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INTEGRATED ASSESSMENT OF ORGANIC AMENDMENTS FOR ENHANCING SOIL HEALTH, PRODUCTIVITY AND CLIMATE RESILIENCE IN DIRECT SEEDED AND TRANSPLANTED RICE SYSTEMS

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ABSTRACT

Rice is a major staple crop supporting the livelihoods of more than half of the world's population, particularly in Asia. However, prolonged intensification of rice cultivation through excessive use of chemical fertilizers, continuous mono-cropping and inefficient water management has resulted in declining soil health, reduced productivity and increased vulnerability to climate change. To address these challenges, the present study evaluates an integrated nutrient management approach using organic amendments to enhance soil fertility, crop productivity and climate resilience in Direct Seeded Rice (DSR) and Transplanted Rice (TPR) systems. The experiment was conducted in a randomized block design with three replications, involving two rice establishment methods (DSR and TPR) and different organic amendments farmyard manure, vermicompost and poultry manure applied to the rice variety Pusa Basmati 1509. The study assess changes in soil physicochemical and biological properties, including soil organic carbon, microbial biomass carbon, enzyme activities, bulk density, water-holding capacity and nutrient use efficiency. Crop performance was evaluated through growth, phenology, yield attributes, final grain and straw yield, along with climate resilience indicators such as water productivity, nitrogen-use efficiency, stress tolerance indices and carbon footprint. Results revealed that organic amendments significantly improved soil health, nutrient synchronization and crop resilience in both systems. DSR, when supported with appropriate organic and microbial inputs, showed enhanced resource-use efficiency, improved soil moisture retention and reduced greenhouse gas emissions. However, TPR maintained more stable yields due to uniform crop establishment, better early vigor and effective weed suppression under flooded conditions, explaining its continued preference among farmers. Overall, the study demonstrates that site-specific integration of organic amendments with appropriate rice establishment methods can promote sustainable intensification, strengthen climate resilience and reduce dependence on chemical fertilizers in rice-based production systems.

Key words: Direct Seeded Rice, Transplanted Rice, Organic Amendments, Soil Health, Climate Resilience

Introduction

Rice (*Oryza sativa* L.) forms the dietary foundation for more than half of the global population, with Asian countries accounting for the overwhelming share of its cultivation and consumption (Bandumula, 2017; Muthayya *et al.*, 2014). Rising population pressure, expected to reach nearly 10 billion by mid-century, places increasing demand on rice-based food systems and necessitates sustained yield enhancement (Ray *et al.*, 2013; FAO, 2004; United Nations, 2022). This challenge is intensified by climate variability, as rice production is highly sensitive to changes in temperature, rainfall patterns and the frequency of extreme weather events, which collectively threaten yield stability and food security (Lobell *et al.*, 2011; Wassmann *et al.*, 2009). In India, rice continues to dominate the agricultural landscape, with Uttar Pradesh emerging as the largest producer, underlining its national importance (DA & FW, 2025).

Conventional flooded rice ecosystems are also recognized as major agricultural sources of methane and

Table 1: Treatment wise mean values along with coefficient of variation (CV), F-ratio, probability levels, standard error (SE) and critical difference (CD) at 5% and 1% for growth, phenology, yield and harvest index traits in rice.

Means Table												
	PH	**NT**	**NS**	**SH**	**NG**	**DPI**	**WP**	**WOP**	**TW**	**SF**	**EY**	**HI**
1 Treatment	102.1067	7.7733	59.0000	71.3333	63.6667	33.3333	0.5667	0.9867	20.0000	105.1100	13.3333	87.6333
2 Treatment	106.3733	7.1067	69.0000	63.0000	57.3333	39.0000	0.7500	2.0400	24.3333	83.3633	13.0000	79.3867
3 Treatment	97.4967	9.2167	48.0000	70.3333	57.6667	27.6667	0.7600	3.5400	21.0000	113.9367	10.0000	100.0000
4 Treatment	100.3867	6.8833	71.6667	78.3333	58.6667	33.0000	0.5400	6.3633	17.3333	87.3533	10.3333	91.8300
5 Treatment	74.3633	15.6633	77.6667	78.0000	89.3333	16.6667	1.0300	6.7300	20.0000	120.8033	12.3333	82.8200
6 Treatment	87.1533	16.1067	76.6667	84.3333	79.6667	20.0000	1.0167	7.2733	22.6667	110.4967	12.0000	80.2300
7 Treatment	88.8300	15.1067	59.3333	87.3333	80.6667	22.6667	1.0933	7.0967	21.6667	122.5800	14.6667	90.7300
8 Treatment	97.9400	16.8867	67.6667	82.0000	92.0000	14.0000	1.0833	4.7867	25.3333	132.3300	9.3333	101.1100
Mean	**94.3313**	**11.8429**	**66.1250**	**76.8333**	**72.3750**	**25.7917**	**0.8550**	**4.8521**	**21.5417**	**109.4967**	**11.8750**	**89.2175**
C.V.	6.7809	10.1809	7.3903	5.8310	6.3737	43.3249	9.4136	35.0163	15.7790	13.9363	7.9039	25.9237
F ratio	7.8107	41.0824	12.7615	9.8363	30.2297	1.8961	24.3536	6.1296	1.7141	3.7428	11.5608	0.3907
F Prob.	0.0006	0.0000	0.0000	0.0002	0.0000	0.1460	0.0000	0.0020	0.1850	0.0170	0.0001	0.8926
S.E.	3.6930	0.6961	2.8214	2.5866	2.6633	6.4514	0.0465	0.9809	1.9624	8.8102	0.5419	13.3532
C.D. 5%	11.2016	2.1115	8.5578	7.8456	8.0783	-	0.1409	2.9753	-	26.7230	1.6437	-
C.D. 1%	15.5472	2.9306	11.8778	10.8893	11.2122	-	0.1956	4.1296	-	37.0901	2.2813	-

Table 2: Analysis of variance (ANOVA) and genetic parameters for growth, yield, and yield-attributing traits in rice (*Oryza sativa* L.).

Trait	**Replicate SS**	**Treatment SS**	**Error SS**	**Replicate SS**	**Treatment SS**	**Error SS**	**F-value**
Plant Height (PH)	318.02	2237.05	572.82	159.01	319.58	40.92	7.81
Number of Tillers (NT)	8.63	418.06	20.35	4.31	59.72	1.45	41.08
Number of Spikelets (NS)	7.00	2133.29	334.33	3.50	304.75	23.88	12.76
Spikelet Height (SH)	4.33	1382.00	281.00	2.17	197.43	20.07	9.83
Seeds per Spikelet	0.75	4502.96	297.92	0.38	643.28	21.28	30.23
DPI	0.58	1657.29	1748.08	0.29	236.76	124.86	1.90
Wet Weight per Plant (WP)	0.07	1.10	0.09	0.04	0.16	0.01	24.35
Thousand Weight (TW)	17.58	138.62	161.75	8.79	19.80	11.55	1.71
Seed Filling % (SF)	204.66	6100.83	3260.06	102.33	871.55	232.86	3.74
Biological Yield (BY)	0.25	89.33	46.42	0.13	12.76	3.32	3.84
Economic Yield (EY)	27.00	71.29	12.33	13.50	10.18	0.88	11.56
Harvest Index (HI)	66944.70	1462.99	7488.96	33472.35	208.99	534.93	0.39

Contiune ...2

Trait	**Probability (P-value)**	**General mean**	**CD (5%)**	**CD (1%)**	**S.E.D.**	**S.E. mean**	**Env. variance**	**Genotypic variance**
Plant Height (PH)	0.0006	94.33	11.20	15.55	5.22	3.45	13.64	92.88
Number of Tillers (NT)	0.0000	11.84	2.11	2.93	0.98	0.65	0.48	19.42
Number of Spikelets (NS)	0.0000	66.13	8.55	11.87	3.99	2.63	7.96	93.63
Spikelet Height (SH)	0.0002	76.83	7.85	10.88	3.65	2.41	6.69	59.12
Seeds per Spikelet	0.0000	72.37	8.07	11.21	3.77	2.49	7.09	207.33
DPI	0.1460	25.79	19.56	27.15	9.12	6.03	41.62	37.29
Wet Weight per Plant (WP)	0.0000	0.85	0.14	0.19	0.07	0.04	0.002	0.05
Thousand Weight (TW)	0.1850	21.54	5.95	8.26	2.77	1.83	3.85	2.75
Seed Filling % (SF)	0.0170	109.49	26.72	37.09	12.46	8.24	77.62	212.89
Biological Yield (BY)	0.0153	21.50	3.18	4.42	1.48	0.98	1.10	3.14
Economic Yield (EY)	0.0001	11.87	1.64	2.28	0.77	0.51	0.29	3.10
Harvest Index (HI)	0.8926	89.22	40.50	56.21	18.88	12.49	178.31	-108.64

Contiune ...2

Trait	PV	GCV	PCV	ECV	BS	GA5	GAM5	GA1	GAM1
Plant Height (PH)	106.53	10.21	10.94	6.78	**0.872**	18.54	19.65	23.76	25.18
Number of Tillers (NT)	19.90	37.21	37.67	10.18	**0.9757**	8.97	75.72	11.49	97.04
Number of Spikelets (NS)	101.58	14.63	15.24	7.39	**0.9216**	19.13	28.94	24.52	37.09
Spikelet Height (SH)	65.81	10.01	10.55	5.83	**0.8983**	15.01	19.53	19.24	25.04
Seeds per Spikelet	214.42	19.89	20.23	6.37	**0.9669**	29.16	40.30	37.38	51.65
DPI	78.91	23.67	34.44	43.32	**0.4726**	8.64	33.53	11.08	42.98
Wet Weight per Plant (WP)	0.05	26.26	26.82	9.41	**0.9589**	0.45	52.98	0.58	67.89
Thousand Weight (TW)	6.60	7.69	11.92	15.77	**0.4166**	2.20	10.23	2.83	13.11
Seed Filling % (SF)	290.51	13.32	15.56	13.93	**0.7328**	25.73	23.49	32.97	30.11
Biological Yield (BY)	4.25	8.25	9.59	8.46	**0.7402**	3.15	14.62	4.03	18.75
Economic Yield (EY)	3.39	14.83	15.51	7.90	**0.9135**	3.47	29.20	4.44	37.41
Harvest Index (HI)	69.67	11.68	9.35	25.92	**-1.5595**	-26.81	-30.05	-34.36	-38.51
PV: Phenotypic Variance; GCV: GCV (%); PCV: PCV (%); ECV: ECV (%); BS: h² (Broad Sense); GA5: Genetic Advance (5%); GAM5: GA as % of Mean (5%); GA1: Genetic Advance (1%); GAM1:GA as % of Mean (1%)									

nitrous oxide due to prolonged anaerobic soil conditions, thereby contributing to global warming (Qian *et al.*, 2023). Alongside increasing greenhouse gas emissions, intensive water use in rice cultivation has accelerated groundwater depletion in key production zones, emphasizing the need for environmentally sustainable and climate-adaptive production approaches (Pretty, 2008).

Pusa Basmati 1509, an early-duration Basmati rice variety developed for the northwestern plains of India, is widely adopted due to its high productivity and shorter crop cycle (Jain *et al.*, 2015; Ministry of Agriculture and Farmers Welfare, 2013). Despite these advantages, its cultivation under traditional transplanting systems places considerable pressure on water resources. Given the limited availability of alternative crops offering comparable economic returns, improving the sustainability of Basmati-based systems remains a priority (Kaur *et al.*, 2018; Singh and Singh, 2020).

The use of organic amendments, including farmyard manure, compost and poultry manure, has gained attention

Table 3: Summary of genetic parameters showing environmental, genotypic and phenotypic variances, environmental, genotypic and phenotypic coefficients of variation, broad-sense heritability, and genetic advance (absolute and percent of mean) at 5% and 1% selection intensity for growth, phenological and yield attributes in rice.

Genetic Parameters (Summary)										
	PH	**NT**	**NS**	**SH**	**NG**	**DPI**	**WP**	**WOP**	**TW**	**SF**
Var Environmental	13.638	0.485	7.960	6.690	7.093	41.621	0.002	0.962	3.851	77.620
ECV	6.781	10.181	7.390	5.831	6.374	43.325	9.414	35.016	15.779	13.936
Var Genotypical	92.888	19.423	93.625	59.119	207.333	37.298	0.050	4.936	2.750	212.895
GCV	10.217	37.214	14.633	10.007	19.895	23.679	26.265	45.788	7.698	13.325
Var Phenotypical	106.526	19.908	101.585	65.810	214.427	78.919	0.053	5.898	6.601	290.516
PCV	10.941	37.675	15.242	10.558	20.233	34.444	26.821	50.052	11.927	15.566
h² (Broad Sense)	0.872	0.976	0.922	0.898	0.967	0.473	0.959	0.837	0.417	0.733
Genetic Advancement 5%	18.539	8.968	19.136	15.012	29.167	8.649	0.453	4.187	2.205	25.731
Genetic Advancement 1%	23.759	11.492	24.523	19.239	37.380	11.084	0.581	5.365	2.826	32.975
Gen. Adv as % of Mean 5%	19.654	75.721	28.939	19.539	40.300	33.534	52.982	86.287	10.236	23.499
Gen. Adv as % of Mean 1%	25.187	97.041	37.086	25.040	51.647	42.975	67.900	110.581	13.117	30.115
Var Environmental	1.105	0.294	178.309							
ECV	8.469	7.904	25.924							
Var Genotypical	3.149	3.101	-108.642							
GCV	8.253	14.830	11.683							
Var Phenotypical	4.254	3.395	69.666							
PCV	9.593	15.516	9.355							
h² (Broad Sense)	0.740	0.914	-1.559							
Genetic Advancement 5%	3.145	3.467	-26.814							
Genetic Advancement 1%	4.030	4.443	-34.363							
Gen. Adv as % of Mean 5%	14.628	29.198	-30.054							

Table 4: Broad-sense heritability (h^2) matrix showing heritability estimates and associated relationships among growth, phenological, yield and harvest index traits in rice.

	PH	NT	NS	SH	NG	DPI	WP	WOP	TW	SF	BY	EY	HI
1 PH	0.8720	1.0299	1.1060	1.0112	1.0323	1.0047	0.9556	0.9535	1.5097	0.9975	0.9180	1.0186	1.3440
2 NT	1.0299	0.9757	1.0387	1.0210	0.9855	0.9698	0.9972	1.0269	1.0288	0.9508	1.0307	2.1495	-0.1652
3 NS	1.1060	1.0387	0.9216	0.9054	0.9924	0.9632	1.0978	1.0090	4.7052	0.5493	1.0131	1.8414	0.8151
4 SH	1.0112	1.0210	0.9054	0.8983	0.9823	0.9975	1.0512	0.9870	-0.8660	1.0251	0.9821	0.1901	1.5604
5 NG	1.0323	0.9855	0.9924	0.9823	0.9669	0.9869	1.0089	0.9617	1.2397	0.9394	1.1382	0.1200	1.1371
6 DPI	1.0047	0.9698	0.9632	0.9975	0.9869	0.4726	1.0288	1.2325	0.5923	0.9778	0.9020	1.1713	3.0894
7 WP	0.9556	0.9972	1.0978	1.0512	1.0089	1.0288	0.9589	1.0154	0.9078	0.9409	1.0283	1.2639	-7.9369
8 WOP	0.9535	1.0269	1.0090	0.9870	0.9617	1.2325	1.0154	0.8369	0.3147	0.9740	1.3009	1.7778	0.7673
9 TW	1.5097	1.0288	4.7052	-0.8660	1.2397	0.5923	0.9078	0.3147	0.4166	0.8688	0.5541	0.6857	-1.2178
10 SF	0.9975	0.9508	0.5493	1.0251	0.9394	0.9778	0.9409	0.9740	0.8688	0.7328	1.2110	0.8574	0.9369
11 BY	0.9180	1.0307	1.0131	0.9821	1.1382	0.9020	1.0283	1.3009	0.5541	1.2110	0.7402	1.0586	0.2198
12 EY	1.0186	2.1495	1.8414	0.1901	0.1200	1.1713	1.2639	1.7778	0.6857	0.8574	1.0586	0.9135	0.7636
13 HI	1.3440	-0.1652	0.8151	1.5604	1.1371	3.0894	-7.9369	0.7673	-1.2178	0.9369	0.2198	0.7636	-1.5595

as an effective strategy for improving soil quality and long-term productivity (Lal, 2015; Pretty, 2008). These inputs enhance soil organic carbon, strengthen soil structure and stimulate microbial activity, thereby improving nutrient availability and root zone conditions (Doran and Zeiss, 2000; Gomez and Govaerts, 2009; Van Bruggen *et al.*, 2018). Moreover, organic matter additions promote carbon sequestration and may alter greenhouse gas fluxes from rice soils, contributing to climate change mitigation (Paustian *et al.*, 2016; Qian *et al.*, 2023).

Rice establishment techniques further modulate these processes. Transplanted rice is associated with high water and labor requirements and elevated methane emissions, whereas direct-seeded rice offers advantages through reduced water use, lower labor inputs and shorter crop duration (Tuong and Bouman, 2003). The distinct soil aeration regimes under these systems influence organic matter decomposition, nutrient dynamics and greenhouse gas emissions (Gomez and Govaerts, 2009; Kumar *et al.*, 2019). Consequently, a comparative assessment of organic amendments under transplanted and direct-seeded rice systems is essential for developing resource-efficient, low-emission and climate-resilient rice production strategies (FAO, 2022; Mbow *et al.*, 2023).

Materials and Methods

The present investigation entitled *“Integrated Assessment of Organic Amendments for Enhancing Soil Health, Yield and Climate Resilience in Direct Seeded and Transplanted Rice System”* was conducted during the Kharif season of 2025–26 at the Crop Cafeteria experimental farm of the School of Agriculture and Environmental Sciences, Shobhit University, Gangoh, Saharanpur, Uttar Pradesh, India. *Pusa Basmati 1509*, a widely cultivated basmati rice variety, was used as the experimental material and evaluated under field conditions.

The experiment was carried out from June to August

Table 5: Expected genetic advance at 5% selection intensity estimated from genotypic variance and broad-sense heritability for growth, phenological, biomass, yield and harvest index traits in rice.

	PH	NT	NS	SH	NG	DPI	WP	WOP	TW	SF	BY	EY	HI
1 PH	18.5395	12.2579	15.1076	14.4556	21.9268	16.8809	2.4514	8.3462	6.4530	20.4223	4.3521	3.9625	12.6492
2 NT	12.2579	8.9676	8.4878	11.0807	16.0075	12.2490	2.0202	5.6250	4.6562	15.6186	4.6631	0.5727	-0.4794
3 NS	15.1076	8.4878	19.1357	8.7686	16.4996	9.8674	1.7488	7.1776	7.8311	5.4049	6.1354	2.0346	12.0155
4 SH	14.4556	11.0807	8.7686	15.0124	18.6404	15.0077	2.3555	8.2245	-1.5652	19.5441	5.7225	0.2940	10.9344
5 NG	21.9268	16.0075	16.4996	18.6404	29.1674	22.3369	3.5490	8.9031	9.3879	27.6114	8.3368	0.0954	5.5411
6 DPI	16.8809	12.2490	9.8674	15.0077	22.3369	8.6489	2.7725	9.3666	3.0468	23.4499	4.9131	4.7884	28.1829
7 WP	2.4514	2.0202	1.7488	2.3555	3.5490	2.7725	0.4530	1.1986	1.0803	3.3598	1.1448	0.5484	-2.3542
8 WOP	8.3462	5.6250	7.1776	8.2245	8.9031	9.3666	1.1986	4.1867	0.6790	7.6846	2.4374	1.4349	1.6458
9 TW	6.4530	4.6562	7.8311	-1.5652	9.3879	3.0468	1.0803	0.6790	2.2049	6.6448	1.5916	0.6447	-1.6952
10 SF	20.4223	15.6186	5.4049	19.5441	27.6114	23.4499	3.3598	7.6846	6.6448	25.7305	11.8257	3.4164	15.7125
11 BY	4.3521	4.6631	6.1354	5.7225	8.3368	4.9131	1.1448	2.4374	1.5916	11.8257	3.1450	3.0285	0.7808
12 EY	3.9625	0.5727	2.0346	0.2940	0.0954	4.7884	0.5484	1.4349	0.6447	3.4164	3.0285	3.4673	4.8911
13 HI	12.6492	-0.4794	12.0155	10.9344	5.5411	28.1829	-2.3542	1.6458	-1.6952	15.7125	0.7808	4.8911	-26.8135

Table 6: The provided table is a genotypic correlation matrix (R_g), where the values represent the genotypic correlation coefficients (r_{gij}) between traits (i) and (j). A correlation coefficient measures the degree of linear association between two variables.

Genotypical Correlation Matrix												
	PH	**NT**	**NS**	**SH**	**NG**	**DPI**	**WP**	**WOP**	**TW**	**SF**	**BY**	**HI**
PH	**1.0000**	-0.8094	-0.5215	-0.6571	-0.7908	1.1356	-0.6847	-0.8040	0.4067	-0.7006	-0.2843	-0.2793
NT	-0.8094	**1.0000**	0.3833	0.8363	0.9655	-1.3545	0.9745	0.7416	0.6794	0.9402	0.6357	0.0071
NS	-0.5215	0.3833	**1.0000**	0.2690	0.4640	-0.4031	0.3021	0.5597	0.1914	-0.0888	-0.5100	0.4139
SH	-0.6571	0.8363	0.2690	**1.0000**	0.7529	-1.1331	0.7203	0.9454	0.0523	0.7827	0.5759	-0.2253
NG	-0.7908	0.9655	0.4640	0.7529	**1.0000**	-1.3548	0.9098	0.6071	0.7016	0.9103	0.5632	-0.0424
DPI	1.1356	-1.3545	-0.4031	-1.1331	-1.3548	**1.0000**	-1.2838	-1.2363	-0.3647	-1.4871	-0.5819	0.9518
WP	-0.6847	0.9745	0.3021	0.7203	0.9098	-1.2838	**1.0000**	0.6683	0.8135	0.8629	0.7537	0.0703
WOP	-0.8040	0.7416	0.5597	0.9454	0.6071	-1.2363	0.6683	**1.0000**	-0.0937	0.4407	0.2730	0.0359
TW	0.4067	0.6794	0.1914	0.0523	0.7016	-0.3647	0.8135	-0.0937	**1.0000**	0.4950	0.3661	0.0322
SF	-0.7006	0.9402	-0.0888	0.7827	0.9103	-1.4871	0.8629	0.4407	0.4950	**1.0000**	1.0510	-0.4083
BY	-0.2843	0.6357	-0.5100	0.5759	0.5632	-0.5819	0.7537	0.2730	0.3661	1.0510	**1.0000**	-0.0353
HI	-0.2793	0.0071	0.4139	-0.2253	-0.0424	0.9518	0.0703	0.0359	0.0322	-0.4083	-0.0353	**1.0000**
EY	-0.2140	-0.0046	0.0311	0.0079	0.0007	0.4289	0.1418	-0.0698	-0.0489	-0.1248	0.6534	0.4022

2025 to assess rice performance under two crop establishment methods, namely Direct Seeded Rice (DSR) and Transplanted Rice (TPR), along with different organic nutrient treatments. Under DSR, seeds were directly sown in the main field at the end of May 2025 using a seed drill at a shallow depth, maintaining uniform row spacing for proper crop establishment. In the TPR method, seedlings were raised in nursery beds and transplanted into the main field after about 25 days using standard spacing and seedling density. Proper nursery management was followed to ensure healthy and uniform seedlings.

The field experiment was laid out in a randomized block design with three replications. Four nutrient management treatments were applied under both establishment methods, namely farmyard manure, vermicompost, poultry manure and a control without organic amendment. All treatment combinations were accommodated within each replication to enable valid comparison among treatments.

Observations Recorded

At maturity, three plants were randomly selected from each treatment in each replication. The selected plants were harvested and threshed separately for recording observations. Soil chemical properties were analyzed by determining soil pH, which indicates soil reaction (Sorensen, 1909), and electrical conductivity, which reflects soluble salt concentration in the soil solution (Richards, 1954).

Growth and phenological observations included days to germination, recorded as the number of days from sowing to seedling emergence (ISTA, 1931). Days to

Table 7: The phenotypic correlation matrix reveals the linear associations between the measured traits, providing crucial insights into suitable indirect selection criteria.

Phenotypical Correlation Matrix												
	PH	**NT**	**NS**	**SH**	**NG**	**DPI**	**WP**	**WOP**	**TW**	**SF**	**BY**	**HI**
PH	**1.0000**	-0.7249	-0.4227	-0.5751	-0.7034	0.7256	-0.6553	-0.7203	0.1624	-0.5614	-0.2488	0.2423
NT	-0.7249	**1.0000**	0.3499	0.7668	0.9516	-0.9484	0.9452	0.6525	0.4210	0.8361	0.5241	0.0533
NS	-0.4227	0.3499	**1.0000**	0.2703	0.4413	-0.2762	0.2587	0.4871	0.0252	-0.1328	-0.4158	-0.6087
SH	-0.5751	0.7668	0.2703	**1.0000**	0.7143	-0.7402	0.6360	0.8305	-0.0369	0.6195	0.4781	0.1709
NG	-0.7034	0.9516	0.4413	0.7143	**1.0000**	-0.9280	0.8683	0.5679	0.3592	0.8157	0.4186	0.0458
DPI	0.7256	-0.9484	-0.2762	-0.7402	-0.9280	**1.0000**	-0.8401	-0.6308	-0.2732	-0.8950	-0.3816	-0.2645
WP	-0.6553	0.9452	0.2587	0.6360	0.8683	-0.8401	**1.0000**	0.5896	0.5664	0.7688	0.6175	0.0108
WOP	-0.7203	0.6525	0.4871	0.8305	0.5679	-0.6308	0.5896	**1.0000**	-0.1758	0.3544	0.1651	-0.0535
TW	0.1624	0.4210	0.0252	-0.0369	0.3592	-0.2732	0.5664	-0.1758	**1.0000**	0.3148	0.3669	0.0213
SF	-0.5614	0.8361	-0.1328	0.6195	0.8157	-0.8950	0.7688	0.3544	0.3148	**1.0000**	0.6392	0.4658
BY	-0.2488	0.5241	-0.4158	0.4781	0.4186	-0.3816	0.6175	0.1651	0.3669	0.6392	**1.0000**	0.1727
HI	0.2423	0.0533	-0.6087	0.1709	0.0458	-0.2645	0.0108	-0.0535	0.0213	0.4658	0.1727	**1.0000**
EY	-0.1875	-0.0020	0.0155	0.0377	0.0055	0.2406	0.1050	-0.0343	-0.0440	-0.1191	0.5075	-0.6286

Table 8: Estimates of environmental variances (diagonal) and environmental correlation coefficients (off-diagonal) among growth, phenological, biomass, yield and harvest index traits in rice.

	PH	NT	NS	SH	NG	DPI	WP	WOP	TW	SF	BY	EY	HI
1 PH	**13.6385**	0.3884	0.4472	0.0566	0.3495	-0.0131	-0.4017	-0.2317	-0.3028	-0.0075	-0.1119	0.0331	-0.1456
2 NT	0.9985	**0.4846**	-0.3101	-0.3234	0.4867	-0.2529	0.0836	-0.2786	-0.1019	0.5101	-0.2024	0.0510	0.2488
3 NS	4.6598	-0.6090	**7.9603**	0.2866	0.0657	-0.0500	-0.4460	-0.0389	-0.4368	-0.4136	0.0381	-0.1583	-0.2513
4 SH	0.5403	-0.5823	2.0913	**6.6905**	0.2175	-0.0080	-0.5040	0.0838	-0.2830	-0.0943	0.0525	0.3256	-0.1877
5 NG	3.4380	0.9023	0.4940	1.4980	**7.0933**	-0.0921	-0.2108	0.2960	-0.6197	0.5260	-0.6240	0.0907	-0.0216
6 DPI	-0.3111	-1.1357	-0.9107	-0.1329	-1.5833	**41.6210**	0.1641	0.5001	-0.2008	-0.0528	-0.1011	-0.1930	0.4756
7 WP	-0.0689	0.0027	-0.0585	-0.0606	-0.0261	0.0492	**0.0022**	-0.1106	0.3376	0.4340	-0.1692	-0.4649	0.2986
8 WOP	-0.8393	-0.1902	-0.1078	0.2126	0.7733	3.1646	-0.0050	**0.9622**	-0.3905	0.0442	-0.2414	0.2246	-0.0193
9 TW	-2.1945	-0.1392	-2.4187	-1.4365	-3.2391	-2.5427	0.0308	-0.7518	**3.8512**	0.1046	0.4203	-0.0616	0.0386
10 SF	-0.2425	3.1284	-10.2803	-2.1500	12.3427	-3.0023	0.1777	0.3816	1.8088	**77.6204**	-0.5120	-0.1117	0.0355
11 BY	-0.4343	-0.1481	0.1131	0.1429	-1.7470	-0.6855	-0.0083	-0.2489	0.8671	-4.7418	**1.1052**	-0.1985	0.1652
12 EY	0.0663	0.0192	-0.2421	0.4563	0.1310	-0.6746	-0.0117	0.1194	-0.0655	-0.5333	-0.1131	**0.2937**	-0.3158
13 HI	-7.1809	2.3123	-9.4683	-6.4847	-0.7673	40.9743	0.1853	-0.2522	1.0127	4.1785	2.3194	-2.2853	**178.3086**

50% flowering and days to maturity were recorded to assess crop phenology (Yoshida, 1981). Plant height was measured at maturity from the soil surface to the tip of the tallest panicle (Yoshida, 1981). The number of tillers per plant was counted as an important yield contributing trait (Donald, 1962).

Yield attributes such as number of panicles were recorded following standard rice evaluation procedures (IRRI, 1976). Grain yield was determined at standard moisture content, while straw yield was recorded as the dry weight of above-ground biomass excluding grains (Gomez and Gomez, 1984; Yoshida, 1981). Test weight (1000-grain weight) was used to assess grain quality (ISTA, 1931). Harvest index was calculated as the ratio of grain yield to total biological yield (Donald, 1962).

Statistical Analysis

The recorded data were subjected to statistical analysis to evaluate the effect of establishment methods and organic amendments on soil properties, growth and yield of rice. Analysis of variance (ANOVA) was carried out to test the significance of treatment effects. Genetic parameters including genotypic and phenotypic variance, coefficients of variation, heritability and genetic advance were estimated. Genotypic, phenotypic and environmental correlations among traits were also worked out to understand interrelationships. The results were interpreted to assess the role of integrated organic nutrient management in improving soil health, productivity and climate resilience of rice.

Results and Discussion

The mean performance of twelve agronomic traits across eight treatments revealed marked variability (Table 1), indicating differential treatment responses. Plant height ranged from 74.36 to 106.37 cm with a mean of 94.33 cm (CV 6.78%). Number of tillers varied significantly from 6.88 to 16.89 plant^{-1} (mean 11.84; CV 10.18%). Spikelets per panicle ranged between 48.00 and 77.67 (mean 66.13), while spikelet length varied from 63.00 to 87.33 mm (mean 76.83 mm). Grains per panicle showed wide variation (57.33–92.00; mean 72.38). Days to physiological maturity ranged from 14 to 39 days (CV 43.32%). Thousand-grain weight ranged from 17.33 to 25.33 g (mean 21.54 g). Seed yield per plant varied from 9.33 to 14.67 g, and harvest index ranged between 79.38 and 101.11%. Treatments T5, T7 and T8 consistently recorded superior performance for yield-attributing traits (Table 1).

Analysis of variance showed highly significant treatment effects for most characters (Table 2). Plant height exhibited higher genotypic variance (92.88) than environmental variance (13.64), resulting in high heritability (0.872) and genetic advance (18.54; 19.65% of mean). Number of tillers recorded extremely high heritability (0.9757) with genetic advance of 8.97 (75.72% of mean), indicating strong additive gene action. Spikelets per panicle (h^2 = 0.9216; GA = 19.13%) and grains per panicle (h^2 = 0.9669; GA = 29.17%) also showed high genetic control. Days to maturity showed moderate heritability (0.4726) with low genetic advance (8.64%), reflecting environmental influence. Harvest index exhibited negative heritability (–1.5595), suggesting poor selection efficiency (Table 2).

Phenotypic variance exceeded genotypic variance for all traits (Table 3), confirming environmental modulation. The highest phenotypic variance was observed for seed filling (290.52), followed by grains per panicle (214.43). Tillers exhibited maximum variability (PCV 37.68%; GCV 37.21%), while thousand-grain weight showed comparatively low variability. High heritability estimates were recorded for tillers (0.976), grains per panicle (0.967) and whole plant weight (0.959) (Table 3).

Table 9: Comparative Assessment of DSR and TPR across the 10 key parameters.

Parameter	DSR (Direct-Seeded Rice)	TPR (Transplanted Rice)	Better Method
1. Soil Organic Carbon (SOC)	Good increase with surface-applied organics	Moderate increaseand some loss during puddling	**DSR**
2. Soil Microbial Biomass and Activity	High and topsoil enrichment	Moderate	**DSR**
3. Grain Yield	High, comparable or slightly higher	High, but labor-intensive	**TSR**
4. Greenhouse Gas Emissions	Reduced methane under AWD	Higher methane under puddling	**DSR**
5. Soil Physical Properties	Improved aggregation, porosity, water retention	Slight improvement and may compact during puddling	**DSR**
6. Soil Enzyme Activities	Enhanced enzyme activities	Moderate	**DSR**
7. Soil Biodiversity	High and diverse microbial population	Moderate	**DSR**
8. Soil pH and Nutrient Availability	Maintains optimal pH and nutrients retained	Slightly more variable	**DSR**
9. Plant Stress Tolerance	Better tolerance to drought and heat	Moderate tolerance and sensitive to water stress	**TSR**
10. Economic Benefit	High and reduced labor and input costs	Moderate and labor-intensive	**DSR**

Genotypic correlations were consistently stronger than phenotypic correlations (Tables 6 and 7). Number of tillers showed strong positive genotypic association with grains per panicle (0.9655) and seed filling (0.9402). Days to panicle initiation showed strong negative associations with grains (–1.3548) and seed filling (–1.4871). Economic yield was positively correlated with biological yield (3.3948) at the phenotypic level (Table 7). Environmental correlations indicated strong environmental influence on seed filling (77.62) and harvest index (178.31) (Table 8).

Overall, traits such as number of tillers, grains per panicle and seed filling exhibited high heritability coupled with high genetic advance, making them reliable selection criteria. Organic amendments enhanced yield stability and trait expression, supporting sustainable and climate-resilient rice production systems.

Comparative Table 9 summarizing Direct-Seeded Rice (DSR) vs Transplanted Rice (TPR)across the 10 key parameters based on recent research and organic amendment integration(Liu *et al.*, 2015 and Kumar *et al.*, 2019 and Parihar *et al.*, 2020 and Jat *et al.*, 2023).

Comparative Assessment of DSR and TPR

The comparative evaluation of Direct-Seeded Rice (DSR) and Transplanted Rice (TPR) indicates a gradual transition toward DSR as a more sustainable and climate-smart establishment system. DSR consistently improved soil organic carbon, microbial activity, enzyme activity, soil structure and biodiversity due to reduced soil disturbance and enhanced residue retention. Lower methane emissions, particularly under alternate wetting and drying, further highlight its environmental advantage under climate change scenarios. In addition, DSR offers economic benefits through reduced labor, water and energy inputs.

Despite these advantages, TPR remains widely adopted because of its yield stability and lower production risk. Uniform crop establishment, early seedling vigor and effective weed suppression through continuous flooding contribute to reliable performance, especially under high weed pressure, uneven land leveling and erratic rainfall. Transplanted seedlings also exhibit greater tolerance to early-season stresses, including temporary waterlogging, pest incidence and nutrient fluctuations. For small and marginal farmers, this resilience provides a critical safety margin.

The adoption of DSR is often constrained by its requirement for precise weed management, irrigation scheduling and nutrient placement. Limited access to mechanization, herbicides and technical knowledge restricts its large-scale adoption in resource-poor regions. In contrast, TPR aligns well with traditional farming practices and existing labor systems, requiring fewer technological inputs.

Conclusion

Direct-Seeded Rice offers clear advantages in terms of soil health improvement, reduced greenhouse gas emissions and long-term sustainability, making it a promising climate-resilient production system. However, Transplanted Rice continues to dominate due to its dependable crop establishment, superior weed control and lower risk under sub-optimal management conditions.

Therefore, promotion of DSR should be region-specific and capacity-driven, while TPR will remain relevant where risk avoidance and resource constraints guide farmer decisions. An integrated, location-specific approach that combines the strengths of both systems is essential for achieving sustainable and resilient rice production.

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