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RESEARCH ARTICLE

Microbial consortium mediated recycling of rice residue in rice-wheat cropping system

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Abstract

Crop residue management plays an important role in improving the physio-chemical properties of soil, which are essential for sustainable crop production, particularly in rice-based cropping systems. This study investigated the effects of various rice residue management strategies, specifically the incorporation of paddy straw at 5 t ha^{-1} combined with different levels of recommended NPK doses and the application of a decomposer, on soil physico-chemical properties and the availability of macro- and micronutrients across different soil depths. The results indicated that incorporating residues significantly reduced bulk density while increasing particle density, organic carbon content and the availability of nitrogen, phosphorus and potassium at different soil depths. The most notable improvements were recorded in treatments that combined straw incorporation with 125 % of the recommended nitrogen dose and hyper lignocellulolytic fungal consortium (*Aspergillus* spp., *Phlebia radiata* and *Trichoderma viride*), applied as 10 L of inoculum mixed with 200 L of water per acre of straw, with a viable count of 10^7 cfu/mL. However, these treatments also led to a decrease in soil pH (7.66), likely due to the formation of organic acids during the decomposition process. EC levels rose as a result of mineralization and the release of soluble salts. Overall, the study highlights that integrated residue management through paddy straw incorporation alongside balanced fertilization and microbial decomposer application enhances decomposition for improved soil physical structure and nutrient availability, ultimately supporting soil health and sustainable productivity in rice-wheat cropping systems.

Keywords: Crop residue management; decomposer consortium; organic carbon; paddy straw incorporation; soil fertility; sustainable rice-wheat system

Introduction

The rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) cropping system, which dominates large regions across South Asia, is known for its high nutrient demand and intensive resource use. This system also generates substantial amounts of crop residues, approximately 34 % from rice and 22 % from wheat, much of which is often left unmanaged or burned *in situ*, leading to serious environmental concerns (1).

Globally, agricultural biomass production is estimated at around 140 billion metric tons annually, with crops such as rice, wheat, maize (stover, husk, skins), millet (stover) and sugarcane (tops, bagasse, molasses) being the major contributors. Countries like India, Bangladesh, Indonesia and Myanmar collectively produce around 500 million tons of crop residues per year, with India alone accounting for approximately 141 million tons of surplus residues. Of this, an alarming 92 million tons are burned annually, contributing significantly to air pollution and greenhouse gas (GHG) emissions (2). More recent estimates highlight that in 2019, approximately 458 million tons of crop residues were burned globally, resulting in the emission of 1238 kilotons of methane (CH_4) and 32 kilotons of nitrous oxide (N_2O) potent greenhouse gases that significantly exacerbate climate change (3). In the Indian context, crop residue burning remains prevalent, with an estimated 87 million tons burned annually, surpassing agricultural waste production in other Asian countries (2).

According to the Intergovernmental Panel on Climate Change (IPCC), over 25 % of global crop residues are burned in the field, leading to extensive emissions of particulate matter, carbon monoxide and volatile organic compounds, thereby aggravating regional and global air quality problems (IPCC, 2019). Despite numerous mitigation policies and awareness campaigns, the practice continues largely unabated in major agricultural belts.

Crop residues are important sources of plant nutrients and play a vital role in sustaining ecological balance in agriculture. However, burning them leads to severe environmental impacts, raising CO_2 emissions by 70 %, carbon monoxide by 7 % and nitrogen dioxide by 2.1 %. According to a 2010 report by the Department of Soils, Ludhiana, burning rice straw results in major nutrient losses up to 80 % nitrogen, 25 % phosphorus, 21% potassium and 4-60% sulfur. In conservation agriculture (CA), *in- situ* crop residue management is key to realizing its full benefits (4). Though residue decomposition can sometimes affect crop growth, an integrated soil management approach including decomposition, erosion control, nutrient recycling, weed and pest control and conservation tillage is essential for attaining high productivity (5).

Effective annual nutrient cycling is essential for maintaining productive agricultural systems and enhancing nutrient use efficiency (6). Crop residues that are high in carbon serve as key substrates for soil microorganisms, driving biological nutrient transformations. Building soil organic matter through the combined application of crop residues and appropriate nitrogen fertilization supports soil health and long-term sustainability (7). Incorporating rice straw into the soil enhances soil quality by improving nutrient recycling, increasing soil organic carbon stocks and contributing significantly to soil fertility and nutrient availability, especially due to its high potassium content and abundant availability as an organic resource (8). Rice straw contains significant quantities of nitrogen, phosphorus, potassium, sulfur and silicon, all of which contribute to soil nutrient enrichment (9). Studies in Vietnam (10) have shown that straw incorporation can enhance soil pH, organic carbon and nutrient levels. However, straw addition may also lead to temporary nitrogen immobilization, which reduces its immediate availability and can affect crop productivity, as observed in Vietnam's alluvial soils (11).

Residue application significantly improves the physical, chemical and biological properties of soil, especially when applied as mulch. In addition to supplying secondary and micronutrients, mulching with crop residues helps retain soil moisture, boosts soil organic carbon levels and enhances fertility, ultimately leading to better yields in rice-wheat systems. Nonetheless, post-harvest practices often involve burning around 80 % of rice and 50 % of wheat residues, despite their valuable nutrient content N (5-8 kg), P (0.7-1.2 kg) and K (12-17 kg) (12). Effective management of these residues can contribute to healthier soils and more stable crop production.

Crop residue burning significantly contributes to GHGs and air pollution, causing serious risks to human health through respiratory diseases, cardiovascular issues and increased hospitalizations (13). The intense heat produced during burning, which can reach over 400 °C, kills helpful microorganisms in the rhizosphere, such as nitrogen-fixing bacteria, phosphate-solubilizing microbes and arbuscular mycorrhizal fungi (14). This microbial loss disrupts nutrient cycling, reduces soil organic carbon and reduces soil structure and fertility (15). Hence, adopting sustainable residue management practices, including microbial decomposition, mulching and conservation tillage, is important for maintaining soil health and environmental sustainability.

Therefore, this study aims to evaluate the effects of different rice residue management practices on soil organic carbon dynamics and macro- and micronutrient status within the rice-wheat cropping system. It is hypothesized that increased residue incorporation will enhance organic carbon accumulation and nutrient concentrations, particularly within the coarse and fine particulate organic matter fractions of the soil, thereby contributing to improved soil health and sustainability of the cropping system.

Materials and Methods

Experimental site

A field experiment was conducted at Student Instructional Farm, Acharya Narendra Deva University of Agriculture and Technology, Narendra Nagar (Kumarganj), Ayodhya, Uttar Pradesh, during the Rabi (winter) seasons of 2019-20 and 2020-21 and the study is currently ongoing. The objective of the experiment was evaluating the effects of different rice straw management practices in a rice-wheat cropping system, incorporating varying levels of nitrogen (applied through urea) along with the recommended doses of phosphorus and potassium.

The experimental site was located in the subtropical region of the Indo-Gangetic Plains, characterized by alluvial soils. Geographically, the site lies between 24.4° and 26.5° N latitude and 82.12° and 83.98° E longitude, at an elevation of approximately 113 m above mean sea level. The region experiences a sub-humid subtropical climate, with hot summers and relatively cool winters. The area receives an average annual rainfall of approximately 1200 mm, with nearly 90 % of the total precipitation occurring during the southwest monsoon (Kharif season) between July and September. The mean annual potential evapotranspiration (PET) is around 1450 mm.

Soil Characteristics

The experimental soil was classified as Inceptisol with a sandy loam texture. The initial physicochemical properties of the soil at different depths are presented in Table 2. In the surface layer (0-15 cm), the soil had a pH of 8.40, EC of 0.34 dS m^{-1} and organic carbon content of 0.38 %. The bulk density and particle density at the same depth were 1.40 Mg m^{-3} and 2.41 Mg m^{-3} respectively. The available nutrient levels in the surface layer were 159.7 kg ha^{-1} nitrogen, 13.18 kg ha^{-1} phosphorus and 232.16 kg ha^{-1} potassium. Among micronutrients, the available Cu, Zn, Fe and Mn were 0.41, 1.12, 5.36 and 5.39 mg kg^{-1} respectively.

A gradual decline in organic carbon and available nutrient concentrations was observed with increasing soil depth (15-30 and 30-45 cm), indicating higher fertility status in the surface horizon. The remaining detailed values of physicochemical and nutrient characteristics at all depths are provided in Table 2.

Experimental Design and Treatments

The experiment was conducted in a randomized block design (RBD) with 7 treatments and 4 replications. Treatments were designed to assess the combined effects of rice residue management and nitrogen levels on soil fertility and crop performance under the rice-wheat cropping system (Table 1).

Table 1. Treatment details

Treatment	Description
T_1	Recommended NPK @ 120:60:40 kg/ha + No Paddy straw incorporation.
T_2	Recommended dose NPK @ 120:60:40 kg/ha + Paddy straw @ 5 t/ha incorporation.
T_3	Recommended NPK @ 120:60:40 kg/ha + Paddy straw @ 5 t/ha incorporation + Top dressing of Nitrogen @ 20 kg/ha after incorporation of Paddy straw.
T_4	Recommended dose NPK @ 120:60:40 kg/ha + Paddy straw @5 t/ha incorporation + bioaugmentation with a hyper-lignocellulolytic fungal consortium (*Aspergillus spp.*, *Phlebia radiata*, *Trichoderma viride*) applied as (10^7 cfu/mL) mixed in 200 L water per acre.
T_5	125% of RD N +60 P + 40 K, kg/ha +Paddy straw @ 5 t/ha incorporation.
T_6	125% of RDN +60 P + 40 K, kg/ha + Paddy straw @ 5 t/ha incorporation+ Top dressing of Nitrogen @ 20 kg/ha after incorporation of Paddy straw.
T_7	125% of RDN +60 P + 40 K, kg/ha +Paddy straw @ 5 t/ha incorporation+ Top dressing of Nitrogen @ 20 kg/ha after incorporation of Paddy straw + bioaugmentation with a hyper-lignocellulolytic fungal consortium (*Aspergillus spp.*, *Phlebia radiata*, *Trichoderma viride*) applied as (10^7 cfu/mL) mixed in 200 L water per acre.

Table 2. Initial value of physio chemical properties of soil of experimental site

S. N.	Particular	Experimental value depth (cm)		
		0-15	15-30	30-45
1	Bulk Density	1.40	1.41	1.44
2	Particle density	2.41	2.46	2.52
3	pH	8.40	8.26	7.98
4	O. C	0.38	00.35	0.32
5	E.C (dsm^{-1})	0.34	0.32	0.29
6	Available N (kg ha^{-1})	159.7	157.3	146.3
7	Available P (kg ha^{-1})	13.18	12.8	11.09
8	Available K (kg ha^{-1})	232.16	216.02	202.43
9	Copper (mg $kg^{-1)}$	0.41	0.47	0.49
10	Zink (mg kg^{-1})	1.12	1.01	0.96
11	Iron(mg kg^{-1})	5.36	5.28	4.10
12	Manganese(mg kg^{-1})	5.39	5.03	4.86

These treatments were designed to evaluate improvements in nutrient cycling, soil organic matter buildup and crop productivity under integrated residue and nutrient management strategies.

Soil Sampling and Laboratory Analysis

Soil samples were collected randomly from each experimental plot at varying depths following the wheat harvest, 2 years after the initiation of the study. These freshly collected samples were placed in clean, labelled polyethylene bags and transported to the laboratory under cool and dry conditions to preserve their original characteristics. In the laboratory, the samples were analyzed for various physico-chemical properties, including pH, organic carbon and available macro and micronutrients such as nitrogen, phosphorus, potassium, zinc, copper, manganese and iron, using standard analytical protocols.

Soil pH and electrical conductivity (EC) were analyzed using a 1:2.5 soil-to-water suspension, following the standard procedure (16). Organic carbon content was estimated using the rapid titration method (17). Available nitrogen was observed using the alkaline $KMnO_4$ method as per the standard protocol (18). Available phosphorus was determined using 0.5 M sodium bicarbonate ($NaHCO_3$) at pH 8.5, following the standard method (19). Micronutrients such as Zn, Cu, Mn and Fe were extracted and analyzed using the DTPA (Diethylene Triamine Penta Acetic Acid) method (20).

Statistical analyses

The collected data were applied to statistical analysis using the randomized block design (RBD) framework. Treatment means were compared using the Critical Difference (CD) test at the 5% level of significance ($p \le 0.05$), following the procedure proposed by (21). Statistical analyses were performed to assess treatment effects on soil fertility parameters and crop productivity.

Results and Discussion

Residue management practices influence various physico-chemical properties of soil, including soil moisture content, temperature, soil density, porosity, hydraulic conductivity and the availability of nutrients. Data related to bulk density and soil particle density under different treatment conditions are presented in Table 2. The results indicated that higher amounts of rice residues left on the soil surface help reduce evaporation rates and prolong the duration of the first stage of soil drying. Consequently, soils covered with crop residues generally retain more moisture compared to bare soils, except during prolonged drought periods.

Bulk density of soil

The data presented in Table 2 indicates that soil bulk density significantly decreased with the incorporation of paddy straw across all examined soil depths. The highest bulk density at surface soil (1.37 Mg m^{-3}) was recorded in treatment T_3, which involved paddy straw incorporation at 5 t ha^{-1} along with the recommended NPK dose (120:60:40 kg ha^{-1}) and top dressing of nitrogen at 20 kg ha^{-1}. This was followed in descending order by T_2, T_6, T_5, T_7 and T_4. At 15-30 cm soil depth, treatment T_2 (paddy straw incorporation 5 t ha^{-1} with recommended NPK) recorded the highest bulk density, followed by T_1, T_7, T_6, T_4, T_3 and T_5. In the deeper 30-45 cm soil layer, the maximum bulk density was recorded under treatment T_1, followed by T_2, T_3, T_6, T_5 and T_4. A decreasing trend in BD with increasing addition of organic residues and nutrient application was observed at all depths, suggesting improved soil physical properties with residue management. (Table 3)

The reduction in bulk density observed with paddy straw incorporation can be attributed to increased organic matter content, which enhances soil porosity and promotes the formation of stable soil aggregates. Residue addition facilitates microbial activity through decomposition of crop residue and improves soil structure through the decomposition of crop residue, thereby reducing compaction and facilitating root proliferation (22). More recent research reinforces these results. For instance, a significant reduction in soil bulk density with residue retention under zero tillage in a rice-wheat system was observed in Punjab (23). Similarly, residue incorporation improved soil aggregation and decreased bulk density across soil depths (24). The positive effect of crop residue on physical soil quality is also confirmed in another study (25), which emphasized that organic matter inputs through residue retention enhance soil structure and reduce compaction.

Particle density of soil

The data presented in Table 4 indicated that soil particle density significantly increased in response to various rice residue management treatments. Among the treatments, the highest particle density (2.65 Mg m^{-3}) was recorded under the incorporation of paddy straw at 5 t ha^{-1} combined with the recommended dose of NPK (120:60:40 kg ha^{-1}) and the application of a microbial decomposer (T_4). This was followed, in descending order, by treatments T_7, T_5, T_1, T_6, T_2 and T_3 at 0-15 cm soil depth. A similar trend was observed at 15-30 cm and 30-45 cm depths. The increase in particle density under treatment T_4 can be attributed to the synergistic effect of rice straw incorporation and decomposer application, which enhanced the decomposition process, improved soil aggregation and subsequently increased particle density at all depths. The decomposer likely accelerated the mineralization of organic residues, facilitating tighter packing of soil particles and contributing to a higher mineral content, thereby enhancing overall particle density.

These findings align with earlier studies reporting the beneficial effects of residue incorporation on soil physical properties such as bulk density and porosity. Research has demonstrated that the retention and incorporation of rice straw improve soil structure, aeration and water-holding capacity, thus creating a more conducive environment for crop growth (26). Moreover, long-term incorporation of crop residues in rice-based systems has been associated with improved soil quality and greater sustainability of cropping systems in the Indo-Gangetic Plains (27).

Soil pH

Soil pH significantly decreased under rice residue management practices. The lowest pH value (7.66) was recorded in treatment involving the addition of paddy straw at 5 t ha^{-1} combined with 125 % of the recommended nitrogen dose, 60 kg ha^{-1} of phosphorus, 40 kg ha^{-1} of potassium, a top dressing of nitrogen 20 kg ha^{-1} after straw incorporation and application of a decomposer (T_7). This was followed in order by treatments T_5, T_3, T_6, T2, T_1 and T_4 at the 0-15 cm soil depth. A similar trend was observed at 15-30 cm and 30-45 cm depths, with pH values gradually increasing with soil depth.

Several studies have reported increase in soil pH regardless of whether crop residues were burnt, incorporated, or mulched. The rise in pH following residue burning is generally attributed to ash deposition, which is rich in carbonates of alkali and alkaline earth metals. Ash also contains variable amounts of silica, heavy metals, sesquioxides, phosphates and small quantities of organic and inorganic nitrogen. Conversely, the observed decline in pH in residue-incorporated treatments may result from the production of organic acids during the decomposition of residues, especially in the presence of microbial decomposers. Similar findings have been reported in earlier studies (28, 29).

Table 3. Depth wise (cm) bulk density and particle density (Mg m^{-3}) of soil after harvest (pooled data of 2 years)

Treatment	Depth wise (cm)					
	Bulk density (Mg m^{-3})			Particle density (Mg m^{-3})		
	0-15	15-30	30-45	0-15	15-30	30-45
T_1	1.32	1.40	1.45	2.62	2.63	2.66
T_2	1.36	1.41	1.47	2.57	2.64	2.68
T_3	1.37	1.34	1.36	2.50	2.54	2.62
T_4	1.33	1.37	1.42	2.65	2.68	2.71
T_5	1.34	1.34	1.43	2.63	2.65	2.68
T_6	1.35	1.38	1.44	2.61	2.67	2.69
T_7	1.34	1.40	1.49	2.64	2.68	2.71
SEm ±	0.04	0.04	0.04	0.08	0.07	0.08
CD (P=0.05)	0.11	0.11	0.12	0.23	0.22	0.23

Table 4. Depth wise (cm) pH, electrical conductivity and organic carbon (%) of soil after harvest (Pooled data of 2 years)

Treatment	Depth wise (cm)								
	pH			E C (dSm^{-1})			Organic carbon (%)		
	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
T_1	8.32	8.40	8.20	0.28	0.26	0.24	0.40	0.34	0.33
T_2	8.02	8.16	8.24	0.32	0.28	0.28	0.54	0.44	0.43
T_3	7.89	7.67	7.54	0.34	0.31	0.29	0.56	0.53	0.46
T_4	8.40	8.35	8.24	0.36	0.33	0.31	0.59	0.55	0.48
T_5	7.88	8.04	8.07	0.35	0.32	0.29	0.62	0.57	0.54
T_6	7.91	8.07	8.19	0.33	0.31	0.28	0.64	0.58	0.56
T_7	7.66	7.98	8.11	0.36	0.34	0.33	0.72	0.68	0.64
SEm ±	0.24	0.25	0.25	0.01	0.01	0.00	0.02	0.02	0.01
CD(P=0.05)	0.71	0.72	0.72	0.02	0.02	0.02	0.08	0.06	0.05

Electrical conductivity of soil

The data of electrical conductivity (EC) presented in Table 4, revealed that the highest EC value (0.36 dS m^{-1}) was recorded in the incorporation of paddy straw at 5 t ha^{-1} along with the recommended dose of NPK (120:60:40 kg ha^{-1}) and decomposer application (T_4). This was followed by treatment involving incorporation of paddy straw at 5 t ha^{-1} with 125 % of the recommended nitrogen dose, 60 kg ha^{-1} phosphorus, 40 kg ha^{-1} potassium, a top dressing of 20 kg ha^{-1} nitrogen after straw incorporation and decomposer application (T_7), followed by treatments T_5, T_3, T_6, T_2 and T_1 at 0-15 cm soil depth. Similar patterns were observed at 15-30 cm and 30-45 cm depths, with minor fluctuations in EC values.

The increase in EC under these treatments can be attributed to mineralization of organic matter and subsequent release of soluble salts during the decomposition of paddy straw, especially in presence of microbial decomposers. Similar findings, indicated that residue incorporation enhances EC by increasing ionic concentrations and nutrient mobility in the soil environment (30, 31).

Soil organic carbon

The data presented in Table 4 revealed that soil organic carbon content significantly increased with the incorporation of rice residues. The highest organic carbon concentration (0.72 % OC) was observed under the treatment involving the incorporation of paddy straw at 5 t ha^{-1}, along with 125 % of the recommended nitrogen dose, 60 kg ha^{-1} phosphorus, 40 kg ha^{-1} potassium, top dressing of nitrogen at 20 kg ha^{-1} following straw incorporation and application of a microbial decomposer (T_7). This was followed in descending order by treatments T_6, T_5, T_4, T_3, T_2 and T_1 at 0-15 cm soil depth. A comparable trend was noted at 15-30 cm and 30-45 cm soil depths. Crop residue incorporation increase OC due to fresh carbon inputs, improved aggregation and stabilization of particulate organic matter. These findings are consistent with the previous results (32- 34), which also highlighted the positive impact of crop residue incorporation on soil organic carbon enrichment.

Depth wise (cm) available N, P and K status after harvest

Soil available nitrogen

As present in Table 5, the highest soil available nitrogen (165.54 kg ha^{-1}) was recorded under the treatment involving the incorporation of paddy straw at 5 t ha^{-1}, along with 125 % of the recommended nitrogen dose, 60 kg ha^{-1} phosphorus, 40 kg ha^{-1} potassium, top dressing of nitrogen at 20 kg ha^{-1} after straw incorporation and application of a microbial decomposer (T_7). This was followed by treatments T_6, T_5, T_4, T_2, T_3 and T_1 in descending order at the 0-15 cm soil depth. A similar trend was observed at the 15-30 cm and 30-45 cm depths, with nitrogen content decreasing with depth.

The increase in available nitrogen can be attributed to the enhanced decomposition of incorporated residues, which not only improved organic carbon content but also increased microbial activity introduced through the decomposer. This microbial proliferation facilitated the mineralization of organically bound nitrogen, thereby increasing the concentration of plant-available nitrogen after harvest. These observations are supported by earlier findings reported by (35, 36).

Soil available phosphorus

The incorporation of crop residues also significantly influenced the available phosphorus content in the soil, as shown in Table 5. The highest available phosphorus (20.82 kg ha^{-1}) was recorded under treatment T_7, which included the incorporation of paddy straw at 5 t ha^{-1}, 125 % of the recommended nitrogen dose, 60 kg ha^{-1} phosphorus, 40 kg ha^{-1} potassium, nitrogen top dressing at 20 kg ha^{-1} and decomposer application. This was followed by treatments T_6, T_5, T_4, T_3, T_2 and T_1 in that order at the 0-15 cm soil depth. Similar patterns were observed at 15-30 cm (with a maximum of 19.56 kg ha^{-1}) and 30-45 cm depths (with a maximum of 18.03 kg ha^{-1}), showing a decline in phosphorus levels with increasing soil depth.

The enhanced phosphorus availability may be attributed to the combined effect of nitrogen fertilization and microbial decomposer activity, which facilitated the mineralization of crop residues. Organic acids released during decomposition likely contributed to the solubilization of both native and applied phosphorus, increasing its availability in the soil. These findings are consistent with the results reported by (37- 39).

Soil available potassium

The data of soil available potassium is presented in Table 5. It indicated that the highest soil available potassium (254.63 kg ha^{-1}) was recorded under incorporation of paddy straw @ 5 t ha^{-1} with recommended dose NPK @ 120:60:40 kgha^{-1} and application of decomposer (T_4) followed by T_7, T_3,T_5,T_2,$T_6$and T_1at 0-15 cm depth and more or less similar strands were observed at depth of 15-30 cm and 30-45 cm depth of soil in decreasing order according to depth. The increasing in the status of potassium is due to application of residue secreted organic acids during process of decomposition which leads to mineralized the fixed potassium and increased its availability. Similar findings were also reported by (40, 41).

Table 5. Depth wise (cm) available nitrogen, phosphorus and potassium (Pooled data of 2 years)

Treatment	Depth wise (cm)								
	Nitrogen (kg ha^{-1})			Phosphorus (kg ha^{-1})			Potassium (kg ha^{-1})		
	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
T_1	154.60	145.46	135.75	14.01	13.08	12.77	234.58	230.99	228.81
T_2	160.03	155.16	154.65	16.16	15.23	14.92	243.58	239.18	235.68
T_3	154.87	151.37	148.74	16.55	16.61	15.05	244.83	240.51	258.56
T_4	159.15	155.86	150.56	17.26	16.04	15.51	254.63	241.68	240.89
T_5	162.84	158.23	156.50	19.03	18.56	17.95	244.35	240.46	238.25
T_6	160.87	159.15	156.43	19.87	18.32	17.58	242.08	241.01	239.97
T_7	165.54	157.67	153.71	20.82	19.56	18.03	245.36	242.84	240.25
SEm ±	4.73	4.60	4.54	0.58	0.53	0.46	6.92	7.07	7.54
CD (P=0.05)	13.66	13.29	13.01	1.66	1.53	1.33	19.98	20.42	21.78

Soil Available Micronutrients

Depth wise (cm) status of soil available copper: The data of soil available copper (mg kg^{-1}) is presented in Table 6. It showed that the available copper status of soil was increased non significantly due to incorporation of rice residue. The highest available copper (0.52 mg kg^{-1}) was recorded under incorporation of paddy straw @ 5 t/ha with recommended NPK @ 120:60:40 kgha^{-1} and top dressing of nitrogen @ 20 kgha^{-1} after incorporation of paddy straw (T_3), incorporation of paddy straw @ 5 t ha^{-1} with 125 % of recommended dose of nitrogen, 60 kgha^{-1}P, 40 kgha^{-1}K (T_5) and incorporation of paddy straw @ 5 t ha^{-1} with 125 % of recommended dose of nitrogen, 60 kgha^{-1}P, 40 kgha^{-1}K, top dressing of nitrogen @ 20 kg ha^{-1} after incorporation of paddy straw and application of decomposer (T_7) followed by T_6(0.515 mg kg^{-1}), T_4(0.51 mg kg^{-1}), T_1(0.47 mg kg $^{-1}$) and T_2(0.45 mg kg^{-1}) at 0-15 cm depth and more or less similar strands were observed at depth of 15-30 cm and 30-45 cm depth of soil in decreasing order according to depth. Use of organic sources affects soil physio-chemical properties which in turn affect the micronutrient nutrition of crops by providing better environment for root growth as well as by adding some additional micronutrients to soil also (41). Influence of rice residue on soil micronutrient availability and their uptake by plants was observed in many findings both in direct and indirect manner (42).

Depth wise (cm) status of soil available zinc: Table 6 indicates the data of highest available zinc content in soil after harvest (1.35 mg kg^{-1}). This observation was recorded under treatment involving incorporation of paddy straw at 5 t ha^{-1} combined with 125 % of the recommended nitrogen dose, 60 kg ha^{-1} phosphorus, 40 kg ha^{-1} potassium, top dressing of nitrogen at 20 kg ha^{-1} after straw incorporation and decomposer application (T_7). This was followed by treatments, T_6 (1.28 mg kg^{-1}), T_4(1.26 mg kg^{-1}), T_3 (1.25 mg kg^{-1}), T_2 (1.20 mg kg^{-1}), T_5 (1.18 mg kg^{-1}) and T_1 (1.14 mg kg^{-1}) at 0 -15 cm depth. No clear increasing or decreasing trends were observed among treatments and similar patterns were seen at 15-30 cm and 30-45 cm depths, with available zinc decreasing gradually with soil depth.

Incorporating crop residues into soil provides multiple benefits, including enhancing micronutrient availability by supplying organic matter along with essential nutrients. While solid organic matter can reduce zinc solubility, interaction between organic matter as well as nitrogen significantly increases available zinc by forming complexes with dissolved organic compounds, which enhance zinc solubility and mobility (21, 43). Higher zinc concentrations in wheat cultivars (*Triticum aestivum* and *T. durum*) grown organically with farmyard manure compared to conventional cultivation was reported (44).

Depth wise (cm) soil available iron: Available Fe content of soils after harvest was significantly increased by incorporating crop residue and highest value was obtained by incorporation of paddy straw @ 5 t ha^{-1} with 125% of recommended dose of nitrogen, 60 kgha^{-1}P, 40 kgha^{-1}K, top dressing of nitrogen @ 20 kg ha^{-1} after incorporation of paddy straw and application decomposer (T_7) and without decomposer T_6(6.55 mg kg^{-1}) , followed by T_3 (6.44 mg kg^{-1}), T_2(6.22 mg kg^{-1}), T_1 (5.47 mg kg^{-1}), T_4 (5.45 mg kg^{-1}) and T_5(5.38 mg kg^{-1}) at 0-15 cm depth with increasing trends and more or less similar strands were observed at 15-30 cm and 30-45 cm depth of soil in decreasing order and presented in Table 7. The application of crop residue and nitrogen increased available Fe content in soils significantly (45). A significant rise in DTPA-extractable Zn, Cu, Fe and Mn in the surface layer loamy sand soil of Fatehpur in case of FYM application under maize-wheat sequence was previously reported (46). When FYM was applied @ 10 ton ha^{-1} yr^{-1}, level of DTPA-Fe increased from 5.5 to 5.8 mg kg^{-1}, Mn from 5.0 to 5.7 mg kg^{-1}, Zn from 0.21 to 0.32 mg kg^{-1} and Cu from 0.22 to 0.26 mg kg^{-1} after the maize harvest.

Depth wise (cm) soil available manganese: Table 7 shows the available Mn content of soils after harvest was increased with the incorporation of crop residue. The highest value of available Mn (6.140 mg kg^{-1}) was obtained by incorporation of paddy straw at 5 t ha^{-1} with 125 % of the recommended dose of nitrogen, 60 kg ha^{-1} P, 40 kg ha^{-1} K, top dressing of nitrogen at 20 kg ha^{-1} after incorporation of paddy straw and application of decomposer (T7), followed by T6 (5.94 mg kg^{-1}), T3 (5.92 mg kg^{-1}), T4 (5.83 mg kg^{-1}),

Table 6. Depth wise (cm) status of soil available copper and zinc (Pooled data of 2 years)

Treatment	Depth wise (cm) Copper (mg kg^{-1})			Depth wise (cm) Zinc (mg kg^{-1})		
	0-15	15-30	30-45	0-15	15-30	30-45
T_1	0.47	0.51	0.48	1.14	1.16	1.20
T_2	0.45	0.43	0.51	1.20	1.12	1.14
T_3	0.52	0.50	0.51	1.25	1.11	1.13
T_4	0.51	0.42	0.49	1.26	1.10	1.16
T_5	0.52	0.46	0.51	1.18	1.12	1.20
T_6	0.51	0.47	0.50	1.28	1.16	1.20
T_7	0.52	0.49	0.47	1.35	1.12	1.14
SEm ±	0.01	0.01	0.01	0.03	0.03	0.03
CD(P=0.05)	0.44	0.04	0.04	0.10	0.09	0.09

Table 7. Depth wise (cm) soil available iron and manganese (Pooled data of 2 years)

Treatment	Depth wise (cm) Iron (mg kg^{-1})			Depth wise (cm) Manganese (mg kg^{-1})		
	0-15	15-30	30-45	0-15	15-30	30-45
T_1	5.47	5.07	5.62	5.47	5.22	5.37
T_2	6.22	5.04	5.14	5.43	5.03	5.19
T_3	6.44	5.05	5.12	5.92	5.01	5.15
T_4	5.45	5.04	5.24	5.83	5.02	5.12
T_5	5.38	5.05	5.18	5.74	5.04	5.16
T_6	6.55	5.06	5.27	5.94	5.02	5.14
T_7	6.55	5.05	5.18	6.14	5.03	5.02
SEm ±	0.17	0.15	0.16	0.18	0.15	0.16
CD (P=0.05)	0.50	0.43	0.48	0.54	0.45	0.47

T5 (5.74 mg kg^{-1}), T2 (5.43 mg kg^{-1}) and T1 (5.47 mg kg^{-1}) at 0-15 cm depth with increasing trends and more or less similar strands were observed at 15-30 cm and 30-45 cm depths of soil in decreasing order. The application of crop residues and nitrogen increased available Mn content in soils significantly (28, 47).

Conclusion

The burning of rice residues has detrimental effects on soil health, leading to a significant loss in microbial biodiversity, reduced microbial biomass and the overall decline of soil fertility. In contrast, rice residues, when recycled through *in-situ* incorporation, act as valuable organic inputs that substantially enhance the physico-chemical properties of soil. The integration of 125 % of the recommended nitrogen dose (RDN), along with 60 kg ha^{-1} phosphorus and 40 kg ha^{-1} potassium, combined with the incorporation of paddy straw at 5 t ha^{-1} and a nitrogen top dressing of 20 kg ha^{-1} post-incorporation, resulted in marked improvements in soil physical parameters, including reduced bulk density and enhanced soil structure. On the chemical front, the treatment led to increased organic carbon content, stabilized pH, improved electrical conductivity and greater nutrient retention. Additionally, the application of a hyper-lingnocellulolytic fungal consortium (*Aspergillus* Spp., *Phlebia radiate* and *Trichoderma viride*), as bio-augmentation inoculum, further accelerated residue decomposition and enhanced microbial activity. This integrated residue management practice significantly improved the availability of both macronutrients (N, P, K) and micronutrients (Zn, Fe, Mn, Cu) all of which are essential for maintaining soil fertility and supporting long-term crop productivity.

Futuristically, this integrated approach offers a sustainable pathway to restoring soil health and boosting nutrient cycling in intensively cultivated rice-wheat systems. Continued research on bio-decomposers and residue management, coupled with precision nutrient management, can further optimize nutrient availability and uptake. Adoption of such eco-friendly practices at the field scale will help mitigate the adverse effects of conventional residue burning, ensuring long-term soil fertility, enhanced crop productivity and resilience against climate-induced stresses.

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Authors' contributions

AKB carried out the research, experimentation and residue management operations, performed data analysis and prepared and wrote the initial draft. AKP and RK conceptualized the study, supervised the experiment, conducted the research and residue management operations, reviewed the manuscript and created the necessary facilities. KKP, DNY, NKM, HSS and SK assisted in conducting the research, experimentation and residue management operations, contributed to data analysis and helped in preparing and writing the initial draft.

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