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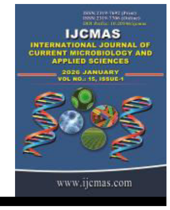

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Long-Term Fertilizer Regimes and their Effects on Soil Physical and Chemical Status in Vertisol-Based Rice-Wheat Systems

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ABSTRACT

This study examined the long-term effects of fertilizer management and organic matter amendments on soil physical, chemical, and nutrient properties in a rice–wheat cropping system. Across treatments, bulk density ranged from 1.32 to 1.45 Mg m−3 and particle density from 2.35 to 2.39 Mg m^{-3}, with no significant alteration in either density under long-term management. The FYM-inclusive mix (YT 6/2.5 t ha^{-1} + FYM; designated as T5) consistently produced the lowest bulk density, followed by T3 (YT 5/2 t ha^{-1}), T2 (GRD), and T4 (YT 6/2.5 t ha^{-1}), whereas the control (T1) exhibited the highest bulk density. Incorporation of FYM with inorganic fertilizers reduced bulk density, in line with prior reports, implying improved soil structure and porosity. Particle density remained largely unchanged across organic and inorganic amendments, reflecting its intrinsic soil character. Soil porosity followed a similar pattern, with organic-amended treatments—particularly those including FYM—yielding the highest porosity values and the control the lowest. Overall porosity increased with the addition of organic matter and varied fertilizer regimes, attributable to higher organic matter content, improved soil aggregation, and shifts in pore-size distribution. Infiltration rates ranged from 0.38 to 0.67 mm h^{-1}, with the FYM-inclusive treatment (T5) achieving the highest rate significantly above other treatments; the control recorded the lowest. The tendency for infiltration to rise with integrated organic–inorganic inputs aligns with established evidence. Water holding capacity (WHC) was significantly enhanced by higher fertilizer rates, with WHC values ranging from 34.98% to 41.92% in kharif and 34.88% to 41.57% in rabi, and the FYM-inclusive regime (T5) yielding the greatest WHC. Soil pH (7.73–8.03) and EC (0.13–0.18 dS m^{-1}) showed no consistent treatment effects, while cation exchange capacity (38.88–41.95 cmol(+) kg^{-1}) was highest under FYM-inclusive management, reflecting increased exchange sites from higher organic matter. Soil organic carbon increased significantly with inorganic fertilizer applied alone or in combination with FYM, with the highest SOC under T5 (pre-rice 0.60%, post-wheat 0.62%) and the lowest under control. Available macronutrients (N, P, K) were highest under FYM-inclusive regimes and remained superior to control, indicating sustained nutrient supply. Micronutrients showed a similar pattern, with the strongest pre-rice levels under FYM-inclusive management, while overall treatment differences were modest. Collectively, integrated nutrient management incorporating FYM enhances soil physical structure, WHC, CEC, SOC, and nutrient pools without altering intrinsic particle density or baseline pH and EC, underscoring the benefits of combining organic and inorganic inputs for sustained soil fertility and potential crop productivity.

Keywords

Long-term fertilizer management, Farmyard manure, Organic–inorganic nutrient management, micronutrients, bulk density, porosity, infiltration

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Introduction

Soil quality reflects the integrated influence of natural-resource management on key soil properties that determine crop productivity and long-term sustainability. Soil is a dynamic, living medium that performs multiple essential functions within terrestrial ecosystems. Beyond supporting plant growth, soil properties also buffer and modulate the formation and breakdown of hazardous compounds. Evaluations of soil quality provide a robust framework for assessing the sustainability of agricultural and land-management systems. Soils exhibit varying quality levels, underpinned by enduring intrinsic properties shaped by pedogenic factors and modified by management practices (Larson & Pierce, 1991). Soil quality has declined due to contamination by organic and inorganic chemicals, altering its chemical, physical, and biological properties. The Green Revolution markedly boosted food-grain production in the Indo-Gangetic Plain through sustained chemical-fertilizer use, yet it also fostered secondary and micronutrient deficiencies arising from limited application of organic manures. Concerns persist that soil health may deteriorate with prolonged fertilizer use, particularly under continuous cropping with imbalanced nutrient applications (N or NP) in the absence of organic manures, which has lowered crop productivity. Overall, the sustainability of cropping systems is challenged by these nutrient imbalances and their impacts on soil properties and plant performance (Tiwari *et al.*, 2002). The quality of soil emerges from the integrated effects of cropping-system components, such as crop rotation and tillage, together with fertility management that incorporates inorganic fertilizers and organic manures (Purakayastha *et al.*,2008).

Prolonged continuous cultivation has led to a reduction in soil organic matter, accompanied by deterioration of general soil physical quality (Bhattacharyya *et al.*, 2007). Enduring improvements in soil quality require sustaining SOM above a specified threshold for extended durations (Aune *et al.*, 1997). Without organic amendments, the sustained productivity of intensive cropping systems is compromised despite NPK fertilizer inputs (Yaduwanshi, 2003). Integrating organic manures, however, strengthens soil physical and biological health and thereby improves soil fertility and crop performance (Mandal *et al.*, 2003). The addition of organic matter elevates soil organic carbon, an important proxy for soil quality and a predictor of crop yields (Lal, 2003). Organic manures play a significant role in sustaining productivity, acting as nutrient sources and altering soil physical properties, while also improving the efficiency of applied nutrients (Sahadevareddy and Aruna, 2008). Organic manures enhance soil biological quality by increasing microbial abundance and delivering growth-promoting compounds. In parallel, improvements in soil physical properties occur as soil organic carbon content rises, reflecting direct and indirect effects of elevated organic matter on soil structure and function (Haynes and Naidu 1998). SOC content shows a positive response to organic waste inputs (manures and compost) relative to equivalent inorganic fertilization (Gregorich *et al.*, 2001). Generic fertilizer recommendations can cause nutrient losses through leaching, volatilization, and runoff, contributing to environmental degradation and reduced sustainability of crops. In contrast, location-specific, yield-based nutrient recommendations offer the potential to harness the genetic potential of a variety at a given site, enabling more efficient use of soil resources. The conjunctive use of manures with chemical fertilizers raises soil organic carbon and helps narrow the gap between potential and actual yields, a benefit that is substantial in practice (Tolanur and Badanur, 2003). Yield stagnation or decline has been observed across multiple cropping systems nationwide, driven by nutrient depletion, deterioration of soil structure, imbalanced nutrient use, soil acidification, and insufficient integration of manures and fertilizers. The risk to soil quality intensifies under intensive cropping systems, particularly in rice–wheat rotations, which are among the most affected systems in India. Rice (Oryza sativa L.) is one of the world's most important cereals, contributing roughly 60% of global staple-food production. India ranks second in rice production, with approximately 110.15 million tonnes and a productivity of about 2.55 tonnes per hectare across ~43.19 million hectares. In Chhattisgarh, rice production stands at about 8.05 million tonnes with a productivity near 2.10 t ha^{-1} over ~3.83 million hectares. As a major staple, wheat covers about 32.16 million hectares in India and yielded around 98.38 million tonnes during the 2016–17 Rabi season. Wheat productivity in Chhattisgarh is relatively low, at approximately 1.39 t ha^{-1}, on ~0.11 million hectares, producing about 0.16 million tonnes (Agriculture statistics 2017). Rising populations and growing food demand necessitate greater reliance on farming than ever before. Prolonged mining of soil nutrients and concurrent losses from erosion and other factors threaten future crop production and soil health if unchecked. Continuous cropping without attention to nutritional needs degrades soil fertility. The application of manures and fertilizers alters soil chemical, physical, and biological properties, with implications for system sustainability. Maintaining soil quality at an optimal level is complex, given the interactions among soil, climate, human practices, and crops. There is an urgent need to adopt integrated soil and crop-management practices to curb soil degradation and sustain soil quality. Long-term fertilizer experiments provide valuable insights into crop productivity and soil-quality trajectories under different management scenarios. Long-term fertilizer experiments (LTFE) provide a key framework for understanding sustainability, capturing the complex interactions among plants, soils, climate, and management practices and their effects on crop productivity. LTFE enable monitoring of sustained changes in yields and nutrient balances and help identify the drivers of these dynamics. There is growing emphasis on integrating organic manures and efficiently utilizing available renewable crop-residue nutrients alongside inorganic fertilizers to maintain soil health and sustain crop production over the long term. This crop-specific approach provides a scientific basis for balanced fertilization, aligning fertilizer nutrients with soil nutrients. The focused-performance concept harmonizes fertilizing the crop with fertilizing the soil, promoting integrated nutrient management tailored to each crop.

Materials and Methods

Study Area

Geographically, Raipur lies near the center of Chhattisgarh, at approximately 21°16′ N latitude and 81°60′ E longitude, with an elevation of about 289.56 meters above mean sea level. The research farm, located along NH 6 in the eastern part of Raipur, is near 20°04′ N latitude and 81°39′ E longitude, at an altitude of 293 meters above mean sea level.

Soil Characteristics

The experimental soil, locally known as Kanhar, is a fine montmorillonitic, hyperthermic Udic chromustert within the Vertisol order, identified as the Arang II series. It is typically deep, with clay content exceeding 44.8 percent, and ranges from dark brown to black in color. The soil pH is neutral to alkaline, reflecting lime presence.

Treatment Details

The study was conducted at the Research Farm of IGKV Raipur (Chhattisgarh). It used a *Vertisol* soil and the cropping system involved rice (Oryza sativa) and wheat (Triticum aestivum), using the MTU1010 rice variety and the GW-366 wheat variety. Experimental plots covered 16 square meters each, arranged with a row-to-plant spacing of 5 m by 8.5 m. The experiment employed five treatments, replicated four times, following a randomized block design (RBD).

Soil Sample Collection, Processing and Analysis

Soil samples were collected from the 0–15 cm layer prior to rice transplanting and again after wheat harvest from all experimental plots. These samples served to assess soil-quality parameters. A portion of the collected soil was air-dried, ground, and passed through a 2 mm sieve. The remaining material was analyzed for a range of physical and chemical soil parameters.

The bulk density of soil was determined by the core method. The particle density of the soil sample was measured of the oven-dry mass per unit volume of soil solids only. To determine the particle density by Pycnometer is the most common method. The clay fraction, silt fraction and the sand fraction were determined using the pipette method as described by Piper (1966). Water holding capacity was determined as per the method is given by Piper (1950). The infiltration rate was determined in the field by using the double ring infiltrometer. Soil pH was determined by glass electrode pH meter in 1:2.5 soil-water suspensions given by piper (1967). The electrical conductivity of the supernatant liquid was estimated by conductivity meter as given by Black (1965). Soil Organic carbon was determined by Walkley and Black's rapid titration method (1934).

The available nitrogen in the soil was estimated by using alkaline $KMnO_4$ method as given by Subbiah and Asija (1965). The available Phosphorous in soil was estimated by using 0.5M $NaHCO_3$ as determined by Olsen's *et al* (1954). Available soil potassium was estimated by Flame Photometer after extraction by 1 N ammonium acetate method of Hanway and Heidel, 1952.

Cation exchange capacity was measured by leaching with neutral 1 N ammonium acetate (1N NH_4OAc).method given by Chapman, 1965. The micronutrients Zn, Cu, Mn, and Fe were extracted by using 0.005M DTPA, 0.01M calcium chloride dehydrate and 0.1M triethanol amine buffered at 7.3 pH (Lindsay and Novell, 1978).

Results and Discussion

Bulk density and Particle density of soil

Table.1 represented bulk density ranging from 1.32 to 1.45 Mg m^{-3} and particle density from 2.35 to 2.39 Mg m^{-3} across treatments; long-term fertilizer management did not produce a significant alteration in either density. Among treatments, the lowest bulk density occurred with the FYM-inclusive mix (YT 6/2.5 t ha^{-1} + FYM, designated as T5), followed by the T3 (YT 5/2 t ha^{-1}), T2 (GRD), and T4 (YT 6/2.5 t ha^{-1}) treatments, with the highest density observed in the control (T1). Incorporation of FYM with inorganic fertilizers reduced bulk density, consistent with findings reported by Hati *et al*. (2007), Bhattacharya *et al*. (2007), and Hati *et al*. (2006). In contrast, particle density remained essentially unchanged by organic or inorganic amendments, reflecting its status as an intrinsic soil property; Ram *et al*. (2010) and Schjonning *et al*. (1994) reported similar stability in particle density under comparable treatments.

Table.1 Effects of long-term fertilizer management on soil bulk density and particle density after wheat harvest

Treatments	Treatments details	Bulk Density (Mgm^{-3})	Particle density (Mgm^{-3})
T1	Control	1.45	2.37
T2	GRD	1.39	2.39
T3	YT5t/2ha^{-1}	1.38	2.35
T4	YT6t/2.5ha^{-1}	1.40	2.36
T5	YT6t/2.5 ha^{-1}+FYM	1.32	2.39
	CD(p=0.05)	NS	NS

*GRD for rice (100:60:40), for wheat (80:50:30)

Porosity and infiltration rate

Soil porosity was assessed in relation to long-term fertilizer and organic-matter management, with porosity ranging from 38.57% to 44.75% across treatments. Treatments incorporating organic amendments, particularly farmyard manure (FYM) alongside inorganic nutrients, produced the highest porosity values, followed by other organic-inorganic combinations; the control exhibited the lowest porosity. Overall, total porosity increased with the inclusion of organic matter and varying fertilizer regimes, an effect attributable to higher organic matter content, improved soil aggregation, and shifts in pore-size distribution. Similar patterns have been reported in previous studies (Hati *et al*., 2007; Reddy *et al*., 2017).

Table.2 shows that infiltration rates ranging from 0.38 to 0.67 mm h^{-1}. The highest infiltration was observed in the FYM-inclusive treatment (T5: 6/2.5 t ha^{-1} + FYM), significantly exceeding all other treatments, while the control (T1) showed the lowest rate. Treatments with inorganic-plus-organic combinations such as T4 (6/2.5 t ha^{-1}) and T3 (5/2 t ha^{-1}) were statistically comparable to T2 (GRD). The superior infiltration in T5 is attributed to reduced bulk density and enhanced soil porosity following FYM–inorganic fertilizer co-application. The tendency for infiltration to rise with combined organic and inorganic inputs aligns with findings reported by Sarkar *et al*. (2003) and Bhattacharya *et al*. (2007).

Table.2 Effects of long-term fertilizer management on soil porosity and infiltration rate measured after wheat harvest

Treatments	Treatments details	Porosity (%)	Infiltration Rate (mm/hr)
T1	Control	38.57	0.38
T2	GRD*	41.5	0.54
T3	YT5t/2 ha-^{1}	41.22	0.55
T4	YT6t/2.5 ha-^{1}	40.55	0.57
T5	YT6t/2.5ha-^{1}+ FYM	44.75	0.67
	CD(p=0.05)	4.46	0.06

*GRD for rice (100:60:40), for wheat (80:50:30)

Water holding capacity

Table.3 shows that water holding capacity (WHC) was significantly influenced by higher fertilizer rates and exceeded the control. WHC varied from 34.98% to 41.92% during the kharif season and from 34.88% to 41.57% during the rabi season. The greatest WHC was observed with the FYM-inclusive treatment (T5: 6/2.5 t ha^{-1} + FYM), followed by T4 (6 t/2.5 ha^{-1}), T3 (5 t/2 ha^{-1}), and T2 (GRD), with all these surpassing the control at pre-rice and post-wheat sampling. Incorporating FYM before the preceding crop further enhanced soil WHC. The highest WHC values were achieved under balanced fertilizer applications and integrated nutrient management practices. Soils with organic inputs generally exhibited higher WHC than control or fallow soils, in line with findings reported by Bandyopadhyay *et al*. (2011). Similar trends were reported by Rasool *et al*. (2008).

Table.3 Effects of long-term fertilizer management on water holding capacity measured before rice and after wheat harvest

Treatments	Treatments details	Water holding capacity (%)	
		Before Rice	After Wheat
T1	Control	34.98	**34.88**
T2	GRD*	39.73	**38.53**
T3	YT5t/2ha^{-1}	39.86	**39.73**
T4	YT6t/2.5ha^{-1}	40.91	**39.98**
T5	YT6t/2.5ha^{-1}+FYM	41.92	**41.57**
	CD(p=0.05)	**4.27**	**4.61**

Soil Reaction and Electrical Conductivity

Table.4 indicates that long-term fertilizer-management practices did not produce significant changes in soil pH or electrical conductivity (EC). Across treatments, soil pH ranged from 7.73 to 8.03, while EC varied from 0.13 to 0.18 dS m^{-1}. The highest pH was recorded under the control and imbalanced fertilizer doses, whereas the lowest pH appeared with balanced fertilizer inputs including FYM. EC was greatest with the FYM-assisted treatment (T5: 6/2.5 t ha^{-1} + FYM) and lowest in the control (T1). Overall, the differences in pH and EC among treatments were minor and statistically non-significant. These observations align with findings reported by Parvathi *et al*. (2013), Verma *et al*. (2012), Pothare *et al*. (2007), and Dwivedi *et al*. (2007), who reported little or no consistent influence of long-term fertilization on soil pH and EC under varied management regimes.

Cation Exchange Capacity

Table.5 shows soil Cation Exchange Capacity (CEC) ranged from 38.88 to 41.95 cmol(+) kg^{-1}, with differences among treatments that were not statistically significant. The highest CEC occurred with the FYM-inclusive treatment (T5: 6/2.5 t ha^{-1} + FYM), followed by T4 (6 t/2.5 ha^{-1}), T3 (5 t/2 ha^{-1}), while the control (T1) registered the lowest CEC. Higher CEC with FYM is attributed to increased organic matter, which enhances exchange sites. The observed rise in CEC under the combined organic–inorganic nutrient regimens aligns with findings from Bellakki *et al*. (1998) and is supported by Brar *et al*. (2015), Chouhan *et al*. (2017), Sharma *et al*. (2014), and Rezig *et al*. (2012), who reported elevated CEC with organic amendments or integrated nutrient management.

Table.4 Effects of long-term fertilizer management on soil pH and electrical conductivity (EC) measured before rice transplanting and after wheat harvest.

Treatments	Treatments details	pH		EC	
		Before rice	After wheat	Before rice	After wheat
T1	Control	7.96	7.87	0.13	**0.14**
T2	GRD	7.92	7.90	0.16	**0.15**
T3	YT5/2tha^{-1}	8.03	7.90	0.17	**0.15**
T4	YT6/2.5tha^{-1}	7.98	7.95	0.17	**0.17**
T5	YT6/2.5tha^{-1}+FYM	7.82	7.73	0.18	**0.17**
	CD(p=0.05)	NS	NS	NS	NS

Table.5 Effects of long-term fertilizer management on soil Cation Exchange Capacity (CEC) measured after wheat harvest

Treatments	Treatments details	CEC(cmol (+)/kg of soil)
T1	Control	38.88
T2	GRD	39.38
T3	YT5/2tha^{-1}	40.70
T4	YT6/2.5tha^{-1}	40.60
T5	YT6/2.5tha^{-1} +FYM	41.95
	CD(p= 0.05)	4.04

Table.6 Status of soil organic carbon (SOC %) under long-term fertilizer management measured before rice transplantation and after wheat harvest

Treatments	Treatments details	Organic Carbon(%)	
		Before Rice	After Wheat
T1	Control	0.28	**0.27**
T2	GRD*	0.48	**0.49**
T3	YT5/2tha^{-1}	0.49	**0.51**
T4	YT6/2.5tha^{-1}	0.50	**0.53**
T5	YT6/2.5tha^{-1}+FYM	0.60	**0.62**
	CD(p=0.05)	**0.05**	**0.05**

Table.7 Available N, P and K status of soil in relation to long term fertilizer management practices at before rice and after harvesting of wheat

Treatments	Treatments details	Before Rice			After Wheat		
		Av. N	Av. P	Av. K	Av. N	Av. P	Av. K
T1	Control	171.43	6.32	436.61	169.12	6.12	**427.67**
T2	GRD	224.52	24.84	483.45	223.95	24.23	**488.21**
T3	YT5/2tha^{-1}	227.78	19.05	500.83	225.33	19.53	**504.66**
T4	YT6/2.5tha^{-1}	229.22	20.49	512.37	229.62	21.01	**518.80**
T5	YT6/2.5tha^{-1}+FYM	238.84	23.48	545.46	238.71	23.91	**550.94**
	CD(p=0.05)	**27.09**	**2.16**	**54.73**	**24.40**	**2.11**	**57.40**

Table.8 Changes in average micronutrients of soil in relation to long term fertilizer management practices at before rice and after harvesting of wheat

Treatments details		Mn	Fe	Cu	Zn	Mn	Fe	Cu	Zn
T1	Control	6.82	7.42	2.76	2.42	6.79	7.41	2.74	**2.41**
T2	GRD	6.66	7.35	2.70	2.39	6.61	7.34	2.70	**2.37**
T3	YT5/2tha^{-1}	6.67	7.34	2.71	2.40	6.59	7.35	2.71	**2.38**
T4	YT6/2.5tha^{-1}	6.67	7.34	2.70	2.40	6.59	7.36	2.71	**2.38**
T5	YT6/2.5tha^{-1}+FYM	7.07	7.52	2.82	2.46	7.04	7.51	2.81	**2.40**
	CD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Soil Organic Carbon

Table.6 shows that soil organic carbon (SOC) increased significantly with the application of inorganic fertilizer alone or in combination with farmyard manure (FYM). No seasonal differences in SOC were detected. Across treatments, SOC ranged from 0.28% to 0.60% before rice transplanting and from 0.27% to 0.62% after wheat harvest. The highest SOC was observed with the FYM-inclusive treatment (T5: 6/2.5 t ha^{-1} + FYM), while the control (T1) recorded the lowest. Treatments combining inorganic fertilizer with organic amendments (e.g., T4, T3, and T2) were statistically comparable. Increases in SOC under long-term FYM fertilization are attributed to direct input of organic matter, improved root growth, and greater residue return. Inorganic fertilizer alone also raised SOC relative to the unfertilized control, likely due to enhanced biomass inputs from crops. The observed SOC gains with balanced fertilizer-plus-organic-manure regimens align with findings by Hati *et al*. (2007) and are corroborated by Kaur *et al*. (2005), Yadav *et al*. (2017), and Datta *et al*. (2018).

Macronutrients

Table.7 shows the status of available macronutrients (N, P, K) in soil, expressed as kg ha−1, with no pronounced difference between the pre-rice and post-wheat sampling, though treatment effects varied. The FYM-inclusive regime (T5: 6/2.5 t ha^{-1} + FYM) yielded the highest macronutrient availability, followed by T4 (6 t/2.5 ha^{-1}), T3 (5 t/2 ha^{-1}), and T2 (GRD); all were significantly higher than the control (T1). The observed increases across treatments reflect adequate macronutrient inputs and consistent nutrient supply, which influenced soil nutrient pools for both crops. Continuous application of inorganic fertilizers with FYM enhanced soil macronutrient content relative to unfertilized controls. The findings align with prior reports: long-term chemical fertilizer use with manure elevates N, and phosphorus availability increases with combined phosphorus fertilization and FYM; similar patterns have been reported by Kundu (2016), Kachot *et al*. (2001), Yeshpal *et al*. (2017), Mishra *et al*. (2008), Thakur *et al*. (2011), Sharma *et al*. (2007), Sharma *et al*. (2014), Tadesse *et al*. (2013), Meena *et al*. (2019), Munehwar *et al*. (2015), Singh *et al*. (2015).

Micronutrients

Table.8 presents micronutrient (Fe, Mn, Cu, Zn) status in ppm, showing higher micronutrient levels before rice transplanting than after wheat harvest. Among treatments, micronutrient concentrations were highest under the FYM-inclusive regime (T5: 6/2.5 t ha^{-1} + FYM) with the rice/wheat yield targets, followed by the control (T1); other treatments did not differ significantly. Overall, treatment effects on soil micronutrients were not pronounced, likely because no micronutrient inputs were applied given apparent sufficiency in the experimental fields. Consequently, soil micronutrient status remained largely unchanged between pre-rice and post-wheat sampling under the long-term fertilizer and cropping-system regime. Trends reported here are consistent with Swarup *et al*. (2000), Gowda *et al*. (2017), and Choudhary *et al*. (2018).

In Conclusion, this study demonstrates that long-term integrated management of organic and inorganic nutrients markedly influences soil physical, chemical, and biological properties, as well as crop productivity in acid soils. Incorporating organic amendments such as farmyard manure (FYM) with inorganic fertilizers consistently improved soil quality indicators, including soil pH stabilization, increased soil organic carbon, higher cation exchange capacity, and enhanced porosity and water holding capacity, which in turn supported higher or more stable yields under rice–wheat rotations. Biochar and crop residues varied in their effects depending on residue type, carbon content, and application rate, but generally contributed to soil structure, nutrient dynamics, and resilience against acidity-related constraints. Across sites (Palampur and Ranchi), residue- and FYM-based strategies showed potential to mitigate acidity effects, improve nutrient availability (N, P, K, and micronutrients), and reduce reliance on mineral NPK inputs when integrated thoughtfully. However, feasibility concerns remain for large-scale FYM application due to resource constraints, underlining the need for locally appropriate, sustainable management options that leverage available organic resources and residue management. The findings support a move toward integrated nutrient management (INM) that balances crop yield goals with soil health and environmental sustainability, particularly in intensely cropped, acidic soils common in parts of India. Further work should refine optimal residue types, carbon-equivalent dosing, and site-specific INM frameworks, and assess long-term environmental and economic implications.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author contributions

Priyanka Sahu: formal analysis , methodology , writing–original draft; Lalit Kumar Srivastava: conceptualization, data curation, formal analysis, methodology, writing – original draft. Vinay Bachkaiya: formal analysis, writing – original draft; Anusuiya Panda: formal analysis , data curation, methodology, writing – original draft.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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