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RESEARCH ARTICLE

Comparative assessment of establishment methods and residue management on yield and profitability in rice–rice cropping system

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Abstract

Rice straw management is a challenging issue in rice-rice production systems, especially in areas with a shorter sowing/planting window. It was imperative to ascertain the productive and profitable rice establishment method and residue management practice for rice double cropping. In this study, four rice establishment methods-wet direct seeded rice (DSR), modified system of rice intensification (MSRI), mechanical transplanting and manual line planting-were set up in the main plots and five rice residue management treatments were tested in the subplots. Swarna and Improved Lalat varieties of rice were adopted in the Kharif and Rabi seasons, respectively. Fertilizer recommendations, depending on the soil test-based fertiliser recommendation (STBFR) results, which indicated medium soil N and low soil P and K levels for each crop. MSRI had the highest grain yield in Kharif 2022-23 (5.678 t ha^{-1}); in Rabi 2022-24 (4.377 t ha^{-1}). Farmyard manure outperformed (5.678 t ha^{-1}) other treatments like straw incorporation, biochar application and open burning in grain yield in Kharif and in Rabi. MSRI with FYM resulted in the highest mean cost of cultivation in the rice-rice cropping system. The maximum net return was recorded in wet DSR with FYM addition, but the highest BCR of 1.647 was recorded in wet DSR with straw incorporation. The maximum system profitability of ₹370 ha^{-1} day^{-1} was recorded in wet DSR along with FYM.

Keywords: benefit-cost ratio; cost of cultivation; production economics; productivity and system profitability

Introduction

More than half the world depends on rice (*Oryza sativa* L.) as a staple food and its growth is especially important in South and Southeast Asia. In heavily cropped areas, mainly in the Indo-Gangetic Plains of India, the rice-rice system is a dominant cropping pattern. Maintaining the profitability and high output in this system is difficult because of soil deterioration, insufficient water and issues connected to burning residue and puddled transplanting on fields (1, 2). Puddled transplanted rice (PTR) is labour-, water- and energy-intensive and long-term puddling damages the soil, leading to a decrease in the system's productivity (3).

Open field burning of rice residues leads to both air pollution and the loss of nutrients, which aggravates the sustainability issues (4). As a result, approaches such as direct-seeded rice (DSR), machine -transplanted rice (MTR) and conservation agriculture (CA)-based farm residue management practices are used to improve farming output and respect the environment (5, 6). It was found in recent studies that combining DSR with residue retention reduces water and labour use, lowers emissions and maintains or increases yields (7). In the same way, using mechanized transplanting, which keeps residue, can increase system productivity and profitability (8). However, the performance of these methods varies with agro-ecological conditions, residue management strategies and socio-economic factors, necessitating site-specific assessment. The purpose of this study is to check the profitability of the rice-rice system with different methods of rice establishment and residue management practices. The findings are expected to contribute to evidence-based recommendations for sustainable intensification of the rice-rice system.

Materials and Methods

The 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°15'N latitude, 85° 52'E longitude and at an elevation of 25.9 m above sea level. The design of the experiment was split plot design. Seed beds of 1 m width and 15 cm height were prepared and channels of 30 cm width were provided between the two beds of irrigation/ drainage. The surface of the bed was levelled and 0.25 kg of sprouted seeds from the varieties Swarna and Improved Lalat were sown for the Kharif and Rabi seasons, respectively. The climate was normal during the cropping period (Fig. 1 & 2). Well-decomposed FYM was applied to the beds at a rate of 1 kg/m^2, mixed with soil and then the seeds were sown. When using a

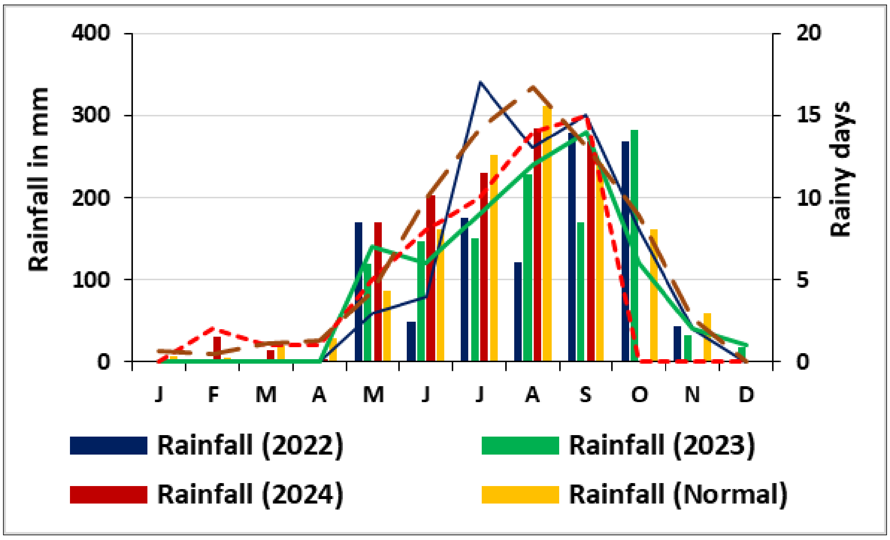

Fig. 1. Rainfall distribution pattern at the Agronomy Main Research farm, OUAT, Bhubaneswar during 2022 to 2024 compared with the normal.

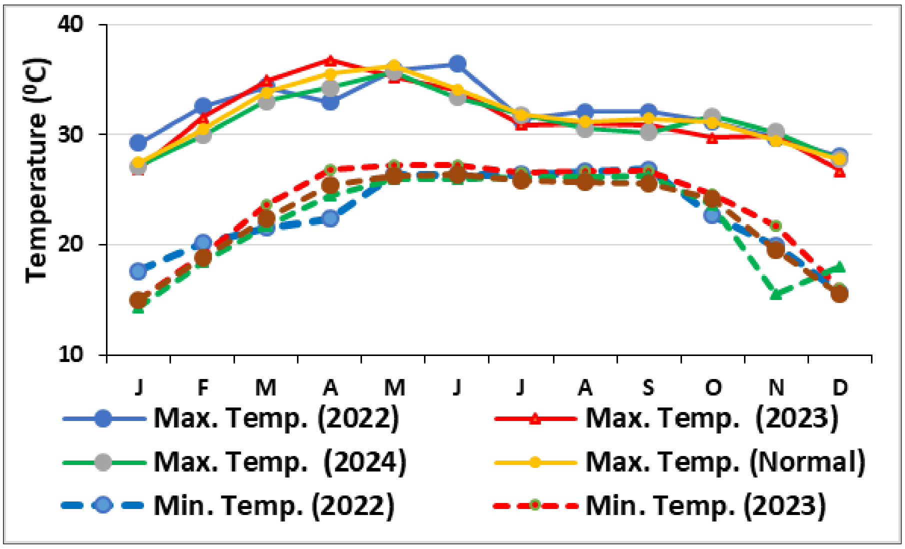

Fig. 2. Diurnal maximum and minimum temperature variations at the Agronomy Main Research farm, OUAT, Bhubaneswar during 2022 to 2024 compared with the normal.

mechanical planter, seedlings were taken out at 18 days but when the manual method was used, they were taken out at 25 days before the transplantation to 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 treatment M_1, the seeds were sown directly at 20 cm x 10 cm spacing by using a four-row drum seeder (Table 1). In 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 x 25 cm. For M_3, the seedlings were transplanted by a four-row transplanter at 18 DAS at a spacing of 20 cm x 10 cm. In M_4, the seedlings were transplanted manually at 25 DAS at a spacing of 20 cm x 10 cm. Plots were marked with manually constructed bunds on all four sides.

To generate rice straw for the sub-plot treatments, the cultivar Improved Lalat was cultivated in the Rabi season of 2021 -22 in 12 main plots. Each main plot was divided in five sub-plots, designated as S_1, S_2, S_3, S_4 and S_5. In sub-plots with S_1, the straw was completely removed from the field, as some farmers are adopting this practice. In S_2, straw was directly burnt in the plot according to the straw yield of the previous season from the same plot. In S_3, the straw was incorporated directly in the field according to the straw yield of the previous season from the same plot. In 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 S_5, well decomposed FYM was applied at 5 t ha^{-1} representing another common farmer 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 treatments 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 at 5 t ha^{-1}	S_5

STBFR = Soil test-based fertilizer recommendation.

Recording of grain yield and crop/system productivity

Grain yield

The crop was harvested from the plot, excluding the border and sampling areas. After sun-drying for 3-4 days, threshing was performed using a power-operated thresher. Grain yield was recorded separately in kg plot^{-1} and converted to t ha^{-1}. The recorded yield was adjusted to 14 % moisture content, considering the moisture levels after threshing and drying.

Crop productivity

Crop productivity refers to the amount of crop produced per unit of land area. It was measured in kilograms per hectare per day (kg ha^{-1}day^{-1}) by using the following formula.

$$\text{Crop productivity} = \frac{\text{Total crop yield (kg/ha)}}{\text{Duration of crop in field}} \quad \text{(Eqn. 1)}$$

The system productivity (kg ha^{-1}day^{-1}) was calculated by totalling the yield from each crop in a year (kg ha^{-1}) divided by 365 days.

$$\text{System productivity} = \text{Total system yield (kg/ha)}/365 \quad \text{(Eqn. 2)}$$

Production economics

The market values of the inputs produced and by-products were taken into consideration while calculating the economics of production for each treatment on a per-hectare basis. The net return benefit cost ratio was calculated:

$$\text{Net return (₹ ha}^{-1}) = \text{Gross return (₹ ha}^{-1}) - \text{cost of cultivation (₹ ha}^{-1}) \quad \text{(Eqn. 3)}$$

$$\text{Benefit cost ratio} = \frac{\text{Gross return (₹/ha)}}{\text{Total cost of cultivation (₹/ha)}} \quad \text{(Eqn. 4)}$$

Crop profitability (₹ ha^{-1}/day^{-1})

Crop profitability was calculated by dividing the net profit per hectare by the crop duration in the field. The system profitability was calculated by dividing the net profit from the rice-rice system by 365 days.

$$\text{Crop profitability} = \frac{\text{Gross return (₹/ha) - Total cultivation cost (₹/ha)}}{\text{Duration of crop in field (days)}} \quad \text{(Eqn. 5)}$$

$$\text{System profitability} = \frac{\text{Gross return (₹/ha) - Total cultivation cost (₹/ha)}}{\text{365 days}} \quad \text{(Eqn. 6)}$$

Statistical analysis

To evaluate the impact of various treatments, the data gathered during the study were analyzed using the analysis of variance (ANOVA) split-plot design method (9-11). Fisher and Yates table was consulted for comparing F values and determining critical differences at a 5 % significance level (12). The standard error of mean (SEm) and critical difference (CD) were calculated and the mean data were analysed accordingly. Correlation coefficients between seed yield and its attributing factors were computed and interpreted based on the findings.

Results

Studies on Kharif rice

Grain yield

The grain yield of rice was significantly influenced by the establishment methods and residue management practices in Kharif in 2022 and 2023 (Table 2). Grain yield differed significantly between the Kharif seasons of both years. However, the interaction effect between establishment methods and residue management practices was not significant. The treatment M_2 produced the highest grain yields of 5.495, 5.857 and 5.676 t ha^{-1}in 2022, 2023 and in pooled data, respectively, followed by the wet M_1, which recorded 5.291, 5.604 and 5.447 t ha^{-1}during the same periods. Grain yields followed the order of $M_2 > M_1 > M_3$ and M_4. In the pooled data, the grain yield in M_2 was 4.2 %, 13.43 % and 25.85 % higher than the M_1, M_3 and M_4, respectively.

Among the rice residue management practices, FYM application (S_5) achieved the maximum grain yields of 5.595 t ha^{-1} (Kharif 2022), 5.76 t ha^{-1}(Kharif 2023) and 5.678 t ha^{-1}in pooled data across years. This was followed by straw incorporation (S_3), straw biochar application (S_4), straw open burning (S_2) and straw removal (S_1), with grain yield reductions of 5.27 %, 8.75 %, 14.58 % and 17.05%, respectively. The lowest grain yield was recorded under straw removal (4.71 t ha^{-1}), which was statistically comparable to S_2 (4.85 t ha^{-1}). So, in residue management for grain yield, $S_5 > S_3 > S_4 > S_2 > S_1$.

Crop productivity

Crop productivity of rice varied significantly across different rice establishment methods and residue management practices during the Kharif seasons of 2022 and 2023, as well as in the combined analysis over both years (Table 3). Crop productivity differed significantly between the Kharif seasons of both years. However, the interaction effect between establishment methods and residue management practices was not significant. The treatment M_2 achieved the highest crop productivity of 40.307, 43.82 and 42.064 kg ha^{-1}day^{-1} in the Kharif seasons of 2022 and 2023 and across both years. This was significantly higher than all other rice establishment methods in Kharif 2022 and the pooled data, but was on par with M_1 in Kharif 2023. In the pooled data, M_2 achieved 2.89 %, 14.31 % and 29.17 % higher crop productivity over M_1, M_3 and M_4, respectively. So, in pooled data among the four establishment methods with respect to crop productivity, $M_2 > M_1 > M_3 > M_4$.

The treatment S_5 recorded the highest crop productivity of 40.848, 42.865 and 41.856 kg ha^{-1}day^{-1}in the Kharif seasons of 2022 and 2023 and across both years, respectively. This was significantly higher than all other residue management practices

Table 2. Effect of treatments on grain yield of Kharif and Rabi seasons and rice-rice system.

Treatments	Grain yield (t ha^{-1}) Kharif rice			Grain yield (t ha^{-1}) Rabi rice			Grain yield (t ha^{-1}) Rice-rice system		
	2022	2023	Pooled	2023	2024	Pooled	2022-23	2023-24	Pooled
Establishment methods									
M_1: wet DSR	5.291	5.604	5.447	4.154	4.370	4.262	9.445	10.020	9.732
M_2: modified SRI	5.495	5.857	5.676	4.266	4.489	4.377	9.761	10.300	10.031
M_3: machine planting	4.883	5.126	5.004	4.035	4.157	4.096	8.918	9.283	9.101
M_4: manual line planting	4.452	4.567	4.510	3.740	3.816	3.778	8.193	8.383	8.288
S. Em. (±)	0.0971	0.0817	0.0634	0.0416	0.0583	0.0358	0.1130	0.0910	0.0726
C. D. (0.05)	0.336	0.283	0.195	0.144	0.202	0.110	0.391	0.315	0.224
Rice residue management									
S_1: STBFR + straw removal	4.541	4.878	4.710	3.718	3.758	3.738	8.259	8.636	8.447
S_2: STBFR + straw open burning	4.688	5.012	4.850	3.870	3.939	3.905	8.558	8.951	8.754
S_3: STBFR + straw incorporation	5.273	5.486	5.379	4.172	4.459	4.316	9.445	9.945	9.695
S_4: STBFR + straw biochar application	5.055	5.306	5.181	4.028	4.320	4.174	9.083	9.626	9.355
S_5: STBFR + FYM application	5.595	5.760	5.678	4.456	4.564	4.510	10.051	10.324	10.188
S. Em. (±)	0.1085	0.1237	0.0823	0.0898	0.0868	0.0624	0.1575	0.1513	0.1092
C. D. (0.05)	0.312	0.356	0.232	0.259	0.250	0.176	0.454	0.436	0.308

Table 3. Effect of treatments on crop productivity of rice during Kharif (2022 and 2023) and Rabi (2023 and 2024) and system productivity of rice-rice system during 2022-23 and 2023-24.

Treatments	Crop productivity (kg ha^{-1} day^{-1})						System productivity (kg ha^{-1} day^{-1})		
	Kharif 2022	Kharif 2023	Pooled	Rabi 2023	Rabi 2024	Pooled	2022-23 (1st year)	2023-24 (2nd year)	Pooled
Establishment methods									
M_1: wet DSR	39.315	42.447	40.881	35.513	36.597	36.055	37.543	39.848	38.695
M_2: modified SRI	40.307	43.820	42.064	35.845	36.973	36.409	38.225	40.379	39.302
M_3: machine planting	35.541	38.054	36.797	33.662	33.993	33.828	34.657	36.122	35.389
M_4: manual line planting	31.829	33.298	32.563	30.826	30.847	30.837	31.357	32.126	31.742
S. Em. (±)	0.6783	0.5573	0.4389	0.4683	0.4305	0.3181	0.4193	0.2936	0.2560
C.D. (0.05)	2.347	1.928	1.352	1.620	1.489	0.980	1.451	1.016	0.789
Rice residue management									
S_1: STBFR + straw removal	33.435	36.634	35.035	31.395	31.109	31.252	32.474	33.994	33.234
S_2: STBFR + straw open burning	34.302	37.430	35.866	32.408	32.300	32.354	33.414	34.984	34.199
S_3: STBFR + straw incorporation	38.257	40.592	39.424	34.666	36.345	35.505	36.579	38.565	37.572
S_4: STBFR + straw biochar application	36.898	39.502	38.200	33.819	35.562	34.690	35.463	37.631	36.547
S_5: STBFR + FYM application	40.848	42.865	41.856	37.519	37.698	37.608	39.297	40.420	39.859
S. Em. (±)	0.7900	0.9154	0.6046	0.7383	0.7087	0.5117	0.5966	0.5946	0.4212
C. D. (0.05)	2.275	2.637	1.708	2.127	2.041	1.445	1.718	1.713	1.190

in both years during Kharif and the pooled data. In the pooled data, Treatment S_5 resulted in 6.17 %, 9.57 %, 16.7 % and 19.47 % higher crop productivity compared to S_3, S_4, S_2 and S_1, respectively. In pooled data among the residue management practices for crop productivity, $S_5 > S_3 > S_4 > S_2 > S_1$.

Economics of production

In Kharif 2022, treatment M_3S_5 recorded the highest cost of cultivation (₹75,243 ha^{-1}). In Kharif 2023, M_2S_5 had the highest cost (₹84,070 ha^{-1}) (Table 4). On average, across both years, the maximum cost of cultivation was observed under treatment M_2S_5 (₹79,296 ha^{-1}), followed by M_4S_5 (₹78,652 ha^{-1}) and modified SRI with biochar addition (₹75,495 ha^{-1}). The lowest cultivation costs were recorded in treatment M_1S_1, amounting to ₹65,313 ha^{-1} in 2022, ₹71,610 ha^{-1} in 2023 and ₹68,461 ha^{-1} on average across both years.

The maximum gross return, in Kharif 2022, was recorded in treatment M_2S_3 (₹1,32,437 ha^{-1}) (Table 4). In Kharif 2023 and on average across both years, M_2S_3 yielded the highest gross return, amounting to ₹1,43,546 ha^{-1} and ₹1,37,991 ha^{-1}, respectively. On average, across both years, M_1S_5 (₹1,25,470 ha^{-1}) and M_2S_3 (₹1,21,035 ha^{-1}) recorded the gross returns at second and third ranks. The lowest gross returns were recorded in manual line planting with straw removal (M_4S_1), with ₹78,718 ha^{-1} in 2022, ₹92,176 ha^{-1} in 2023 under M_4S_2 and an average of ₹85,936 ha^{-1} across both years M_4S_1.

The treatment M_1S_3 recorded the highest net return (₹57,915 ha^{-1}) in the Kharif 2022. Treatment M_1S_5 recorded the highest net return in Kharif 2023, amounting to ₹61,057 ha^{-1} and ₹58,695 ha^{-1} on average across both years (Table 4). On average, across both years, M_1S_5 (₹57,978 ha^{-1}) and M_2S_3 (₹55,397 ha^{-1}) recorded the net returns at second and third ranks. The lowest net returns were recorded in M_4S_1, with ₹11,347 ha^{-1} in 2022, ₹16,589 ha^{-1} in 2023 under M_4S_2 and an average of ₹14,998 ha^{-1} across both years under M_4S_1.

In Kharif 2022, the maximum BCR was recorded in wet DSR with M_1S_3 (1.78), followed by M_2S_5 (1.77) (Table 4). In 2023, the highest BCR was recorded in M_2S_3 (1.74), followed by M_1S_5 (1.69). On average over two years, M_1S_5 recorded the highest BCR at 1.773, followed by M_1S_3 (1.749) and M_2S_5 (1.742).

Crop profitability

The treatment M_2S_5 recorded the highest crop profitability at ₹427 ha^{-1} day^{-1} during Kharif 2022, followed by M_1S_5 (₹403 ha^{-1} day^{-1}) (Table 5). In Kharif 2023, the highest crop profitability was observed in M_1S_5 with the value of ₹456 ha^{-1} day^{-1}, followed by M_2S_3 (₹456 ha^{-1} day^{-1}). However, M_2S_5 recorded the highest crop profitability (₹437 ha^{-1} day^{-1}), averaged across Kharif seasons of 2022 and 2023, followed by M_1S_5 (₹429 ha^{-1} day^{-1}). The lowest crop profitability in Kharif 2022 was recorded under M_4S_1 (₹81 ha^{-1} day^{-1}), while in Kharif 2023, the lowest was observed under M_4S_2 (₹121 ha^{-1} day^{-1}). However, when averaged over both years, the lowest crop profitability was recorded in M_4S_1 (₹109 ha^{-1} day^{-1}).

Studies on Rabi rice

Grain yield

The grain yield of rice was significantly influenced by the rice establishment methods and residue management practices during the Rabi of 2023 and 2024 (Table 2). Grain yield differed significantly between the Rabi seasons of both years and the interaction effect between establishment methods and residue management practices. The treatment M_2 recorded the highest grain yield of 4.266 t ha^{-1} in 2023, 4.489 t ha^{-1} in 2024 and 4.377 t ha^{-1} in pooled data over both years during Rabi seasons, respectively. This was followed by M_1 (4.154, 4.37 and 4.262 t ha^{-1}), M_3 (4.035, 4.137 and 4.096 t ha^{-1}) and M_4 (3.74, 3.816 and 3.778 t ha^{-1}) in descending order during the Rabi seasons of 2023, 2024 and pooled over both years, respectively. However, the grain yields in M_2 and M_1 were statistically similar. In pooled data across two years, M_2 produced 2.7 %, 6.76 % and 15.85 % higher grain yield than M_1, M_3 and M_4, respectively. The treatment M_1S_5 recorded the highest filled grain count per panicle (95.8), followed by M_1S_5 (93.7). In contrast, M_4S_1 recorded the least grain count per panicle (64.9).

Among residue management practices, S_5 produced the highest grain yield, with 4.456 t ha^{-1} in 2023, 4.564 t ha^{-1} in 2024 and 4.51 t ha^{-1} in the pooled data across both years (Table 2). This was followed by S_3, S_4, S_2 and S_1 in descending order, showing a reduction in grain yield of 4.3 %, 7.45 %, 13.41 % and 17.11 % compared to S_5, respectively, assessed during the Rabi seasons of both years. Treatment M_2S_4 recorded the highest grain yield of 4.776 t ha^{-1}, followed by the M_2S_3 (4.689 t ha^{-1}) and M_2S_5 (4.682 t ha^{-1}) (Table 2). In contrast, M_4S_1 recorded the lowest grain yield at 3.495 t ha^{-1}.

Crop productivity

Treatment M_2 achieved the highest crop productivity of 35.845, 36.973 and 36.409 kg ha^{-1}day^{-1} in the Rabi seasons of 2023 and 2024 and across both years (Table 3). This was significantly higher than M_3 and M_4 by 7.63 % and 18.07%, but significantly higher than M_1 in the pooled data. In treatment S_5 recorded the highest crop productivity of 37.519, 37.698 and 37.608 kg ha^{-1} day^{-1}in the Rabi seasons of 2023, 2024 and across both years,

Table 4. Effect of rice establishment methods and residue management practices on production economics of rice during Kharif seasons of 2022 and 2023.

Treatments	Cost of cultivation (₹)			Gross return (₹)			Net return (₹)			BCR		
	Kharif 2022	Kharif 2023	Average	Kharif 2022	Kharif 2023	Average	Kharif 2022	Kharif 2023	Average	Kharif 2022	Kharif 2023	Average
M_1S_1	65313	71610	68461	104865	119608	112236	39552	47997	43775	1.606	1.670	1.638
M_1S_2	65647	72332	68989	104241	125188	114714	38594	52857	45725	1.588	1.731	1.659
M_1S_3	67473	73984	70729	118574	128845	123709	51101	54860	52981	1.757	1.742	1.749
M_1S_4	68654	75579	72117	118489	131566	125027	49835	55987	52911	1.726	1.741	1.733
M_1S_5	70571	79413	74992	125470	140469	132970	54899	61057	57978	1.778	1.769	1.773
M_2S_1	68339	75341	71840	109167	126819	117993	40827	51477	46152	1.597	1.683	1.640
M_2S_2	69676	76784	73230	114335	130392	122363	44659	53607	49133	1.641	1.698	1.670
M_2S_3	71091	78642	74866	121035	139492	130263	49944	60850	55397	1.703	1.774	1.738
M_2S_4	71681	79310	75495	116929	133647	125288	45248	54337	49793	1.631	1.685	1.658
M_2S_5	74522	84070	79296	132437	143546	137991	57915	59476	58695	1.777	1.707	1.742
M_3S_1	68726	70987	69856	100554	109840	105197	31828	38853	35341	1.463	1.547	1.505
M_3S_2	69728	72791	71260	99883	115233	107558	30154	42442	36298	1.432	1.583	1.508
M_3S_3	71811	73722	72766	106984	121412	114198	35173	47691	41432	1.490	1.647	1.568
M_3S_4	73070	74956	74013	104594	114111	109353	31524	39156	35340	1.431	1.522	1.477
M_3S_5	75243	79150	77196	115994	130189	123092	40752	51039	45895	1.542	1.645	1.593
M_4S_1	67371	74505	70938	78718	93154	85936	11347	18649	14998	1.168	1.250	1.209
M_4S_2	69042	75587	72314	87697	92176	89937	18655	16589	17622	1.270	1.219	1.245
M_4S_3	70456	78322	74389	109295	116456	112875	38839	38134	38486	1.551	1.487	1.519
M_4S_4	67705	79556	73630	96968	110047	103507	29263	30491	29877	1.432	1.383	1.408
M_4S_5	73554	83750	78652	109645	116961	113303	36091	33211	34651	1.491	1.397	1.444

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 and **S_5**: STBFR + FYM application.

Table 5. Effect of rice establishment methods and residue management practices on crop profitability during Kharif (2022 and 2023) and Rabi (2023 and 2024) and system profitability in rice-rice system during 2022-23 and 2023-24.

Treatments	Crop profitability (₹ ha^{-1} day^{-1})						System profitability (₹ ha^{-1} day^{-1})		
	Kharif 2022	Kharif 2023	Average	Rabi 2023	Rabi 2024	Average	2022-23 (1st year)	2023-24 (2nd year)	Average
M_1S_1	301	373	336	146	221	184	228	300	264
M_1S_2	290	406	347	237	249	243	265	330	298
M_1S_3	374	408	391	266	339	303	324	376	350
M_1S_4	369	423	396	225	348	287	302	387	345
M_1S_5	403	456	429	241	361	302	328	411	**370**
M_2S_1	301	387	344	173	147	160	242	273	257
M_2S_2	327	400	363	182	167	174	259	289	274
M_2S_3	363	452	407	204	398	302	289	426	358
M_2S_4	332	407	369	306	311	309	320	361	340
M_2S_5	427	447	437	206	332	270	324	392	358
M_3S_1	230	287	258	190	183	186	211	237	224
M_3S_2	218	313	265	131	212	172	178	265	221
M_3S_3	256	354	305	138	249	194	201	304	252
M_3S_4	230	292	261	85	235	160	162	265	213
M_3S_5	298	381	339	255	232	243	278	310	294
M_4S_1	81	137	109	56	179	118	70	157	113
M_4S_2	133	121	127	85	195	140	111	156	133
M_4S_3	278	278	278	184	168	176	234	225	230
M_4S_4	208	222	215	83	164	124	150	194	172
M_4S_5	258	242	250	198	155	177	230	201	216

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 and **S_5**: STBFR + FYM application

respectively. This was significantly higher than all other residue management practices in the Rabi season of 2023 and the pooled data, but was on par with S_3 in the Rabi season of 2024. In the pooled data, Treatment S_5 resulted in 5.92 %, 8.41 %, 16.24 % and 20.34 % higher crop productivity compared to S_3, S_4, S_2 and S_1, respectively.

Economics of production

In Rabi 2023, treatment M_3S_5 recorded the highest cost of cultivation (₹71,943 ha^{-1}). In Rabi 2024, M_2S_5 had the highest cost (₹76,106 ha^{-1}) (Table 6). On average, across both years, the highest cost of cultivation was observed under modified M_2S_5 (₹73,436 ha^{-1}), followed by M_3S_5 (₹73,083 ha^{-1}) and M_4S_5 (₹71,779 ha^{-1}). The lowest cultivation costs were recorded in M_1S_1, amounting to ₹61,859 ha^{-1} in 2022, ₹62,422 ha^{-1}in 2023 and ₹62,141 ha^{-1} on average across both years.

The maximum gross return, in Rabi 2022, was recorded in M_2S_4 (₹1,04,594 ha^{-1}). In Rabi 2023, the M_2S_3 resulted in the highest gross return, amounting to ₹1,19,322 ha^{-1}(Table 6). On average across both years, the highest gross return was recorded under M_2S_4, amounting to ₹1,06,885 ha^{-1}, followed by modified M_2S_5 (₹1,05,708 ha^{-1}) and M_2S_3 (₹1,05,607 ha^{-1}). The lowest gross returns were recorded in manual line planting with M_4S_1, with ₹70,843 ha^{-1}in 2022, ₹85,104 ha^{-1}in 2023 under M_4S_4 and an average of ₹78,742 ha^{-1} across both years under manual line planting with straw removal (M_4S_1).

The treatment M_2S_4 recorded the highest net return (₹36,387 ha^{-1}) in Rabi 2022. M_2S_3 recorded the highest net return in Rabi 2023, amounting to ₹48,698 ha^{-1}(Table 6). On average, across both years, M_2S_4 (₹37,033 ha^{-1}) recorded the highest net return, followed by M_2S_3 (₹36,628 ha^{-1}) and M_1S_3 (₹35,861 ha^{-1}). The lowest net returns were recorded in M_4S_1, with ₹6,772 ha^{-1}in *Rabi* 2022, ₹19,110 ha^{-1}in 2023 M_4S_5 and an average of ₹14,338 ha^{-1} across both years M_4S_1.

In Rabi 2022, the maximum BCR (1.533) was recorded in M_2S_4, followed by M_1S_3 (1.484) (Table 6). In Rabi 2023, the highest BCR (1.69) was recorded in M_2S_3, followed by wet DSR with M_1S_4 (1.631). On average over two years, M_1S_3 recorded the highest BCR (1.557), followed by M_2S_4 (1.532) and M_2S_3 (1.527).

Crop profitability

During Rabi 2023, the highest crop profitability was recorded in M_2S_4 at ₹306 ha^{-1} day^{-1}, followed by M_1S_3 at ₹266 ha^{-1} day^{-1}(Table 5). In Rabi 2024, M_1S_3 achieved the highest crop profitability at ₹398 ha^{-1} day^{-1}, followed by M_2S_5 (₹361 ha^{-1} day^{-1}). However, when averaged across Rabi seasons of 2023 and 2024, M_2S_4 recorded the highest crop productivity (₹309 ha^{-1} day^{-1}), followed by M_1S_3 at ₹303 ha^{-1} day^{-1}. The lowest crop profitability in Rabi 2022 was recorded M_4S_1 (₹56 ha^{-1} day^{-1}), while in Rabi 2023, the lowest was observed under M_2S_1 (₹147 ha^{-1} day^{-1}). However, when averaged over both years, the lowest crop profitability was recorded in M_4S_1 (₹118 ha^{-1} day^{-1}).

Studies on the rice-rice system

Grain yield

The yields in the rice-rice system for 2022-23 and 2023-24 were estimated by combining the grain and straw yields of Kharif 2022 with Rabi 2023 and Kharif 2023 with Rabi 2024, respectively (Table 2). Rice establishment methods and residue management practices significantly impacted system yields and harvest index in the rice-rice system. System grain yield differed significantly across the first (2022-23) and second (2023-24). System grain yield differed significantly between the years of rice-rice cropping system, while the interaction effect between establishment methods and residue management practices was not significant for system grain yield. Treatment M_2 recorded the highest system grain yield with 9.761 t ha^{-1} in 2022-23, 10.3 t ha^{-1} in 2023 -24 and 10.031 t ha^{-1} when pooled across two years (Table 2). In the system, grain yield $M_2 > M_1 > M_3 > M_4$. In treatment M_1 yielded 2.98 % less grain yield than M_2; it outperformed M_3 and M_4 by 6.93 % and 17.23 %, respectively.

Table 6. Effect of rice establishment methods and residue management practices on production economics of rice-rice during Rabi seasons of 2023 and 2024.

Treatments	Cost of cultivation (₹)			Gross return (₹)			Net return (₹)			BCR		
	(Rabi 2023)	(Rabi 2024)	Average	(Rabi 2023)	(Rabi 2024)	Average	(Rabi 2023)	(Rabi 2024)	Average	(Rabi 2023)	(Rabi 2024)	Average
M_1S_1	61859	62422	62141	78836	88667	83752	16977	26245	21611	1.274	1.420	1.347
M_1S_2	62528	63090	62809	90418	92994	91706	27890	29904	28897	1.446	1.474	1.458
M_1S_3	64354	64583	64469	95508	105151	100330	31154	40568	35861	1.484	1.628	1.557
M_1S_4	65201	65764	65482	91490	107293	99391	26289	41530	33909	1.403	1.631	1.517
M_1S_5	66783	69062	67923	94981	112072	103527	28198	43010	35604	1.422	1.623	1.521
M_2S_1	64866	68156	66511	85357	85880	85618	20491	17724	19108	1.316	1.260	1.288
M_2S_2	66202	69827	68015	87925	90194	89059	21722	20367	21045	1.328	1.292	1.309
M_2S_3	67334	70624	68979	91892	119322	105607	24558	48698	36628	1.365	1.690	1.527
M_2S_4	68207	71497	69852	104594	109176	106885	36387	37679	37033	1.533	1.527	1.532
M_2S_5	70766	76106	73436	95163	116254	105708	24397	40148	32272	1.345	1.528	1.437
M_3S_1	65426	65655	65541	88042	87862	87952	22616	22207	22411	1.346	1.338	1.343
M_3S_2	66429	66657	66543	82193	92627	87410	15764	25970	20867	1.237	1.390	1.314
M_3S_3	68512	69074	68793	85194	99815	92505	16683	30740	23711	1.244	1.445	1.347
M_3S_4	69770	69999	69885	79958	98712	89335	10188	28713	19451	1.146	1.410	1.278
M_3S_5	71943	74222	73083	102244	102405	102325	30301	28183	29242	1.421	1.380	1.401
M_4S_1	64071	64737	64404	70843	86641	78742	6772	21904	14338	1.106	1.338	1.223
M_4S_2	65742	66073	65908	75963	90105	83034	10221	24032	17126	1.155	1.364	1.258
M_4S_3	67491	67822	67656	90179	88959	89569	22688	21138	21913	1.336	1.312	1.323
M_4S_4	64405	64737	64571	74477	85104	79791	10072	20367	15219	1.156	1.315	1.233
M_4S_5	70588	72969	71779	94548	92080	93314	23960	19110	21535	1.339	1.262	1.300

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 and **S_5**: STBFR + FYM application.

Among residue management practices, S_5 achieved the highest system grain yield, with 10.051 t ha^{-1} in 2022-23, 10.324 t ha^{-1} in 2023-24 and 10.188 t ha^{-1} when pooled over two years (Table 2). Among residue management practices, system grain yield, S_5> S_3> S_4> S_2> S_1. While S_3 recorded a yield of 9.695 t ha^{-1}, 3.63 % lower than S_5, it outperformed S_4, S_2 and S_1 by 3.63 %, 10.46 % and 17.77 % in pooled data. S_4 ranked third with 9.355 t ha$^{-1,}$ producing 6.87 % and 10.75 % higher grain yield than S_2 and S_1, respectively.

System productivity

System productivity in the rice-rice system varied significantly across different rice establishment methods and residue management practices during 2022-23 and 2023-24, as well as in the combined analysis over both years (Table 3). The treatment M_2 achieved the highest system productivity of 38.225, 40.379 and 39.302 kg ha^{-1}day^{-1} in 2022-23, 2023-24 and across both years. This was significantly higher than all other rice establishment methods, except wet DSR, in both the years of study and the pooled data. In the pooled data, in M_2 achieved 1.57 %, 11.06 % and 23.82 % higher system productivity over M_1, M_3 and M_4, respectively.

FYM addition combined with STBFR (S_5) recorded the highest system productivity of 39.297, 40.42 and 39.859 kg ha^{-1} day^{-1}in 2022-23, 2023-24 and across both years, respectively (Table 3). This was significantly higher than all other residue management practices in both years and the pooled data. In the pooled data, S_5 resulted in 6.09 %, 9.06 %, 16.55 % and 19.93 % higher system productivity, compared to S_3, S_4, S_2 and S_1, respectively.

Economics of production

In 2022-23, treatment M_3S_5 recorded the highest cost of cultivation (₹1,47,186 ha^{-1}), followed by M_2S_5 (₹1,45,288 ha^{-1}) (Table 7). In 2023-2024, treatment M_2S_5 had the highest cost (₹1,60,176 ha^{-1}), followed by M_4S_5 (₹1,56,719 ha^{-1}). On average, across both years, the highest cost of cultivation was observed under modified SRI with FYM application (₹1,52,732 ha^{-1}), followed by manual line planting with FYM application (₹1,50,431 ha^{-1}) and mechanical planting with FYM addition (₹1,50,279 ha^{-1}). The lowest cultivation costs were recorded in treatment M_1S_1, amounting to ₹1,27,172 ha^{-1} in 2022-23, ₹1,34,032 ha^{-1}in 2023-24 and ₹1,30,602 ha^{-1} on average across both years.

The maximum gross return, in 2022-23, was recorded in treatment M_2S_5 addition (₹2,27,599 ha^{-1}), followed by M_2S_4 (₹2,21,523 ha^{-1}) (Table 7). In 2023-24, the treatment M_2S_5 resulted in the highest gross return, amounting to ₹2,59,800 ha^{-1}, followed by M_2S_3 (₹2,58,814 ha^{-1}). On average across both years, the highest gross return was recorded under treatment M_2S_5, amounting ₹243700 ha^{-1}, followed by M_1S_5 (₹2,36,496 ha^{-1}) and M_2S_3 (₹2,35,871 ha^{-1}). The lowest gross returns were recorded in M_4S_1, amounting to ₹1,49,561 ha^{-1}in 2022-23, ₹1,79,795 ha^{-1}in 2023-24 and ₹1,64,678 ha^{-1} across both years.

The treatment M_1S_5 recorded the highest net return (₹83,097 ha^{-1}) in 2022-23, followed by M_2S_5 (₹82,312 ha^{-1}) (Table 7). The treatment M_2S_3 recorded the highest net return in 2022-23, amounting to ₹1,09,548 ha$^{-1,}$ followed by M_1S_5 (₹1,04,067 ha^{-1}). On average, across both years, M_1S_5 (₹93,582 ha^{-1}), followed by M_2S_3 (₹92,025 ha^{-1}) and M_2S_5 (₹90,968 ha^{-1}). The lowest net returns were recorded in M_4S_1, with ₹18,119 ha^{-1}in 2022-23, ₹40,553 ha^{-1} in 2023-24 under M_4S_5 and an average of ₹29,336 ha^{-1} across both years under M_4S_1.

In 2022-23, the maximum BCR (1.621) was recorded in wet DSR with straw biochar (M_1S_4), followed by FYM application (M_1S_5) (1.6). In 2023-24, the highest BCR (1.694) was recorded in wet DSR with FYM addition (M_1S_5), followed by wet DSR with straw incorporation (M_1S_3) (1.686) (Table 7). On average, over two years, wet DSR with straw incorporation (M_1S_3) recorded the highest BCR (1.654), followed by modified SRI with FYM addition (M_2S_5) (1.647) and modified SRI with straw incorporation (M_2S_3) (1.633).

Table 7. Effect of rice establishment methods and residue management practices on production economics of rice-rice cropping system during 2022-23 and 2023-24.

Treatments	Cost of cultivation (₹)			Gross return (₹)			Net return (₹)			BCR		
	System (2022-23)	System (2023-24)	Average	System (2022-23)	System (2023-24)	Average	System (2022-23)	System (2023-24)	Average	System (2022-23)	System (2023-24)	Average
M_1S_1	127172	134032	130602	183701	208275	195988	56529	74242	65386	1.440	1.545	1.493
M_1S_2	128174	135422	131798	194659	218182	206421	66484	82761	74623	1.517	1.600	1.559
M_1S_3	131828	138567	135198	214083	233996	224040	82255	95428	88842	1.621	1.686	1.654
M_1S_4	133855	141343	137599	209979	238859	224419	76124	97517	86821	1.565	1.685	1.625
M_1S_5	137354	148475	142915	220451	252541	236496	83097	104067	93582	1.600	1.694	1.647
M_2S_1	133205	143497	138351	194524	212699	203612	61318	69201	65260	1.457	1.472	1.465
M_2S_2	135878	146611	141245	202259	220586	211423	66381	73974	70178	1.485	1.494	1.490
M_2S_3	138424	149266	143845	212927	258814	235871	74502	109548	92025	1.534	1.732	1.633
M_2S_4	139888	150807	145348	221523	242823	232173	81635	92016	86826	1.582	1.608	1.595
M_2S_5	145288	160176	152732	227599	259800	243700	82312	99624	90968	1.561	1.619	1.590
M_3S_1	134152	136642	135397	188596	197702	193149	54444	61060	57752	1.404	1.444	1.424
M_3S_2	136157	139448	137803	182076	207860	194968	45919	68412	57166	1.335	1.487	1.411
M_3S_3	140323	142796	141560	192179	221227	206703	51856	78431	65144	1.367	1.548	1.458
M_3S_4	142840	144955	143898	184553	212823	198688	41713	67869	54791	1.289	1.466	1.378
M_3S_5	147186	153372	150279	218238	232594	225416	71052	79222	75137	1.481	1.512	1.497
M_4S_1	131442	139242	135342	149561	179795	164678	18119	40553	29336	1.137	1.295	1.216
M_4S_2	134784	141660	138222	163660	182281	172971	28876	40621	34749	1.213	1.290	1.252
M_4S_3	137947	146144	142046	199474	205415	202445	61527	59272	60400	1.444	1.398	1.421
M_4S_4	132110	144293	138202	171445	195151	183298	39335	50858	45097	1.294	1.347	1.321
M_4S_5	144142	156719	150431	204193	209041	206617	60051	52321	56186	1.415	1.328	1.372

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 and **S_5**: STBFR + FYM application.

System profitability

During 2022-23 (1st year), the highest system profitability was recorded in treatment M_2S_5 at ₹328 ha^{-1} day^{-1}, followed by M_1S_3 and M_2S_5, both at ₹324 ha^{-1} day^{-1}(Table 5). During 2023-24 (2nd year), treatment M_2S_3 achieved the highest system profitability at ₹426 ha^{-1} day^{-1}, followed by M_1S_5 (₹411 ha^{-1} day^{-1}). However, when averaged across 2022-23 and 2023-24, M_1S_5 recorded the highest crop profitability (₹370 ha^{-1} day^{-1}), followed by M_2S_5 and M_2S_3, both at ₹358 ha^{-1} day^{-1}. The lowest system profitability in the 1st year (2022-23) was recorded under manual line planting combined with straw removal (₹70 ha^{-1} day^{-1}), while in the 2nd year (2023-24), the lowest was observed under manual line planting with straw open burning (₹156 ha^{-1} day^{-1}). However, when averaged over both years, the lowest system profitability was recorded in manual line planting with straw removal (M_4S_1) (₹113 ha^{-1} day^{-1}).

Discussion

Grain yield

In Kharif, the results indicate that the modified system of rice intensification (M_2) consistently produced the highest grain yields (5.676 t ha^{-1} in pooled data), followed by wet DSR (M_1) with 5.447 t ha^{-1}. MSRI practices, including wider spacing and younger seedling transplanting, enhance tillering, panicle length and grain filling, leading to higher yields (13). The superior performance of MSRI can be attributed to improved root growth, better nutrient uptake and efficient water management (14). Wet DSR also outperformed mechanical planting (M_3) and manual planting (M_4) due to its ability to reduce labour costs and maintain yield potential under favourable conditions (7).

Among residue management practices, FYM application (S_5) achieved the highest grain yield (5.678 t ha^{-1} in pooled data), followed by straw incorporation (S_3). Organic amendments like FYM enhance soil organic carbon, microbial activity and nutrient availability, thereby boosting rice yields (15). Straw incorporation (S_3) also improved yields compared to straw removal (S_1) or open burning (S_2), as it contributes to soil fertility over time (16). The lowest yields under straw removal (S_1) reflect that nutrient depletion reduces soil potassium and other micronutrients (17).

In the Rabi season, treatment M_2 again outperformed other methods with a pooled grain yield of 4.377 t ha^{-1}, though it was statistically similar to M_1. This similarity suggests that under controlled irrigation in Rabi, DSR can match SRI yields (18). The lower yields in Rabi compared to Kharif reflect seasonal differences in temperature and water availability (19). Among residue management practices, FYM (S_5) recorded the highest yield (4.51 t ha^{-1}), reinforcing the benefits of organic amendments in nutrient-poor Rabi soils.

The treatment M_2 recorded the highest system grain yield (10.031 t ha^{-1}), closely followed by wet DSR (M_1) with 9.732 t ha^{-1}. This confirms the robustness of MSRI across seasons (20). Treatment (S_5) achieved the highest system yield (10.188 t ha^{-1}), with straw incorporation (S_3) ranking second. The role of residue retention and organic inputs in sustaining system yields (21). Straw removal (S_1) and open burning (S_2) reduced yields significantly due to soil degradation (22).

The crop yield is a combined outcome of soil and environmental factors, determined by the yield-attributing characters. The yield and yield-attributing characters are the functions of the growth parameters. Early transplantation of younger seedlings in MSRI might have led to vigorous tillering and more productive/ effective tillers (those that produce grain), which increased the overall grain yield. Wider spacing might have ensured that each tiller is well-developed, supporting better grain filling and a higher harvest index. The improved root systems and balanced nutrient availability might have made crops more resilient to abiotic (drought, temperature fluctuations) stresses and biotic (pests, diseases) stresses. This might have resulted in consistent yield improvements. These findings are consistent with those researchers who compared SRI with conventional practices and observed better yield attributes, including a higher number of tillers and effective tillers, greater thousand-grain weight, longer panicle length and lower sterility percentage (23).

By the mineralization process, FYM is decomposed by microorganisms, converting organic nutrients into inorganic forms (such as ammonium, nitrate and phosphate) that are readily available for plant uptake. In rice cultivation, mineralization plays a vital role in enhancing grain yield, straw yield and overall plant growth. Mineralization releases essential nutrients like nitrogen (N), phosphorus (P), potassium (K) and micronutrients from organic matter and crop residues in the soil. On the contrary, residue removal includes increased risk of soil erosion and runoff because of reduced aggregation and decreased soil aggregation, which increases soil susceptibility to crusting and compaction. One of these factors leads to the loss of water and nutrients that adversely affect crop growth, yields and overall agronomic productivity.

Crop productivity

In Kharif, M_2 recorded the highest crop productivity (42.064 kg ha^{-1} day^{-1} in pooled data), followed by M_1. This is likely due to MSRI's ability to optimize resource use efficiency (24). Treatment S5 achieved the highest productivity (41.856 kg ha^{-1} day^{-1}), underscoring the role of organic inputs in sustaining long-term productivity (25). The significant reductions in productivity under treatment S_1 and S_2 align with the practices that degrade soil health and reduce crop performance (26). In Rabi M_2 achieved the highest productivity (36.409 kg ha^{-1} day^{-1}), statistically similar to M_1reflecting efficient resource use in both systems. Treatment S_5 led in productivity (37.608 kg ha^{-1} day^{-1}), with S3 performing comparably in 2024, likely due to cumulative soil fertility improvements (27).

In the rice-rice cropping system, M_2 led in system productivity (39.302 kg ha^{-1} day^{-1}), with M_1 performing comparably. FYM (S_5) achieved the highest productivity (39.859 kg ha^{-1} day^{-1}), reflecting its ability to maintain soil health across seasons (28). The significant reductions under S_1 highlight the importance of residue retention for long-term productivity.

Economics production

In Kharif, the highest cost of cultivation was observed under M_2S_5 (₹79,296 ha^{-1}), reflecting the labour and input-intensive nature of MSRI and FYM application. However, M_1S_5 recorded the highest net return (₹58,695 ha^{-1}) and BCR (1.773), indicating its economic viability. DSR reduces labour costs compared to transplanting methods while maintaining high returns with proper residue management (29). The lowest returns under M_4S_1 highlight the economic inefficiency of labour-intensive methods coupled with poor residue management (30).

In Rabi, the highest cultivation cost was under MSRI with FYM (₹73,436 ha^{-1}), but M_2S_4 yielded the highest net return (₹37,033 ha^{-1}) and BCR (1.532). Biochar is cost-effective because it has the potential to reduce fertilizer needs (31). Wet DSR with straw incorporation also performed well economically due to cost savings as per the lower cost of labours (32). Manual planting with straw removal (M_4S_1) was least profitable, reflecting high labour costs and low yields.

In the rice-rice cropping system, the highest cultivation cost was under MSRI with FYM (₹1,52,732 ha^{-1}), but M_1S_5 recorded the highest net return (₹93582 ha^{-1}) and BCR (1.654). This underscores the economic advantage of DSR in intensive systems (33). Treatment M_2S_3 also performed well, due to residue incorporation enhances returns over time (34). Manual planting with straw removal (M_4S_1) was least profitable, reflecting its unsustainability.

Profitability

The highest crop profitability in Kharif 2022 and 2023 under M_2S_5 and M_1S_5 with STBFR + FYM addition (₹437 and ₹429 ha^{-1} day^{-1}, respectively, averaged across years) aligns with studies that emphasize the economic advantages of SRI and DSR over conventional methods. Modified SRI, characterized by wider spacing, younger seedlings and reduced water use, enhances yield and resource-use efficiency, leading to higher net returns. The addition of FYM in (M_2S_5) and (M_1S_5) likely contributed to enhanced soil fertility and microbial activity, further boosting yields and profitability.

In Rabi, the M_2S_3 and M_2S_4 also resulted in high profitability (₹309 ha^{-1} day^{-1} for MSRI with biochar averaged across 2023-2024). Straw incorporation enhances SOC, improves soil structure and reduces the need for synthetic fertilizers, thereby lowering input costs. A meta-analysis found that straw retention increased rice yields by 5-10 % and net returns by 10-15 % compared to straw removal or burning (35). Biochar addition, as in MSRI with biochar, likely improved soil water-holding capacity and nutrient retention, contributing to higher profitability in Rabi 2023. The application of biochar can increase crop yields by 10-20 % in tropical soils by reducing nutrient leaching and enhancing soil fertility (36).

The highest system profitability under M_1S_5, ₹370 ha^{-1} day^{-1} averaged across 2022-2024 and M_2S_5 and M_2S_3, (₹358 ha^{-1} day^{-1}), reflects the cumulative benefits of these practices across Kharif and Rabi seasons. System profitability accounts for the entire rice-based cropping system, making it a robust indicator of economic sustainability. The superior performance of wet DSR with FYM application and Modified SRI with FYM can be attributed to their ability to maintain soil health, reduce input costs and stabilize yields across seasons. Conservation agriculture practices like DSR with residue retention and organic amendments improve system productivity and profitability by 15-25 % compared to conventional tillage and residue removal (37).

The results advocate for the adoption of modified SRI and wet DSR combined with residue retention (FYM, straw incorporation or biochar) to maximize profitability and sustainability in rice-based systems. These practices not only enhance economic returns but also contribute to environmental benefits, such as reduced greenhouse gas emissions and improved soil health. Policy incentives, such as subsidies for organic amendments or penalties for straw burning, could accelerate their adoption (38).

Conclusion

Rice straw management is a challenging task in areas with rice-rice production systems. A comparison of the production efficiency and profitability of rice under different establishment methods and residue management practices was quite essential for adopting practices of rice double cropping. The findings of the field experiments involving four different rice establishment methods and five residue management practices indicated the highest grain yields across Kharif and Rabi seasons under modified system of rice intensification (MSRI), especially when combined with FYM. FYM addition significantly enhanced productivity, with the highest system grain yield of 10.869 t ha^{-1} recorded under MSRI + FYM. While MSRI + FYM resulted in the highest gross monetary return (₹2,43,700), it produced the third-highest net return, following wet DSR + FYM and MSRI + straw incorporation. Wet DSR with FYM addition was the most profitable system in terms of net return (₹93,582) and daily system profitability (₹370 ha^{-1} day^{-1}). Despite higher cultivation costs, MSRI + FYM showed strong performance in yield and profitability during Kharif but was outperformed by other combinations in Rabi. The lowest economic performance was observed in manual line transplanting with straw removal, which had the lowest returns and benefit-cost ratio. Techno-economic analyses of biochar production, bioenergy generation and industrial applications should be undertaken as an alternative profitable pathway for effective and efficient use of excess rice residues by the farmers. Moreover, study on the production economics of the *in-situ* compost making from the rice residues could profitably substitute the costlier FYM addition thereby could enhance the net return and benefit-cost ratio.

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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. AK contributed to laboratory analysis and data interpretation. The statistical analysis was carried out by JM, SKD, PKS and TRM. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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