

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Abstract

This study tested the hypothesis that integrating biochar with organic manure and recommended inorganic fertilisers can simultaneously enhance rice grain quality, nutrient use efficiency and economic sustainability compared with chemical fertilisers. The urgency of confirming this hypothesis stems from rising fertiliser costs, declining soil fertility, widespread micronutrient deficiencies and the need to sustain rice productivity and quality under changing climate conditions. Synthesising results across two seasons (2023–2024), we found that the integrated approach markedly improved grain quality and nutrient dynamics, with the best performing combination recording protein content of 10.64 % and 11.14 % starch content, of 70.78 % and 71.69 % hulling recovery of 83.64 % and 84.53 % and milling recovery of 73.56 % and 74.21 %, respectively. These improvements were accompanied by the highest nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) content and uptake in both grain and straw, demonstrating enhanced nutrient assimilation and translocation rather than isolated fertiliser effects. The breakthrough of this work lies in establishing a previously underexplored interdisciplinary linkage among soil carbon amendments, micronutrient nutrition, grain quality and processing efficiency, thereby connecting soil health management with food quality and agribusiness outcomes. Integrated application of biochar, farmyard manure and inorganic fertilisers resulted in a significant improvement in rice productivity, a 12–18 % yield increase over sole chemical fertilisation, along with enhanced grain quality and nutrient uptake. Future research should focus on long-term validation across diverse agro-ecological regions, optimisation of biochar sources, carbon footprint and credit assessments with precision nutrient management, while addressing challenges related to biochar availability, standardisation and farmer adoption.

Keywords: biochar; inorganic fertiliser; organic manure; nutrient uptake; rice quality; sustainability

Introduction

Rice (*Oryza sativa* L.) serves as a vital staple food crop worldwide, nourishing over half of the global population (1). It plays a crucial role in the food and nutritional security of billions, especially in Asia. Enhancing rice productivity and quality has become increasingly important in light of growing population pressure, shrinking arable land and changing climate patterns. Besides yield, grain quality and nutrient content are vital parameters that determine its market value and nutritional contribution to human health. Inorganic fertilisers have played a key role in increasing rice production. However, excessive and imbalanced use of chemical fertilisers has led to soil degradation, nutrient imbalances and environmental issues such as water pollution and greenhouse gas emissions (2). To counter these challenges, the combined use of organic and inorganic nutrient sources has been advocated as a sustainable approach. Organic manures like farmyard manure (FYM) not only supply essential nutrients but also improve soil physical, chemical and biological properties (3). They enhance microbial activity and increase nutrient availability, thereby improving crop growth and nutrient uptake. Biochar, a carbon-rich by-product obtained through the pyrolysis of organic biomass, has gained attention as a promising soil amendment in recent years. It improves soil pH, electrical conductivity, organic carbon, available nitrogen

(N), phosphorus (P) and K, soil structure, water retention, cation exchange capacity and nutrient retention, while also serving as a habitat for beneficial microbes (4). Biochar reduces nutrient leaching and enhances nutrient use efficiency, thereby supporting improved crop performance and nutrient uptake (5).

Rice grain quality traits, such as protein and starch content and hulling and milling percentages, are significantly influenced by nutrient management practices. Balanced and efficient nutrient supply not only affects yield but also governs grain nutritional quality, which is critical for food security and human health (6).

Materials and Methods

The present field experiment was carried out at the Agronomy Research Farm, Nawabganj, Department of Soil Science, C. S. Azad University of Agriculture and Technology, Kanpur, during the kharif season of 2023 and 2024. The soil in the experimental field is classified as Inceptisols. It is sandy loam in texture and neutral to alkaline in soil reaction.

Sixteen treatments with three replicates were evaluated: T1 – control, T2 - 50 % Recommended Dose of Fertilisers (RDF), T_3- 75 % RDF, T_4- 100 % RDF, T_5- 50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn, T_6- 75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn, T_7- 100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn, T_8- 50 % RDF + 5.0 t ha^{-1} FYM + Biochar, T_9- 75 % RDF + 5.0 t ha^{-1} FYM + Biochar, T_{10}- 100 % RDF + 5.0 t ha^{-1} FYM + Biochar, T_{11}- 50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar, T_{12}- 75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar, T_{13}- 100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar, T_{14}- 5.0 t ha^{-1} FYM + 5.0 kg Zn, T_{15}- 5.0 t ha^{-1}FYM + Biochar and T_{16}- 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar. The biochar was applied at 5.0 t ha^{-1} in treatments T_8 to T_{16} in combination with farmyard manure and recommended N, P and K fertilisers. The experiment was conducted in a randomised block design (RBD) with 16 treatments and 3 replications and data were statistically analyzed using ANOVA to test treatment effects. The rice variety 27P37, known for its high yield potential, medium maturity duration, and good grain quality traits, is suitable for rainfed conditions in central and eastern India.

Plant samples were collected to analyse nutrient content, nutrient uptake and quality characteristics of the rice crop. During the harvest, straw and seed yields were recorded. Plant samples were collected for chemical analysis of N, P, K and Zn in both seed and straw. The N content in the plant (both grain and straw) was determined by micro-kjeldahl method (7), the determination of P content in the extracts was carried out using standardized procedure (7). Potassium uptake (kg ha^{-1}) was analyzed by flame photometer and total K uptake by grain and straw was worked out separately.

Samples of the plant were subjected to digestion using a diacid mixture composed of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 2:1 proportion. The colour intensity was measured using an atomic absorption spectrophotometer with a Zn hollow cathode lamp (8).

Composite grain and straw samples were collected from each treatment at harvest to analyse N, P, K and Zn content and their uptake (kg ha^{-1}). The plant material was oven dried (70 ± 50 °C for 72 hr) and ground separately and then subjected to analysis. The data obtained from the different characters under study were analysed using standard statistical procedures (9).

Results and Discussion

Effect of integrated nutrient management on rice grain quality parameters

The data presented in Table 1 and Fig. 1 revealed that the application of organic manure, inorganic fertilisers and biochar have a significant effect on the grain quality parameters of rice, including protein content, starch content, hulling and milling percentage. Protein content increased significantly with integrated nutrient management treatments compared with the control. The highest protein content (10.64 g in 2023 and 11.14 g in 2024) was recorded in T_{13} (100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + biochar) followed by T_{12} (10.47 g in 2023 and 10.97 g in 2024) and T_{11} (10.24 g in 2023 and 10.74 g in 2024) while the lowest was observed in T_1 (control) with 9.34 g in 2023 and 9.84 g in 2024. This increase in protein content can be attributed to enhanced N availability and uptake resulting from the synergistic effects of organic manure, biochar and balanced fertilisation (6). Biochar likely improved nutrient retention and microbial activity, facilitating better N assimilation in grain (5). The starch content also improved across treatments, with T_{13} recording the highest mean starch value of (70.78 % in 2023 and 71.69 % in 2024), followed by T_{12} (69.60 % in 2023 and 70.18 % in 2024) and T_{11} (68.98 % in 2023 and 69.78 % in 2024). The lowest starch content was noted in the control (61.20 % in 2023 and 62.32 % in 2024). The increased starch content may result from balanced carbohydrate metabolism, driven by optimal nutrient supply and enhanced physiological efficiency under integrated nutrient regimes (2). The quality parameters, such as hulling and milling percentage, followed a similar trend. The highest hulling percentage (83.64 % in 2023 and 84.53 % in 2024) and milling percentage (73.56 % in 2023 and 74.21 % in 2024) were again recorded in T_{13}. Treatments with biochar in combination with FYM and Zn consistently outperformed those with only the recommended dose of fertilisers. For instance, T_9 and T_{10} involving biochar exhibited higher values compared to their counterparts without biochar, T_6 and T_7, confirming the role of biochar in improving grain physical quality (4). Improved hulling and milling percentages can be linked to better grain filling, structural integrity and reduced grain breakage which are strongly influenced by nutrient availability and balance during grain development (10). The higher values in biochar-treated plots can be attributed to better nutrient retention, reduced loss and improved soil physical properties, enhancing plant health and grain structure. The superior performance of T_{13} compared to treatments with partial integration clearly indicates a true synergistic interaction rather than independent effects. Biochar enhances nutrient retention and microbial activity; FYM supplies carbon and nutrients for sustained mineralization; and Zn ensures efficient metabolic functioning at the plant level. Together, these inputs improve nutrient synchronisation, physiological efficiency and assimilate partitioning. The findings emphasise that grain quality improvement in rice is not solely dependent on nutrient quantity but on nutrient interactions and soil plant system optimisation. The consistent improvements observed across two seasons further

Table 1. Effect of organic manure, inorganic fertiliser and biochar on quality parameters of rice during 2023 and 2024

	Treatments	Quality parameters											
		Protein content in grains (g)		Mean	Starch content in grains (%)		Mean	Hulling (%)		Mean	Milling (%)		Mean
		2023	2024		2023	2024		2023	2024		2023	2024	
T_1	Control	09.34	09.84	9.59	61.20	62.32	61.76	75.34	76.24	75.79	67.23	67.73	67.48
T_2	50 % RDF	09.47	09.97	9.72	62.36	63.23	62.79	75.52	76.82	76.17	67.57	67.95	67.76
T_3	75 % RDF	09.58	10.08	9.83	63.76	64.63	64.19	75.78	76.96	76.37	67.84	68.01	67.92
T_4	100 % RDF	09.66	10.16	9.91	64.12	65.20	64.66	76.89	77.83	77.36	68.37	68.70	68.53
T_5	50 % RDF +5.0 t ha^{-1} FYM + 5.0 kg Zn	09.63	10.13	9.88	64.76	65.89	65.32	76.85	77.80	77.32	68.23	68.65	68.44
T_6	75 % RDF +5.0 t ha^{-1} FYM + 5.0 kg Zn	09.78	10.28	10.03	65.32	66.36	65.84	77.24	78.30	77.77	69.02	69.47	69.24
T_7	100 % RDF +5.0 t ha^{-1} FYM + 5.0 kg Zn	10.02	10.52	10.27	66.56	67.39	66.97	78.45	79.47	78.96	69.68	70.48	70.08
T_8	50 % RDF +5.0 t ha^{-1} FYM + Biochar	09.96	10.44	10.20	66.87	67.98	67.42	78.37	79.41	78.89	69.59	70.33	69.96
T_9	75 % RDF +5.0 t ha^{-1} FYM + Biochar	10.07	10.57	10.32	67.43	68.25	67.84	79.59	80.59	80.09	70.85	71.84	71.34
T_{10}	100 % RDF + 5.0 t ha^{-1} FYM + Biochar	10.16	10.66	10.41	68.54	69.33	68.93	80.81	81.67	81.24	71.43	72.35	71.89
T_{11}	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	10.24	10.74	10.49	68.98	69.78	69.38	81.87	82.76	82.31	71.78	72.89	72.33
T_{12}	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	10.47	10.97	10.72	69.60	70.18	69.89	82.26	83.12	82.69	72.59	73.54	73.06
T_{13}	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	10.64	11.14	10.89	70.78	71.69	71.23	83.64	84.53	84.08	73.56	74.21	73.88
T_{14}	5.0 t ha^{-1} FYM + 5.0 kg Zn	09.57	09.68	9.62	63.46	64.32	63.89	75.86	76.12	75.99	67.48	67.84	67.66
T_{15}	5.0 t ha^{-1} FYM + Biochar	09.69	09.79	9.74	64.23	65.37	64.80	76.54	77.63	77.08	68.24	68.69	68.46
T_{16}	5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	09.74	09.85		65.24	66.21		77.43	78.32	77.87	69.01	69.74	69.37
CD		1.30	1.83	1.47	1.14	11.64	7.63	8.26	7.60	10.17	7.32	9.43	8.45
SEM		0.45	0.64	0.51	0.40	4.03	2.64	2.86	2.63	3.52	4.24	3.26	2.93
SED		0.64	0.90	0.72	0.56	5.70	3.74	4.04	3.72	4.98	5.99	4.62	4.14
CV		7.89 %	10.68 %	8.73 %	6.79 %	9.65 %	6.33 %	6.33 %	5.75 %	7.74 %	10.55 %	8.06 %	7.26 %

Table 2. Effect of organic manure, inorganic fertiliser and biochar on nitrogen content and nitrogen uptake of rice during 2023 and 2024

	Treatments	Plant analysis									
		2023					2024				
		Nitrogen content (%)		Nitrogen uptake (kg ha^{-1})			Nitrogen content (%)		Nitrogen uptake (kg ha^{-1})		
		Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T_1	Control	1.15	0.33	25.31	11.90	38.69	1.15	0.34	25.76	12.36	39.61
T_2	50 % RDF	1.16	0.34	27.40	13.50	42.40	1.17	0.36	27.80	13.67	43.0
T_3	75 % RDF	1.17	0.39	29.80	16.20	47.56	1.18	0.40	28.99	16.36	46.93
T_4	100 % RDF	1.19	0.40	33.23	17.68	52.50	1.20	0.41	34.69	18.09	54.39
T_5	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	1.20	0.42	36.20	19.31	57.13	1.21	0.43	37.89	20.24	59.77
T_6	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	1.20	0.46	46.20	27.59	75.45	1.27	0.47	48.07	28.09	77.90
T_7	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	1.21	0.45	39.30	23.13	64.27	1.22	0.46	39.90	40.89	82.47
T_8	50 % RDF + 5.0 t ha^{-1} FYM + Biochar	1.19	0.45	50.43	27.59	79.66	1.22	0.50	52.39	31.52	85.63
T_9	75 % RDF + 5.0 t ha^{-1} FYM + Biochar	1.21	0.50	52.87	31.53	86.11	1.25	0.55	53.59	34.90	90.29
T_{10}	100 % RDF + 5.0 t ha^{-1} FYM + Biochar	1.23	0.49	49.51	29.75	80.98	1.24	0.50	48.96	31.21	81.91
T_{11}	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	1.32	0.53	58.74	35.29	95.88	1.33	0.55	59.54	36.88	98.30
T_{12}	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	1.40	0.57	61.84	36.50	100.31	1.42	0.58	62.48	37.79	102.27
T_{13}	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	1.45	0.58	62.45	37.59	102.07	1.46	0.59	63.08	38.74	103.87
T_{14}	5.0 t ha^{-1} FYM + 5.0 kg Zn	1.26	0.51	43.94	28.82	74.53	1.27	0.53	44.78	29.17	75.75
T_{15}	5.0 t ha^{-1} FYM + Biochar	1.29	0.53	49.74	31.96	83.52	1.25	0.54	49.98	33.98	85.75
T_{16}	5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	1.31	0.54	56.70	34.48	93.03	1.33	0.56	57.80	35.88	95.57
CD		0.13	0.05	5.03	3.13	6.32	0.12	0.04	4.72	3.45	8.01
SEm		0.05	0.02	1.74	1.08	2.19	0.04	0.01	1.63	1.20	2.77
SED		0.06	0.03	2.46	1.53	3.10	0.06	0.02	2.31	1.69	3.92
CV		6.34 %	6.56 %	6.64 %	7.11	5.15	5.49	5.25	6.13	7.15	6.27

Table 3. Effect of organic manure, inorganic fertilizer and biochar on phosphorus content and uptake of rice during 2023 and 2024

	Treatments	Plant analysis									
		2023					2024				
		Phosphorus content (%)		Phosphorus uptake (kg ha^{-1})			Phosphorus content (%)		Phosphorus uptake (kg ha^{-1})		
		Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T_1	Control	0.19	0.10	4.40	3.47	8.16	0.19	0.08	4.29	2.90	7.46
T_2	50 % RDF	0.20	0.10	5.04	3.77	9.11	0.21	0.10	4.85	3.78	8.94
T_3	75 % RDF	0.21	0.10	5.65	4.22	10.18	0.22	0.10	5.69	4.24	10.25
T_4	100 % RDF	0.23	0.10	6.45	4.42	11.2	0.24	0.10	6.94	4.50	11.78
T_5	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.24	0.10	7.21	4.76	12.31	0.25	0.10	7.78	4.83	12.96
T_6	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.25	0.10	8.13	5.07	13.55	0.26	0.10	8.43	5.21	14
T_7	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.26	0.10	10.08	6.39	16.83	0.27	0.11	11.06	6.55	17.99
T_8	50 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.27	0.11	9.32	6.20	15.9	0.28	0.11	10.07	6.18	16.64
T_9	75 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.27	0.11	11.55	6.81	18.74	0.28	0.11	12.50	6.83	19.72
T_{10}	100 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.28	0.11	10.23	6.65	17.27	0.28	0.11	10.68	6.81	17.88
T_{11}	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.29	0.11	12.22	6.76	19.38	0.29	0.11	12.79	6.85	20.04
T_{12}	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.29	0.11	13.54	7.09	21.03	0.30	0.11	13.60	7.10	21.11
T_{13}	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.30	0.11	14.10	7.39	21.90	0.30	0.12	13.73	7.83	21.98
T_{14}	5.0 t ha^{-1} FYM + 5.0 kg Zn	0.27	0.11	10.55	6.84	17.77	0.28	0.11	11.16	6.86	18.41
T_{15}	5.0 t ha^{-1} FYM + Biochar	0.27	0.11	11.28	7.03	18.69	0.28	0.11	12.06	7.08	19.53
T_{16}	5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.29	0.11	12.30	7.24	19.94	0.29	0.11	12.64	7.26	20.3
CD		0.03	0.02	1.37	0.76	2.08	0.03	0.02	1.64	0.87	2.23
SEm		0.01	0.01	0.48	0.26	0.72	0.01	0.01	0.57	0.30	0.77
SED		0.01	0.01	0.67	0.37	1.02	0.02	0.01	0.80	0.42	1.09
CV		5.94	9.15	8.72	7.70	7.96	7.86	8.62	9.85	8.68	8.21

Table 4. Effect of organic manure, inorganic fertiliser and biochar on potassium content and uptake of rice during 2023 and 2024

	Treatments	Plant analysis									
		2023					2024				
		Potassium Content (%)		Potassium uptake (kg ha^{-1})			Potassium Content (%)		Potassium uptake (kg ha^{-1})		
		Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T_1	Control	0.28	1.28	6.19	46.33	54.08	0.25	1.29	5.85	46.84	54.23
T_2	50 % RDF	0.30	1.29	9.31	50.10	61.00	0.37	1.31	8.94	49.47	60.09
T_3	75 % RDF	0.31	1.31	7.63	56.27	65.52	0.32	1.32	7.82	55.39	64.85
T_4	100 % RDF	0.33	1.32	8.90	58.75	69.30	0.32	1.33	9.56	58.33	69.54
T_5	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.34	1.35	10.22	63.63	75.54	0.34	1.34	10.96	63.76	76.4
T_6	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.34	1.35	11.08	68.31	81.08	0.35	1.35	11.09	67.99	80.78
T_7	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	0.35	1.37	14.19	86.19	102.1	0.36	1.38	15.54	85.98	103.26
T_8	50 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.34	1.41	12.09	80.65	94.49	0.39	1.42	13.65	79.76	95.22
T_9	75 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.35	1.39	14.93	87.12	103.79	0.40	1.40	16.76	87.45	106.01
T_{10}	100 % RDF + 5.0 t ha^{-1} FYM + Biochar	0.39	1.43	17.35	92.35	111.52	0.47	1.44	18.66	93.67	114.24
T_{11}	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.38	1.42	16.49	89.58	107.87	0.39	1.43	16.35	89.54	107.71
T_{12}	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.40	1.47	17.40	96.35	115.62	0.42	1.49	19.47	96.88	118.26
T_{13}	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.41	1.49	17.75	98.96	118.61	0.45	1.52	20.22	100.78	122.97
T_{14}	5.0 t ha^{-1} FYM + 5.0 kg Zn	0.37	1.40	14.14	84.44	100.35	0.43	1.41	15.62	85.34	102.8
T_{15}	5.0 t ha^{-1} FYM + Biochar	0.37	1.39	14.40	85.98	102.14	0.39	1.40	15.56	86.94	104.29
T_{16}	5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	0.38	1.41	16.63	90.53	108.95	0.43	1.44	17.94	91.35	111.16
CD		0.04	0.16	1.92	12.38	13.59	0.06	0.19	2.19	11.36	9.73
SEm		0.01	0.06	0.67	4.29	4.70	0.02	0.06	0.76	3.93	3.37
SED		0.02	0.08	0.94	6.06	6.65	0.03	0.09	1.07	5.56	4.76
CV		6.65	6.95	8.75	9.61	8.85	8.81	8.05	9.39	8.80	6.22

Table 5. Effect of organic manure, inorganic fertiliser and biochar on potassium content and uptake of rice during 2023 and 2024

	Treatments	Plant analysis									
		2023					2024				
		Zinc content (%)		Zinc uptake (kg ha^{-1})			Zinc content (%)		Zinc uptake (kg ha^{-1})		
		Grain	Straw	Grain	Straw	Total	Grain	Straw	Grain	Straw	Total
T_1	Control	14.71	35.47	264.32	1060.32	1374.82	15.01	36.00	268.33	1062.42	1381.76
T_2	50 % RDF	16.85	36.14	389.43	1119.87	1562.29	17.20	36.12	389.43	1120.57	1563.32
T_3	75 % RDF	18.94	36.29	483.06	1232.45	1770.74	19.20	35.21	485.23	1234.43	1774.07
T_4	100 % RDF	20.01	37.68	505.36	1298.76	1861.81	21.10	26.65	512.34	1299.41	1859.5
T_5	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	21.25	38.45	665.07	1367.56	2092.33	22.23	39.22	768.45	1370.50	2200.4
T_6	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	22.36	38.76	761.64	1583.42	2406.18	23.55	40.34	769.22	1585.47	2418.58
T_7	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn	21.46	39.89	698.54	1798.98	2558.87	22.65	39.23	700.25	1800.00	2562.13
T_8	50 % RDF + 5.0 t ha^{-1} FYM + Biochar	18.05	42.36	740.27	1987.24	2787.92	19.24	42.36	755.24	1990.93	2807.77
T_9	75 % RDF + 5.0 t ha^{-1} FYM + Biochar	20.10	43.77	859.74	1990.76	2914.37	21.22	42.56	880.22	1998.32	2942.32
T_{10}	100 % RDF + 5.0 t ha^{-1} FYM + Biochar	21.27	44.98	900.63	2098.53	3065.41	22.34	44.11	910.56	2110.45	3087.46
T_{11}	50 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	23.45	46.15	919.62	2104.98	3094.2	24.34	46.22	920.34	2177.57	3168.47
T_{12}	75 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	24.23	46.20	922.88	2012.28	3005.59	25.34	46.24	924.54	2099.12	3095.24
T_{13}	100 % RDF + 5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	25.63	46.33	924.77	2112.05	3108.78	26.88	47.34	925.34	2166.12	3165.68
T_{14}	5.0 t ha^{-1} FYM + 5.0 kg Zn	21.30	38.99	753.35	1985.34	2798.98	22.44	38.02	754.33	1999.77	2814.56
T_{15}	5.0 t ha^{-1} FYM + Biochar	22.99	39.83	673.26	1876.54	2612.62	23.12	39.45	675.35	1923.65	2661.57
T_{16}	5.0 t ha^{-1} FYM + 5.0 kg Zn + Biochar	23.07	39.66	801.54	1999.04	2863.31	24.34	40.10	805.34	2030.09	2899.87
CD		2.51	4.63	69.86	235.57	376.55	2.71	4.48	107.44	269.44	382.04
SEm		0.87	1.60	24.19	81.56	130.38	0.94	1.55	37.20	93.29	132.28
SED		1.23	2.27	34.21	115.35	184.38	1.32	2.19	52.61	131.93	187.04
CV		7.17	6.82	5.95	8.18	9.06	7.41	6.73	9.01	9.24	9.07

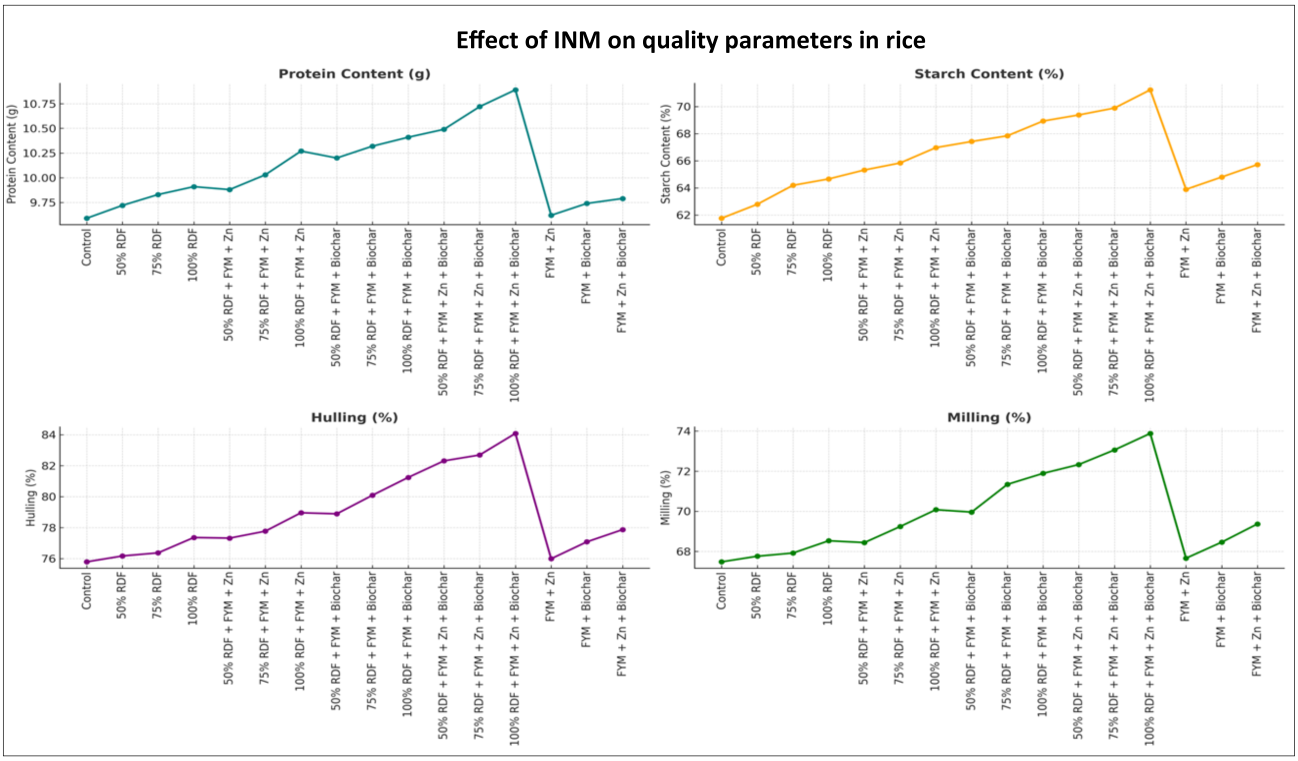

Fig. 1. Effect of organic manure, inorganic fertiliser and biochar on quality parameters of rice during 2023 and 2024.

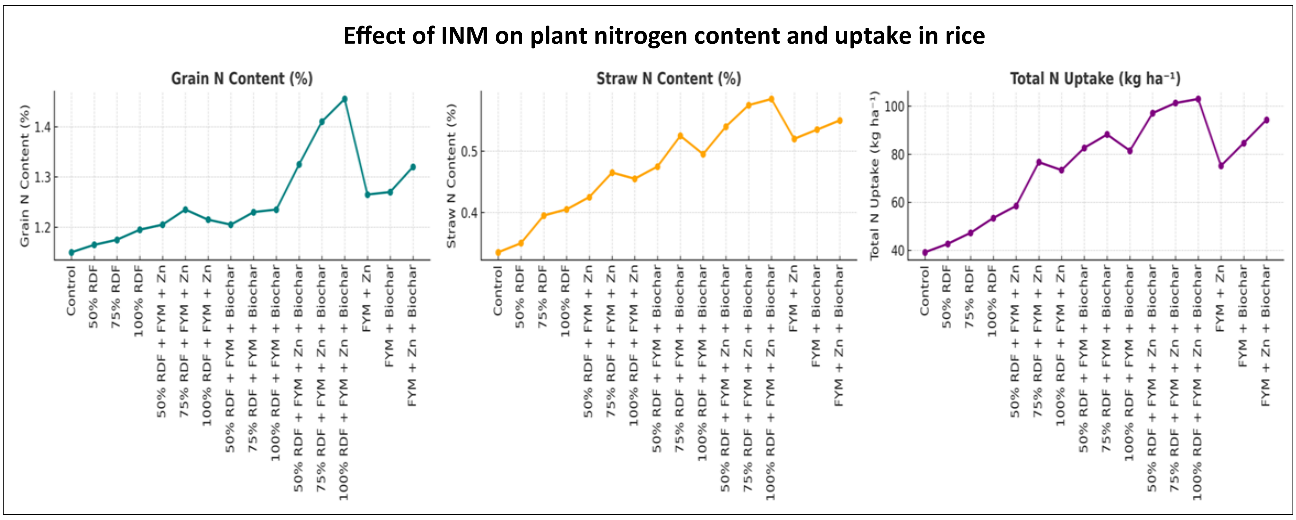

Fig. 2. Effect of organic manure, inorganic fertiliser and biochar on nitrogen content and nitrogen uptake of rice during 2023 and 2024.

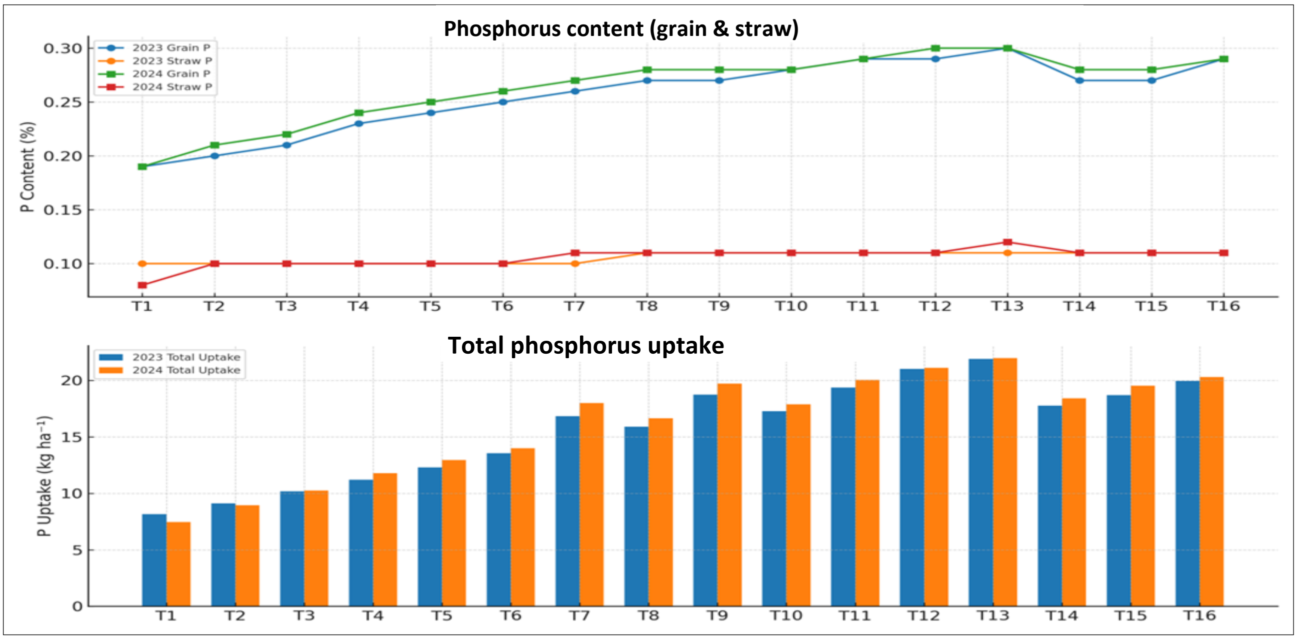

Fig. 3. Effect of organic manure, inorganic fertiliser and biochar on phosphorus content and uptake of rice during 2023 and 2024.

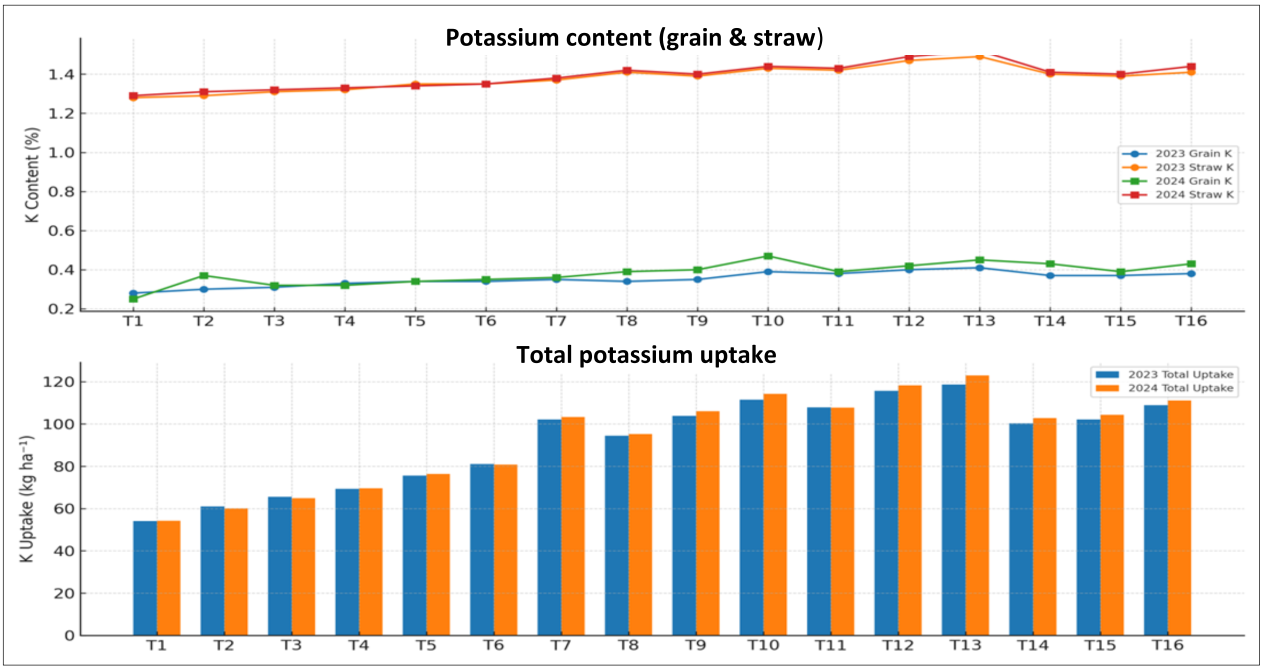

Fig. 4. Effect of organic manure, inorganic fertiliser and biochar on potassium content and uptake of rice during 2023 and 2024.

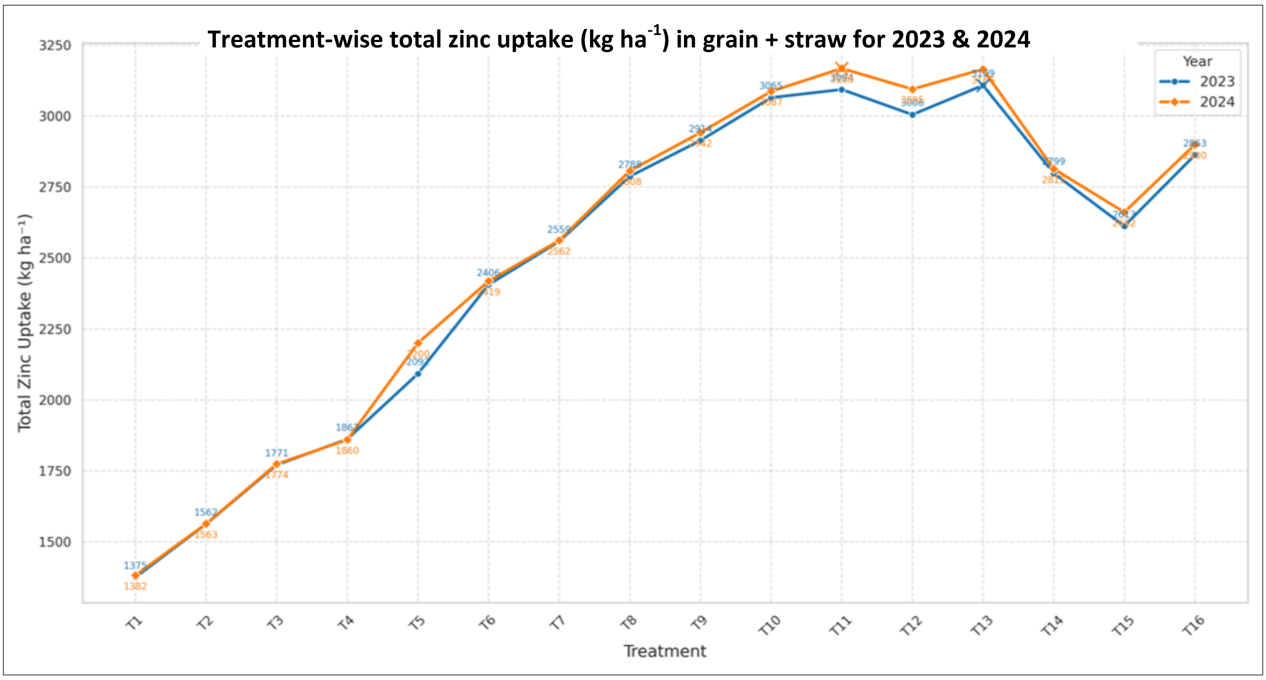

Fig. 5. Effect of organic manure, inorganic fertiliser and biochar on potassium content and uptake of rice during 2023 and 2024.

indicate the stability and robustness of biochar-based integrated nutrient management strategies under rice cultivation (11).

Effect of integrated nutrient management on nutrient content and uptake in rice

The data presented in Tables 2–5 and Fig. 2–5 showed that N content and uptake by rice significantly improved with integrated nutrient management. The highest N content in grain (1.45 % in 2023 and 1.46 % in 2024) and in straw (0.58 % in 2023 and 0.59 % in 2024) and maximum N uptake by grain (62.45 kg ha^{-1} in 2023 and 63.08 kg ha^{-1} in 2024) and by straw (37.59 kg ha^{-1} in 2023 and 38.74 kg ha^{-1} in 2024) were recorded under T_{13} (100 % RDF + 5.0 t FYM ha^{-1} + 5.0 kg Zn + biochar) followed by T_{12}. The control T_1 showed the lowest values. Treatments involving biochar and Zn, with the RDF and FYM, notably enhanced N assimilation (12). Phosphorus content and uptake in rice were significantly influenced by integrated nutrient treatments. The highest P content in grain (0.30 % in 2023 and 0.30 % in 2024) and in straw (0.11 % in 2023 and 0.12 % in 2024) and maximum P uptake by grain (14.10 kg ha^{-1} in 2023 and 13.73 kg ha^{-1} in 2024) and by straw (7.39 kg ha^{-1} in 2023 and 7.83 kg ha^{-1} in 2024) were recorded under T_{13} (100 % RDF + 5.0 t FYM ha^{-1} + 5.0 kg Zn + biochar) followed by T_{12}. The control T_1 showed the lowest values. Treatments with biochar, FYM and Zn enhanced phosphorus availability by reducing fixation and improving soil structure (13). Potassium content and uptake in rice were markedly enhanced by integrated nutrient management. The highest K content in grain (0.41 % in 2023 and 0.45 % in 2024) and in straw (1.49 % in 2023 and 1.52 % in 2024) and maximum K uptake by grain (17.75 kg ha^{-1} in 2023 and 20.22 kg ha^{-1} in 2024) and by straw (98.96 kg ha^{-1} in 2023 and 100.78 kg ha^{-1} in 2024) were recorded under T_{13} (100 % RDF + 5.0 t FYM ha^{-1} + 5.0 kg Zn + biochar) followed by T_{12}. The control T_1 showed the lowest values. This increase is attributed to improved soil structure, nutrient retention and microbial activity, facilitated by biochar and organic matter (14). Zinc content and uptake in rice were significantly enhanced by integrated nutrient management. The highest Zn content in grain (25.63 % in 2023 and 26.88 % in 2024) and in straw (46.33 % in 2023 and 47.34 % in 2024) and maximum Zn uptake by grain (924.77 kg ha^{-1} in 2023 and 925.34 kg ha^{-1} in 2024) and by straw (2112.05 kg ha^{-1} in 2023 and 2166.12 kg ha^{-1} in 2024) were recorded under T_{13} (100 % RDF + 5.0 t FYM ha^{-1} + 5.0 kg Zn + biochar) followed by T_{12}. The control T_1 showed the lowest values. Treatments combining farmyard manure Zn and biochar improved Zn bioavailability and plant absorption. These results corroborate findings that biochar enhances micronutrient availability by improving cation exchange capacity and nutrient retention (15). Integrated application of biochar with organic manures and inorganic fertilisers significantly improved nutrient uptake and enhanced rice grain and straw yield, indicating improved soil fertility, nutrient use efficiency and sustainable rice productivity under integrated nutrient management practices (16). Among all nutrients evaluated Zn content and uptake showed the most pronounced response to integrated nutrient management. Under T_{13}, Zn uptake by grain was more than threefold higher than the control, clearly demonstrating a strong interaction between biochar and Zn. Compared with treatments that received Zn without biochar, Zn uptake was substantially higher when biochar was included, indicating improved Zn bioavailability rather than increased Zn application alone. Biochar enhances Zn availability by increasing soil cation exchange capacity, reducing Zn fixation and maintaining Zn in plant-available forms. Additionally, organic ligands released from farmyard manure decomposition complex Zn ions, preventing precipitation and improving root uptake. Improved root growth and microbial activity under biochar-amended soils further facilitate Zn absorption and translocation to grain and straw. These mechanisms collectively explain the superior Zn nutrition observed under fully integrated treatments (17).

Conclusion

The present study demonstrates that integrated nutrient management involving organic manure, inorganic fertilisers, Zn and biochar substantially improved rice grain quality, nutrient content and nutrient uptake thereby enhancing productivity and nutrient use efficiency. Among all treatments, the combined application of 100 % RDF with FYM, Zn and biochar T_{13} consistently produced superior outcomes across two consecutive seasons. This treatment significantly increased grain protein and starch content, hulling and milling percentages and markedly enhanced the uptake of N, P, K and Zn in both grain and straw, indicating improved nutrient synchronisation and efficient assimilate partitioning. The results highlight that improvements in rice performance are governed not merely by nutrient quantity but by synergistic interactions among soil amendments. Biochar played a critical role in improving soil nutrient retention, cation exchange capacity and micronutrient bioavailability. These components optimized soil plant interactions, reduced nutrient losses and improved nutrient use efficiency under rice cultivation. From a practical perspective, the findings suggest that farmers can achieve higher and more stable rice yields with improved grain quality by adopting biochar-based integrated nutrient management strategies rather than relying solely on chemical fertilisers. For researchers and policymakers, the study provides strong evidence supporting the inclusion of biochar and organic amendments in sustainable rice production systems. Future research should focus on long-term field evaluations of biochar-based integrated nutrient management to assess its residual effects on soil health, carbon sequestration and nutrient dynamics across multiple cropping cycles.

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Authors' contributions

KKY and RK conceptualised the study, conducted the experiments, analysed and curated the data. RK supervised the work, developed the methodology and reviewed the manuscript. KKY, AAD, SK[1], TT, VS, SK[2], SY, RKJ, MK, AS, LM and AKY prepared the final draft and performed revisions. All authors read and approved the final manuscript [SK[1] stands for Sarvesh Kumar and SK[2] for Sumit Kumar].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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