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RESEARCH ARTICLE

Physicochemical transformations of soil under different rice establishment methods and residue management practices in rice-rice system

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Abstract

Mechanized harvesting often leads to residue burning due to narrow sowing windows, which harms both soil health and air quality. While alternatives exist, their impact under different rice establishment methods is not well understood. The experiment followed a split-plot design with four rice establishment methods and three replications. The establishment methods were M_1: Wet Direct Seeded Rice (WDSR), M_2: Modified System of Rice Intensification (MSRI), M_3: mechanical transplanting and M_4: manual line transplanting in main plots and the residue management practices were S_1: straw removal, S_2: open burning, S_3: *in-situ* incorporation, S_4: rice straw biochar application and S_5: FYM application @ 5 t ha^{-1} in subplots. Cv. Swarna and Improved Lalat were used in *Kharif* and *Rabi*, respectively. A fertilizer dose of 80:40:40 kg ha^{-1} for *Kharif* and 60:30:30 kg ha^{-1} for *Rabi* rice was applied based on STBFR for medium N and low P and K soils. In MSRI, 50 % of N came from FYM (0.54 % N). Biochar addition improved bulk density, infiltration rate and water holding capacity. The MSRI method was very effective in improving the pH, EC, SOC and micronutrient status of the soil. Manual line planting was effective in maintaining the macronutrient (N, P and K) status of the soil. Straw incorporation was very effective in maintaining the overall soil health, including SOC, macronutrients and micronutrients. For improving the physical and chemical status of soil, modified SRI and FYM were the best practices.

Keywords: biochar; direct seeded rice; open burning; system of rice intensification

Introduction

Rice (*Oryza sativa* L.) is a vital global food staple, nourishing over half of the world's population and contributing 43 % to global nutritional needs (1,2). The need to increase food production by 30-40 % in the coming three decades is supported by a 2021 meta-analysis in Nature Food, which projects a 35-56 % rise in global food demand between 2010 and 2050 due to population growth and changing diets (3). The *in situ* accumulation of crop residues due to mechanized harvesting has led to challenges during tillage and seeding operations for the next crop. Shorter sowing windows of one or two weeks between two consecutive crops compel the farmers to burn crop residues *in situ* due to the absence of alternative productive and profitable disposal options (4). However, burning releases approximately 13 tonnes per hectare of carbon dioxide (CO_2), polluting the air and depleting the Soil Organic Matter (SOM). This loss of SOM is recognized as a significant threat to the sustainability of rice-rice production systems (5). Farmers have several alternatives to open burning when it comes to managing crop residues (6,7). These alternatives include practices such as soil incorporation, compost production, biochar creation, utilization in pulp and paper manufacturing, employing it as cattle feed, producing briquettes, fostering mushroom growth or converting it into biofuel. Researchers have conducted extensive investigations into the impacts of incorporating rice straw and introducing biochar into the soil. These studies have shown positive outcomes, including increased grain and straw yields, along with improved growth and yield-related attributes in various crops, including rice. However, there is a noticeable gap in the research concerning diverse residue management options across various rice establishment methods, particularly studying the physicochemical transformations in the soil under rice-rice systems.

The conventional method of establishing rice involves transplanting seedlings grown in nurseries into prepared puddled soils (8). Nevertheless, increasing labour expenses and the imperative to enhance rice production through multiple cropping seasons create financial motivations for adopting alternative establishment techniques (9). Nevertheless, increasing labour expenses, the imperative to enhance rice production through multiple cropping seasons and growing concerns over water scarcity and environmental impacts create financial and ecological motivations for adopting alternative establishment techniques (10). These alternatives may encompass direct sowing, mechanized transplanting, Alternate Wetting and Drying (AWD), broadcasting of seedlings (parachute planting) or even a blend of these methods. Direct seeding offers a multitude of advantages, including water conservation, reduced labour, energy and time requirements, diminished greenhouse gas emissions and improved subsequent crop growth, among other benefits (11). The System of Rice Intensification (SRI) enhances root development, nearly doubles tillering, maintains upright crop posture, increases grain weight and reduces pest and disease incidence (12). Though yield advantages under different rice establishment methods have been studied by many researchers (7); however research on the relative performance of different rice establishment methods on the physicochemical transformation of rice soil needs thorough investigation to establish the cause-and-effect relationship of the yield advantages under the rice-rice system. In this context, we have conducted a field experiment with rice crop to assess the physicochemical changes in rice soil as influenced by the rice establishment methods and rice residue management practices.

Materials and Methods

Experimental site and climate

This experiment was carried out in the Agronomy Main Research (AMR) farm at the College of Agriculture, Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, from June 2022 to May 2024. The farm is situated at $20^0 15'$ N latitude, $85^0 52'$ E longitude and at an elevation of 25.9 m above sea level. The climate of Bhubaneswar is tropical, characterized by hot and humid summers and mild winters. The region is generally moist and sub-humid. The southwest monsoon typically begins in mid-June and withdraws by late October. According to a previous study, the city's rainfall classification is D_1E_3(hot arid region); $B_1A_2B_1$ (humid climate, alluvial soils, long growing period (180-210 days); $C_1D_1E_2$(Semi-arid, medium to deep black soils, 90-150 days) (13). The rainfall pattern and the temperature conditions during the cropping period are given in Fig. 1 & 2.

Experimental design

The experiment was carried out in a split-plot design with 20 treatment combinations replicated thrice (R_1, R_2 and R_3). The first treatment consisted of four methods of rice establishment (M_1, M_2, M_3 and M_4) that were assigned to the four main plots and five

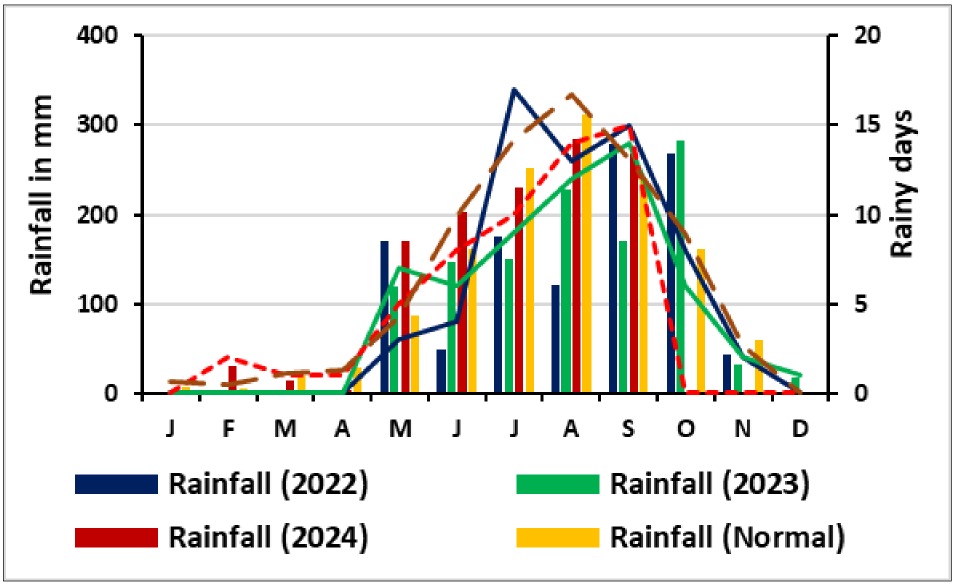

Fig. 1. Rainfall pattern during cropping period.

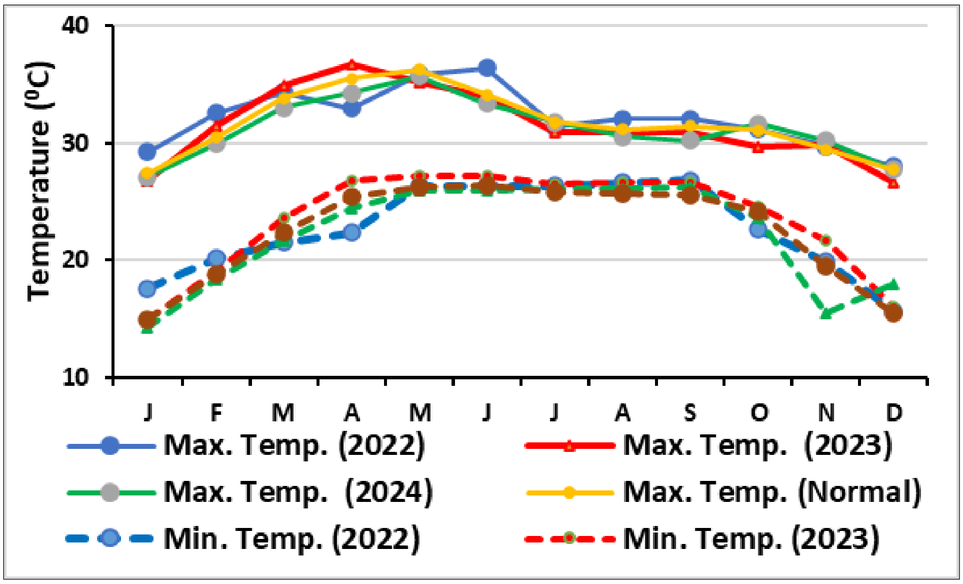

Fig. 2. Temperature variation during cropping period.

rice residue management practices (S_1, S_2, S_3, $S_4$and S_5) were allotted to five sub-plots (Table 1). The treatments were allotted at random with the help of a two-digit random number table. Two ruling rice cultivars, viz. cv. Swarna in *Kharif* and cv. Improved Lalat in *Rabi* were adopted in this experiment. Swarna is a high-yielding variety well-suited for flood-prone, rainfed shallow lowlands in coastal Odisha. Lalat is resistant to gall midge and shows moderate resistance to stem borer, leaf blast, sheath rot and Rice Tungro Virus (RTV).

Agronomic management

Nursery for treatments under MSRI (M_2), conventional rice cultivation (M_1 and M_4) was prepared as per the procedures mentioned previously (7). Seedlings were uprooted at 12 days for MSRI, 18 days for mechanical planting and at 25 days for manual planting before being transplanted into the main field. The main field was ploughed properly with the help of a tractor-drawn mould board plough, followed by harrowing and levelling. In wet direct-seeded rice treatment (M_1), the seeds were sown directly at 20 cm × 10 cm spacing by using a four-row drum seeder. In the MSRI method (M_2), polythene was used at the border of the main plot to avoid seepage of water from the adjacent main plot and transplanting was done 12 Days After Sowing (DAS) at a spacing of 25 cm × 25 cm. For mechanical transplanting (M_3), the seedlings were transplanted by a four-row transplanter at 18 DAS at a spacing of 20 cm × 10 cm. For manual transplanting (M_4), the seedlings were transplanted manually at 25 DAS at a spacing of 20 cm × 10 cm. To generate rice straw for the sub-plot treatments, cv. Improved Lalat was cultivated in the *Rabi* season of 2021-22 in the 12 main plots.

Five sub-plots within each main plot were S_1: straw removal, S_2: straw open burning, S_3: straw *in-situ* incorporation, S_4: straw biochar application and S_5: FYM @ 5 t ha^{-1} application. In sub-plots with straw removal (S_1), the straw was completely removed from the field, as some farmers are adopting this practice. In sub-plots with straw open burning (S_2), straw was directly burnt in the plot according to the straw yield of the previous season from the same plot. In sub-plots with *in situ* straw incorporation (S_3), the straw was incorporated directly in the field according to the straw yield of the previous season from the same plot. In the sub-plot with biochar application (S_4), the biochar was made outside, from the straw of the previous season of the same plot and was incorporated according to the straw yield. In sub-plots with FYM (S_5), well-decomposed FYM @ 5 t ha^{-1} was applied in the designated sub-plots as another farmers' practice. The rice straw harvested from the *Rabi* season of 2021-22 was used for imposing the above sub-plot treatments in the *Kharif* 2022 season as per the actual straw yield.

Table 1. Details of treatment and symbols used

Treatments	Symbols used
Main plot (Methods of rice establishment)	
Wet direct-seeded rice	M_1
Modified SRI	M_2
Machine transplanting	M_3
Manual line transplanting	M_4
Sub plot (Rice residue management practices)	
STBFR + straw removal	S_1
STBFR + straw open burning	S_2
STBFR + straw *in-situ* incorporation	S_3
STBFR + straw biochar application	S_4
STBFR + FYM @ 5 t ha^{-1}	S_5

Soil sampling and analyses

At the beginning of the field experiment, the soil from the entire plot was collected from 10 places by following the standard procedure (14). After mixing all 10 samples, the composite sample was prepared using the quartering method and the soil was then air-dried in the shade. Using a soil grinder, the soil samples were ground, sieved properly and chemical analyses of the samples were done. The bulk density of the soil was determined using the core method, as outlined previously (15) and was expressed in Mg m^{-3}. Soil water holding capacity (%) and infiltration rate (mm hr^{-1}) were determined by engaging the Lab WHC analysis method and a soil infiltrometer. The soil pH was measured in a 1:2.5 soil-to-water suspension using a Systronics 331 digital pH meter, with intermittent stirring of the sample for 30 min, as described elsewhere (16). The EC of the soil-water suspension (1:2 ratio) was measured using a direct reading conductivity meter (model: Systronics-363), as described elsewhere (12). Organic carbon content (%) was then determined using a modified version of Walkley and Black's wet oxidation method, where organic carbon in the sample was oxidized with chromic acid, utilizing the heat from sulfuric acid dilution (17). The available nitrogen (kg ha^{-1}) in soil was estimated by the alkaline permanganate method as outlined previously (18). Available phosphorus (kg ha^{-1}) was determined using the Bray-1 method, as described earlier, with 0.5 M $NaHCO_3$ as the extractant (13). The potassium concentration in the extract was measured using a flame photometer (model Systronics FPM 125), as outlined in a previous study (17). DTPA-extractable Zn, Fe, Mn, Cu (mg kg^{-1}) were analysed by following the previously described method (19). The exchangeable Sulphur (mg kg^{-1}) was estimated using the previously described method (16) and the Azomethine-H method (20) was used to estimate the available boron (B) (mg kg^{-1}).

Statistical analyses

To assess the effects of different treatments, the collected data were analysed using the split-plot ANOVA approach (21,22). The Fisher and Yates tablewas used to compare 'F' values and identify significant differences at the 5 % level (19). Standard Error of Mean (SEm) and Critical Difference (CD) were calculated and the treatment means were interpreted accordingly.

Results

Soil physical properties

Bulk density

Soil physical properties at the end of the rice-rice system each year were analysed in 2022-23 and 2023-24 (Table 2). Rice establishment methods had no significant effect on the Bulk Density (BD) of soil. While straw removal recorded the highest BD (1.28 g cm^{-3}), which was at par with straw burning practice (1.24 g cm^{-3}) and both were significantly higher than other practices. Biochar application (S_4) and FYM (S_5) recorded the same BD at 1.195 and 1.185 g cm^{-3} and were at par with straw incorporation, which had the lowest BD (1.17 g cm^{-3}).

Water Holding Capacity (WHC)

Wet DSR (M_1) had the highest soil WHC, followed by mechanical planting, modified SRI and manual line planting in descending order. While the latter three were statistically similar, they had significantly lower WHC than M_1. Residue management practices

Table 2. Effect of rice establishment methods and rice residue management practices on soil physical properties in rice-rice system during 2022-23 and 2023-24

Treatments	Bulk density (g cm^{-3})			Water holding capacity (%)			Infiltration rate (cm hr^{-1})		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Establishment method									
M_1	1.212	1.197	1.205	30.7 (5.58)	33.7 (5.81)	32.2 (5.70)	88.2	94.3	91.3
M_2	1.201	1.174	1.187	29.1 (5.36)	34.4 (5.73)	31.8 (5.55)	99.1	111.4	105.2
M_3	1.235	1.227	1.231	32.3 (5.62)	31.6 (5.53)	31.9 (5.58)	77.1	86.7	81.9
M_4	1.248	1.218	1.233	31.7 (5.64)	29.6 (5.41)	30.6 (5.52)	70.4	80.7	75.5
S.Em (±)	0.0193	0.0327	0.0190	0.019	0.053	0.28	3.73	4.92	3.09
C.D. (0.05)	NS	NS	NS	0.07	0.18	0.09	12.9	17.0	9.5
Rice residue management									
S_1	1.290	1.270	1.280	20.0 (4.46)	18.6 (4.23)	19.3 (4.35)	57.4	64.0	60.7
S_2	1.250	1.230	1.240	30.2 (5.52)	30.7 (5.53)	30.4 (5.52)	68.5	76.3	72.4
S_3	1.190	1.150	1.170	31.2 (5.59)	34.2 (5.81)	32.7 (5.70)	99.8	113.1	106.5
S_4	1.210	1.180	1.195	38.8 (6.27)	42.9 (6.58)	40.9 (6.42)	92.2	108.0	100.1
S_5	1.180	1.190	1.185	34.5 (5.91)	35.2 (5.96)	34.9 (5.93)	100.7	105.0	102.8
S.Em (±)	0.0230	0.0185	0.0148	0.042	0.053	0.034	5.15	6.06	3.98
C.D. (0.05)	0.066	0.053	0.042	0.12	0.15	0.10	14.8	17.5	11.2

M_1: Wet DSR; M_2: Modified SRI; M_3: Machine planting; M_4: Manual line planting; S1: STBFR + Straw removal; S_2: STBFR + Straw open burning; S_3: STBFR + Straw incorporation; S_4: STBFR + Straw biochar application; S_5: STBFR + FYM application

showed significant differences, with rice straw biochar application (S_4) achieving the highest WHC, significantly surpassing other practices. The lowest soil WHC was observed in straw removal (S_1).

Soil infiltration capacity

Rice establishment methods significantly affected soil infiltration. In 2022-23, modified SRI (M_2) and wet DSR (M_1) were at par with each other, but in 2023-24 and pooled data, MSRI resulted in the highest infiltration rate (105.2 mm hr^{-1}). Mechanical planting and manual planting were also at par with each other for both years and pooled data, with manual line planting recording the lowest values. Among the residue management practices, FYM addition (102.8 mm hr^{-1}), straw incorporation (106.5 mm hr^{-1}) and biochar application (100.1 mm hr^{-1}) were at par with each other in pooled data and significantly higher than straw removal and straw burning practices.

Soil chemical properties

The chemical properties of soil, such as pH, EC, OC and nutrient content of all treatment combinations (N, P, K, S, Cu, B, Fe, Mn and Zn), were studied at the end of each cropping year in 2022-23 and 2023-24.

Soil pH

The highest soil pH was recorded in modified SRI (5.28), followed by wet DSR (5.14), manual planting (5.08) and mechanical planting (5.05) in pooled data (Table 3a). Plots with biochar application recorded the highest soil pH (5.28), significantly higher than straw removal (5.11), FYM application (5.07) and straw incorporation (5.06), but on par with straw open burning (5.18).

Table 3a. Effect of rice establishment methods and rice residue management practices on soil chemical properties in rice-rice system during 2022-23 and 2023-24

Treatments	pH			EC (dS m^{-1})			Soil organic carbon (%)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Establishment methods									
M_1	5.13	5.14	5.13	0.043	0.047	0.045	0.538	0.594	0.566
M_2	5.21	5.35	5.28	0.039	0.037	0.038	0.572	0.639	0.606
M_3	5.06	5.04	5.05	0.044	0.048	0.046	0.531	0.577	0.554
M_4	5.09	5.07	5.08	0.046	0.047	0.047	0.521	0.551	0.536
S.Em (±)	0.046	0.038	0.030	0.0005	0.0020	0.0010	0.0126	0.0270	0.0149
C.D. (0.05)	0.16	0.13	0.09	0.002	0.007	0.003	0.044	0.094	0.046
Rice residue management									
S_1	5.12	5.10	5.11	0.039	0.042	0.041	0.490	0.531	0.510
S_2	5.16	5.19	5.18	0.044	0.041	0.043	0.514	0.557	0.523
S_3	5.03	5.09	5.06	0.043	0.046	0.044	0.607	0.660	0.634
S_4	5.22	5.31	5.26	0.046	0.051	0.048	0.558	0.621	0.589
S_5	5.09	5.06	5.07	0.043	0.044	0.043	0.533	0.583	0.558
S.Em (±)	0.042	0.049	0.032	0.0010	0.0017	0.0010	0.0072	0.0159	0.0087
C.D. (0.05)	0.12	0.14	0.09	0.003	0.005	0.003	0.021	0.046	0.025

M_1: Wet DSR; M_2: Modified SRI; M_3: Machine planting; M_4: Manual line planting; S_1: STBFR + Straw removal; S_2: STBFR + Straw open burning; S_3: STBFR + Straw incorporation; S_4: STBFR + Straw biochar application; S_5: STBFR + FYM application

Soil EC

The rice establishment methods and residue management practices significantly influenced the Electrical Conductivity (EC) of soil (Table 3a). The maximum EC was recorded in the manual transplanting method (M_4) in both the years of experimentation and pooled data as well (0.046, 0.047 and 0.047 dS m^{-1}), which was at par with the wet DSR method (M_1) and the machine planting method (M_3) but significantly higher than modified SRI (M_2). The application of biochar resulted in significantly the highest soil EC values across both the years of study and in pooled data (0.046, 0.051 and 0.048 dS m^{-1}), significantly exceeding all other rice residue management practices. In contrast, straw removal recorded the lowest soil EC values (0.039, 0.042 and 0.041 dS m^{-1}) after the first and second copping years and in pooled data.

Soil organic carbon

Both the establishment methods and residue management practices had significant effects on Soil Organic Carbon (SOC) content in the rice-rice system after the first (2022-23) and the second year (2023-24) (Table 3a). Among the rice establishment methods, modified SRI (M_2) had the highest SOC in 2022-23, 2023 -24 and pooled data over both years, followed by wet DSR method (M_1), machine planting (M_3) and manual line planting (M_4). Straw incorporation (S_3) recorded the highest SOC of 0.607 %, 0.634 % and 0.621 % in 2022-23, 2023-24 and pooled over two years. This was followed by biochar application (0.589 %), FYM application (0.558 %), straw open burning (0.523 %) and straw removal (0.51 %).

Soil nitrogen

Both the rice establishment methods and residue management practices significantly influenced residual soil nitrogen (N) content after rice-rice cropping (Table 3b). Manual line planting (M_4) recorded the highest soil residual N content (302.38, 324.12 and 313.25 kg ha^{-1}) in 2022-23 and 2023-24 and pooled data, respectively, followed by the machine planting method. Both wet DSR and mechanical planting methods were at par with each other in soil residual N content. Among the residue management practices, straw incorporation (S_3) had recorded the highest soil residual N content (308.73, 314.41 and 311.57 kg ha^{-1}) in both the years of experimentation and pooled data, respectively. This was followed by biochar application (S_4), FYM addition, straw removal (S_1) and straw open burning (S_2) in descending order. Among the establishment methods, manual planting method was 0.15 % higher than the MSRI method, which was lowest in P content and among residue management practices, straw incorporation was 19.09 % higher than the straw removal (Table 3b).

Soil phosphorous

Manual transplanting method (M_4) recorded the highest amount of soil residual P content (10.81, 14.4 and 12.61 kg ha^{-1}) in 2022-23, 2023-24 and pooled data, respectively, followed by the mechanical planting method (M_3). MSRI (M_2) recorded the lowest soil P content after crop harvest in both years. Straw incorporation had the highest amount of soil P content (10.83, 14.65 and 12.74 kg ha^{-1}) after rice-rice cropping in both years and pooled data, respectively, followed by biochar (10.39, 13.66 and 12.03 kg ha^{-1}), FYM addition, straw open burning and straw removal.

Soil potassium

Both the establishment methods and residue management practices had a significant effect on soil residual potassium (K) content (Table 3c). Among the establishment methods, the manual transplanting method recorded the highest soil K content of 150.05, 103.62 and 126.84 kg ha^{-1} in 2022-23, 2023-24 and pooled data, respectively, followed by modified SRI, mechanical planting and wet DSR in descending order. Biochar application had the highest residual soil K content at 155.96, 103.28 and 129.62 kg ha^{-1} in both the years of experimentation and pooled data, respectively, followed by straw burning and removal.

Soil sulphur

Rice establishment methods and residue management practices significantly influenced soil sulphur (S) content after the first and second years of rice-rice cropping system (Table 3c). MSRI (M_2) recorded the highest S content, measuring 11.31 ppm in 2022 23, 13.12 ppm in 2023-24 and 12.22 ppm in pooled data, respectively, followed by the manual planting method, which recorded 10.52, 12.13 and 11.33 ppm in respective years and pooled data. Straw incorporation recorded the highest soil S content at 11.93 and 12.52 ppm after 2022-23 and 2023-24 and 13.11 ppm in pooled data across both years, followed by FYM application treatment with 11.06, 12.84 and 11.95 ppm in respective years and pooled data.

Table 3b. Effect of rice establishment methods and rice residue management practices on soil chemical properties in rice-rice system during 2022-23 and 2023-24

Treatments	Nitrogen (kg ha^{-1})			Phosphorus (kg ha^{-1})			Potassium (kg ha^{-1})		
	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled
Establishment methods									
M_1	292.09	292.00	292.04	10.03	12.02	11.02	143.26	97.18	120.22
M_2	275.08	284.03	279.56	9.41	12.34	10.88	139.14	106.24	122.69
M_3	296.54	294.81	295.67	10.56	13.50	12.03	144.86	100.00	122.43
M_4	302.38	324.12	313.25	10.81	14.40	12.61	150.05	103.62	126.84
S.Em (±)	4.311	6.120	3.743	0.220	0.284	0.180	1.161	1.608	0.991
C.D. (0.05)	14.92	21.18	11.53	0.76	0.98	0.55	4.02	5.56	3.05
Rice residue management									
S_1	284.23	289.06	286.64	9.80	11.45	10.62	138.71	98.27	118.49
S_2	277.57	281.68	279.63	9.81	11.71	10.76	148.74	100.97	124.86
S_3	308.73	314.41	311.57	10.83	14.65	12.74	141.50	104.36	122.93
S_4	295.18	311.61	303.40	10.39	13.66	12.03	155.96	103.28	129.62
S_5	291.90	296.94	294.42	10.17	13.85	12.01	136.73	101.91	119.32
S.Em (±)	3.971	5.913	3.561	0.221	0.244	0.165	1.667	1.979	1.294
C.D. (0.05)	11.44	17.03	10.06	0.64	0.70	0.47	4.80	5.70	3.65

M_1: Wet DSR; M_2: Modified SRI; M_3: Machine planting; M_4: Manual line planting; S_1: STBFR + Straw removal; S_2: STBFR + Straw open burning; S_3: STBFR + Straw incorporation; S_4: STBFR + Straw biochar application; S_5: STBFR + FYM application

Table 3c. Effect of rice establishment methods and rice residue management practices on soil chemical properties in rice-rice system during 2022-23 and 2023-24

Treatments	Sulphur (ppm)			Copper (ppm)			Iron (ppm)		
	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled
Establishment methods									
M_1	10.011	11.240	10.625	0.146	0.154	0.150	2.74	2.02	2.38
M_2	11.313	13.119	12.216	0.173	0.180	0.176	2.93	2.53	2.73
M_3	10.345	11.628	10.986	0.152	0.158	0.155	2.90	2.16	2.53
M_4	10.522	12.130	11.326	0.156	0.161	0.159	2.90	2.20	2.55
S.Em (±)	0.2182	0.3238	0.1952	0.0042	0.0045	0.0031	0.068	0.150	0.082
C.D. (0.05)	0.755	1.120	0.602	0.014	0.016	0.009	0.24	0.52	0.25
Rice residue management									
S_1	9.101	11.017	10.059	0.141	0.147	0.144	2.71	2.10	2.40
S_2	9.690	11.143	10.416	0.148	0.157	0.152	2.86	2.25	2.56
S_3	11.931	13.108	12.520	0.176	0.182	0.179	3.03	2.34	2.68
S_4	10.958	12.035	11.497	0.155	0.163	0.159	2.78	2.16	2.47
S_5	11.059	12.842	11.951	0.163	0.168	0.165	2.95	2.29	2.62
S.Em (±)	0.2581	0.3117	0.2023	0.0055	0.0048	0.0036	0.140	0.143	0.100
C.D. (0.05)	0.743	0.898	0.572	0.016	0.014	0.010	0.40	0.41	0.28

M_1: Wet DSR; M_2: Modified SRI; M_3: Machine planting; M_4: Manual line planting; S_1: STBFR + Straw removal; S_2: STBFR + Straw open burning; S_3: STBFR + Straw incorporation; S_4: STBFR + Straw biochar application; S_5: STBFR + FYM application

Soil copper

Rice establishment methods and residue management practices significantly influenced soil copper (Cu) content after the first and second years of rice-rice cropping system (Table 3c). Among the establishment methods, MSRI (M_2) recorded the highest soil Cu content, measuring 0.173 ppm in 2022-23, 0.18 ppm in 2023-24 and 0.176 ppm in pooled data, respectively, followed by manual planting method with 0.156, 0.161 and 0.159 ppm in respective years and pooled data. However, the wet DSR (M_1), the manual planting (M_3) and the mechanical planting (M_4) methods had no significant differences in Cu content. Among rice residue management practices, straw incorporation (S_3) recorded the highest soil Cu content, with 0.176 ppm in 2022-23, 0.182 ppm in 2023-24 and 0.179 ppm in pooled data, respectively. This was followed by FYM addition, which measured 0.163, 0.168 and 0.165 ppm in respective years and pooled data, significantly surpassing the other three residue management practices.

Soil boron

Rice establishment methods and residue management practices significantly influenced soil boron (B) content with rice-rice cropping in 2022-23, 2023-24 and pooled data across both years (Table 3c). Among the establishment methods, the manual planting method (M_4) recorded the highest soil B content, measuring 0.408 ppm in 2022-23, 0.411 ppm in 2023-24 and 0.409 ppm in pooled data across both years. This was followed by modified SRI (M_2) with 0.395, 0.418 and 0.406 ppm in respective years and pooled data. All the establishment methods showed a significant difference in soil B content, except machine planting (M_3), which recorded the lowest value of 0.348 ppm. FYM application (S_5) recorded the highest soil B content, with 0.407 ppm in 2022-23, 0.414 ppm in 2023-24 and 0.411 ppm in the pooled data. This was followed by straw incorporation (S_3), which measured 0.401, 0.419 and 0.41 ppm in respective years and pooled data. Soil boron contents in straw incorporation (S_3), biochar application (S_4) and FYM application (S_5) were statistically at par but significantly higher than the straw removal treatment (S_1).

Soil Fe content

Rice establishment methods significantly influenced soil iron (Fe) content with rice-rice cropping in 2022-23, 2023-24 and pooled data across both years (Table 3c). MSRI method (M_2) recorded the highest soil Fe content, with 2.93 ppm in 2022 23, 2.53 ppm in 2023-24 and 2.73 ppm in pooled data, respectively followed by manual planting method (M_4), measuring 2.9, 2.2 and 2.55 ppm in respective years and pooled data. Whereas the wet DSR method (M_1), manual planting method (M_4) and mechanical planting method (M_3) did not differ significantly in Fe content. Straw incorporation (S_3) had recorded the highest soil Fe content, measuring 3.03 ppm in 2022-23, 2.34 ppm in 2023-24 and 2.68 ppm in pooled data. This was followed by FYM application (S_5) with 2.95, 2.29 and 2.62 ppm in respective years and pooled data. However, all five residue management practices under study did not show any significant difference in soil Fe content statistically.

Soil Mn content

Rice establishment methods and residue management practices significantly influenced soil manganese (Mn) content with rice-rice cropping in 2022-23, 2023-24 and pooled data across both years (Table 3d). Among the establishment methods, the MSRI method (M_2) recorded the highest soil Mn content, measuring 1.104 ppm in 2022-23, 1.189 ppm in 2023-24 and 1.146 ppm in pooled data across both years. This was followed by the manual planting method with 0.916, 1.123 and 1.019 ppm in respective years and pooled data. The soil Mn content followed the order $M_2 > M_4 > M_3 > M_1$, with M_2 being significantly higher than the other three methods, while M_4, M_3 and M_1 had no significant difference. Biochar application (S_4) recorded the highest soil Mn content, measuring 1.017 ppm in 2022-23, 1.131 ppm in 2023-24 and 1.074 ppm in pooled data over two years. This was followed by FYM application, with 0.986, 1.092 and 1.039 ppm in respective years and pooled data. Straw removal recorded the soil Mn content, significantly lower than all other residue management practices.

Table 3d. Effect of rice establishment methods and rice residue management practices on soil chemical properties in rice-rice system during 2022-23 and 2023-24

Treatments	Manganese (ppm)			Zinc (ppm)			Boron (ppm)		
	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled
Establishment methods									
M_1	0.849	0.995	0.922	0.136	0.206	0.171	0.418	0.425	0.421
M_2	1.104	1.189	1.146	0.140	0.224	0.182	0.395	0.418	0.406
M_3	0.896	1.037	0.967	0.129	0.197	0.163	0.310	0.387	0.348
M_4	0.916	1.123	1.019	0.124	0.191	0.157	0.408	0.411	0.409
S.Em (±)	0.0479	0.0319	0.0288	0.0039	0.0040	0.0028	0.0088	0.0346	0.0179
C.D. (0.05)	0.166	0.111	0.089	0.013	0.014	0.009	0.030	0.120	0.055
Rice residue management									
S_1	0.830	0.989	0.910	0.122	0.170	0.146	0.356	0.383	0.369
S_2	0.963	1.093	1.028	0.128	0.187	0.158	0.365	0.405	0.385
S_3	0.910	1.124	1.017	0.131	0.203	0.167	0.401	0.419	0.410
S_4	1.017	1.131	1.074	0.143	0.239	0.191	0.383	0.431	0.407
S_5	0.986	1.092	1.039	0.136	0.223	0.179	0.407	0.414	0.411
S.Em (±)	0.0348	0.0338	0.0243	0.0042	0.0056	0.0035	0.0119	0.0203	0.0117
C.D. (0.05)	0.100	0.097	0.069	0.012	0.016	0.010	0.034	0.058	0.033

M_1: Wet DSR; M_2: Modified SRI; M_3: Machine planting; M_4: Manual line planting; S_1: STBFR + Straw removal; S_2: STBFR + Straw open burning; S_3: STBFR + Straw incorporation; S_4: STBFR + Straw biochar application; S_5: STBFR + FYM application

Soil Zn content

Rice establishment methods and residue management practices significantly influenced soil zinc (Zn) content with rice-rice cropping in 2022-23, 2023-24 and pooled data across both years (Table 3d). MSRI (M_2) recorded the highest soil Zn content, measuring 0.14 ppm in 2022-23, 0.224 ppm in 2023-24 and 0.182 ppm in pooled data across both years. This was followed by wet DSR (M_1) with 0.136, 0.206 and 0.171 ppm in respective years and pooled data, but within the statistical range of significance. Soil Zn content under manual planting (M_4) was significantly the lowest among the establishment methods. Rice residue management practices significantly influenced soil Zn content, with significant variations among all the treatments. Biochar application (S_4) recorded the highest soil Zn content, measuring 0.143 ppm in 2022-23, 0.239 ppm in 2023-24 and 0.191 ppm in the pooled data. This was followed by the treatment with FYM addition (S_5) with 0.136, 0.223 and 0.179 ppm in respective years and pooled data with a significant reduction in values compared to S_4.

Discussion

Soil PH

There was a slight increase in the soil pH towards neutrality after the cropping season compared to the initial values. There was a significant increase in soil pH under modified SRI and with the addition of straw biochar. The direction and magnitude of pH change depend largely on the concentration of organic anions in the residues, the initial soil pH and the degree of residue decomposition (23). The incorporation of crop residues, especially those with high concentrations of excess cations, is recommended for minimizing soil acidification in farming systems (24). The rise in soil pH under MSRI could be attributed to management practices involving the repeated use of a Conoweeder, which releases fixed cations into the clay lattice structure, thereby elevating soil pH (25). The addition of biochar elevated soil pH due to the release of different cations, such as Ca and K, into the soil.

SOC

There was an increase in organic carbon status over the two cropping years in general and modified SRI and rice residue incorporation, in particular. This could be due to the direct contribution of residues to organic carbon build-up. The higher SOC content under organically managed or integrated nutrient management treatments was due to the increased amount of organic matter in the soil. Organic carbon stimulates microbial activities and increases the decomposition of organic matter in the soil (26). The microbial residue decomposition also might have helped in increasing the micronutrient content status of the soil. Furthermore, biochar addition also elevated SOC due to the release of pyrolytic carbon, produced through controlled thermal decomposition (27).

BD, WHC and infiltration capacity of soil

The establishment methods had no significant effect on the BD of soil, but infiltration and WHC differed with the establishment methods in rice-rice cropping. Among the residue management practices, FYM addition had a greater effect in reducing soil BD, increasing infiltration and WHC. However, biochar addition recorded the highest WHC, whereas straw incorporation had the highest infiltration rate. This conforms to a previous study which reported that the integration of rice straw at 5 t ha^{-1} yr^{-1} enhanced the soil's physical qualities (28). In plots treated with FYM and rice straw, the BD, WHC and hydraulic conductivity of saturated soil were higher. Microbial activity and enzymatic activities of soil microbes play a crucial role in crop growth and productivity by performing important functions such as nutrient cycling, organic matter decomposition, disease suppression and plant growth promotion. Organic amendments hold great promise as a source of multiple nutrients and the ability to improve soil characteristics (29).

Soil chemical properties

The build-up of soil available K due to straw application may be due to the addition of K applied throughout the solubilizing action of certain organic acids produced during straw decomposition and its greater capacity to hold K in the available form. Relatively higher soil K-level in biochar could be due to the addition of pyrolytic biomass rich in K. Synergistic application of straw along with FYM in MSRI could have lowered the negative pool of the actual K (initial low K content) in soil under such a combination. Significantly higher availability of soil N, P and K and organic carbon with the addition of straw in the rice-wheat system at soil depths of 0-20 cm has also been reported (30). Continuous application of organic manure releases different micronutrients as it undergoes decomposition and mineralization.

Conclusion

This study demonstrates that both rice establishment methods and residue management practices play a critical role in shaping the physical and chemical properties of soil within the rice-rice cropping system. The MSRI, when integrated with *in situ* rice straw incorporation, significantly improves key soil health indicators, such as BD, infiltration rate, water-holding capacity and nutrient availability. These improvements contribute to enhanced soil fertility, better water and nutrient use efficiency and potentially greater crop productivity. The findings advocate for the adoption of these synergistic practices as a sustainable strategy for managing intensive rice cultivation systems. To reinforce these insights, future research should include long-term field validation and comprehensive economic analyses across different agro-ecological regions, thereby enabling widespread and practical adoption by farming communities.

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Authors' contributions

JM was responsible for carrying out the lab and field research work, manuscript preparation and communication of the manuscript. The experiment was conceptualised, designed and monitored by SKD, BKM and AK contributed to laboratory analysis and data interpretation. The statistical analysis was carried out by JM, SKD, PKS, TRM and ZAM. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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