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Prospect of rice yield sustainability by optimizing fertilizer doses and crop establishment methods: A study in rainfed drought prone ecology of Jharkhand

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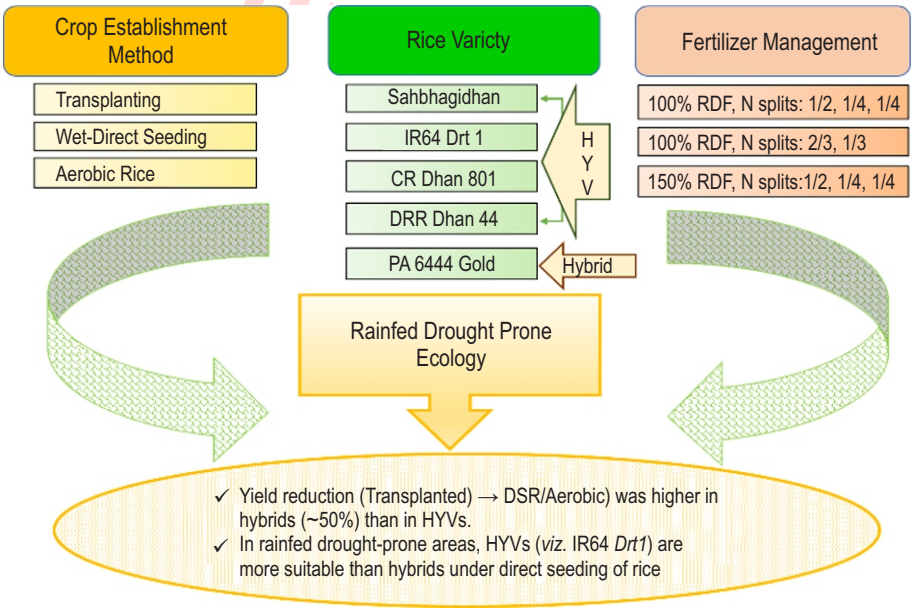
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Abstract

Aim: This study aimed to identify the optimal combination of variety, crop establishment method and fertilizer management to enhance rice productivity under the rainfed drought-prone ecology of Jharkhand.

Methodology: A field trial was conducted (wet seasons of 2019 to 2021) to evaluate different establishment methods (transplanted, aerobic and wet DSR) under various fertilizer management options (different rate and time of nutrient application) for high yielding varieties (HYVs) and hybrid on yield and yield attributes for three consecutive years.



Results: On an average, the plant height and yield attributing parameters (grains per panicle and panicle number m^{-2}) were significantly differed within establishment methods and higher values were recorded in transplanted conditions (106 and 180). Yield attributing characters showed that, different varieties were performing differently and significantly higher panicle number m^{-2} (170) and test weight (28.3 g) were found with IR-64 Drt 1 (HYV), whereas, the highest number of grains per panicle (108) was observed in PA 6444 (hybrid) followed by DRR Dhan 44 (95). In comparison to HYVs, percentage yield reduction was higher in case of hybrid (around 50%) when the method of establishment was changed from transplanted to direct sowing or aerobic (4.74 t ha^{-1} in transplanted to 2.40 and 2.18 t ha^{-1} in WDSR and aerobic method, respectively).

Interpretation: In the rainfed drought prone areas, HYVs should be preferred and adopted for cultivation over hybrids as there is very uncertainty in case of transplanted rice cultivation and should opt for other methods of crop establishment like direct seeded rice.

Key words: Direct seeded rice, Drought prone areas, Fertilizer management, High yielding varieties, Jharkhand, Rainfed

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Introduction

Indian agriculture still depends on arbitrary nature of weather, particularly monsoon for small and marginal farmers (Ray *et al.*, 2026). Rice being the main *kharif* crop requires large amount of water, so, the success of rice production in rainfed drought prone ecology is always dependent upon timely and adequate amount of rainfall. The productivity of rice in these regions may be enhanced with proper fertilizer management accompanied with a suitable variety and crop establishment method. Although, total monsoon rainfall may seem to be adequate for cultivation of rice but the erratic nature of rainfall leads to drastic cut down in rice area and production in different years (Bowden *et al.*, 2023). Rice cultivation in Jharkhand spans diverse topographies *'Tanr'* (upland) and 'Don' (medium and lowland) (Roy *et al.*, 2019); necessitating establishment methods adapted to local soil, climatic and socio-economic conditions. Conventional puddled transplanted rice (PTR) is labour and water intensive, particularly during seedling uprooting and transplanting. In contrast, direct seeded rice (DSR) applies arable crop management principles, requiring substantially less labour (up to 40%), water (up to 60%), and energy compared to puddled transplanted rice (Pathak *et al.,* 2011).

Beyond resource efficiency, PTR systems are significant contributors to greenhouse gas emissions, particularly methane, accounting 10–20% of global annual methane output (Reiner and Aulakh, 2000). Given the escalating scarcity and cost of labour, water, and energy, DSR offers considerable potential for improving water use efficiency, reducing greenhouse gas emissions, and enhancing farm profitability (Mahajan *et al.,* 2004). Compounding these challenges, over 90% of Asian rice is produced by small farmers who, driven by high urea subsidies and yield-maximization objectives, routinely apply nitrogen fertilizer well beyond plant requirements (Ladha *et al.,* 2005). Persistent yield gaps despite technological advances are primarily attributed to imbalanced and excessive fertilizer use based on blanket recommendations (Tilman *et al.,* 2002), resulting in soil degradation, ecological damage, and water pollution (Srivastava *et al.,* 2020). Recent evidence confirms that optimized nutrient management can reduce fertilizer inputs while maintaining or improving yields and nutrient use efficiency (Chivenge *et al.,* 2021; Lal *et al.,* 2020). Rice is grown in a variety of ecological conditions, from irrigated and rainfed upland to rainfed lowland and deep-water areas. The rainfed ecosystem constitutes around 38% of the total rice cultivation area and produces 21% of the world's rice (Kumar *et al.,* 2015).

Frequent occurrence of drought and drought like situation reduced the rice productivity in rainfed ecology. Eastern India contributes about 27 Mha of rice area, out of which nearly 4.28 Mha area is under frequent drought prone condition (Raghav *et al.,* 2019). Rainfed upland rice accounts for about 10-12% of total rice area in India which are mostly located in eastern part of the country (Pathak *et al.,* 2020). Despite several limitations, farmers of this region grow hybrids over high yielding or other local varieties with the objective to get higher yield. But in case of erratic rainfall, early withdrawal of monsoon, non-suitability of land and injudicious use of fertilizer, rice productivity reduced drastically. Hence, selection of suitable varieties and efficient management of other resources (water, fertilizer etc.) are crucial to assure the sustainable rice production even in the adverse situation. Therefore, evaluation of high-yielding rice varieties and subsequent adoption by the farmers may improve productivity in this rainfed drought prone ecology, if suitable crop management is adopted. Furthermore, nutrient availability is influenced by soil water or moisture content, which also varies with different establishment methods. Although earlier studies have examined crop establishment methods, fertilizer management, and varietal performance separately, their interactive effects have not been adequately investigated under the rainfed drought-prone conditions of Jharkhand. This lack of location-specific evidence limits the development of integrated and sustainable production strategies for improving or sustaining the rice productivity. With this background, the present work was undertaken to understand the effect of different nutrient management options (fertilizer doses and time of application), crop establishment methods, rice varieties and their interaction on rice productivity in this drought-prone rainfed ecology.

Materials and Methods

Experimental site and treatment details: A field experiment was conducted at the research farm of Central Rainfed Upland Rice Research Station (ICAR-CRRI), Hazaribag (23°57'43.2"N, 85°21'48.1"E) during three consecutive kharif seasons (wet seasons of 2019 to 2021) consisting of three crop establishment methods, three fertilizer management a long with five rice varieties. The experiment was arranged in a split-split plot design with three replications. The main plot treatments included three crop establishment methods viz transplanting (TPR; M1), wet-direct seeding (WDSR; M2), and aerobic rice (AR; M3). Three fertilizer management strategies were imposed in the sub-plot: F1 – 100% recommended dose of fertilizer (RDF) with three splits of nitrogen (1/2, 1/4, 1/4); F2 – 100% RDF with two splits of nitrogen (2/3, 1/3); and F3 – 150% RDF with three splits of nitrogen (1/2, 1/4, 1/4). The RDF comprised $N:P_2O_5:K_2O$ at 80:40:30 kg ha^{-1}. Five rice varieties (four HYVs and one hybrid) were evaluated in the sub-sub-plot treatments: V1- Sahbhagidhan (110 days maturity), V2- IR64 Drt1 (120–125 days), V3- CR Dhan 801 (140 days), V4- DRR Dhan 44 (115–120 days), and V5- PA 6444 Gold (hybrid; 135 days). The experiment was carried out under shallow lowland field with clay loam soil texture. The soil possessed medium levels of available nitrogen, phosphorus and potassium (292, 22.4, 180 kg ha^{-1} respectively). Rainfall patterns during three experimental years differed considerably across kharif season, and the detailed weather condition of experimental site during crop growth period (June to November) is presented in Fig. 1.

Field and crop management: The field was prepared using a tractor for ploughing followed by laddering before sowing or transplanting. Three-weeks-old seedlings were transplanted into

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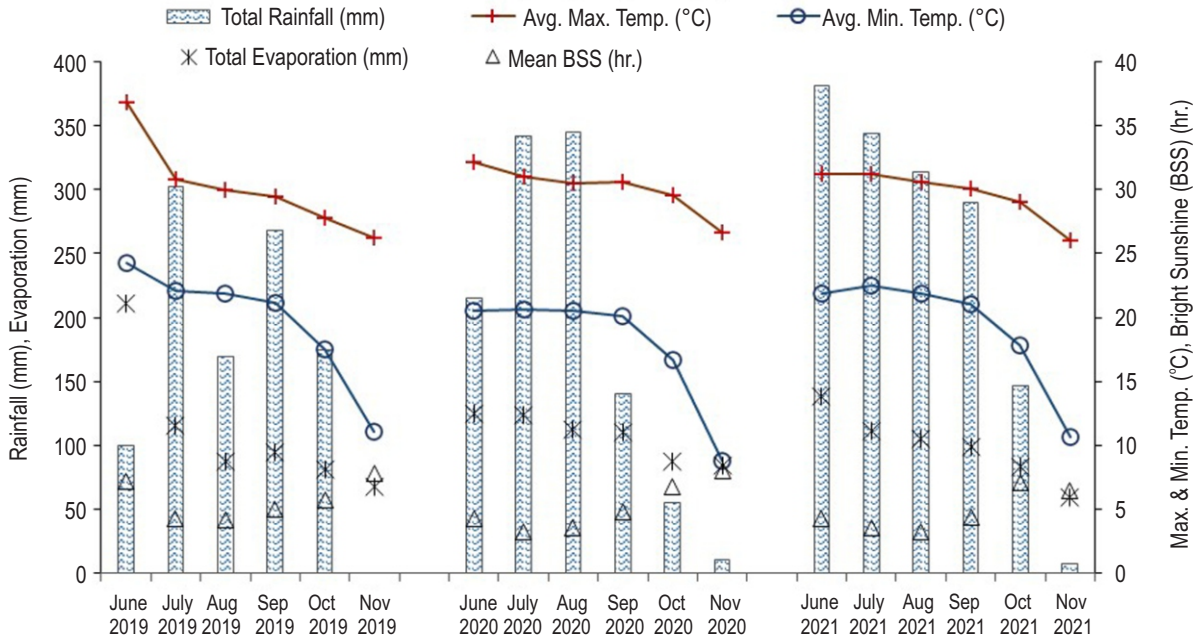


Fig. 1: Weather condition during crop growth (June to November) period (2019 to 2021).

the main field with a spacing of 20 cm × 10 cm, maintaining two to three seedlings per hill under transplanting, however, in (wet) direct seeding method, 2-3 sprouted seeds were dibbled manually at 20 cm × 10 cm spacing in field with negligible or no standing water on surface. In aerobic method also, 2-3 seeds were sown manually at 20 cm × 10 cm spacing. The nursery for transplanting and main field sowing in direct sowing and aerobic was done at the same time to provide equal and uniform growth period. Fertilizers were applied as per the treatments through (di-ammonium phosphate), urea and (muriate of potash) in all the three methods of crop establishments. Life saving irrigation was provided in both transplanted and DSR as per requirement; otherwise, the crops were grown in complete rainfed situation. In the aerobic method, intermittent irrigation was provided so that field moisture was managed to simulate aerobic environment in the field. Other standard crop management practices (weed and pest management) were followed uniformly to the entire experimental plots during three years of field experimentation.

Data collection and analysis: During three seasons (2019-2021) of observations on plant height, panicles per square meter and 50% flowering (DAS) were recorded from the standing crop. Post harvest, the plants were separated into straw (including rachis) and spikelet by hand threshing, thereafter, the grain yield, straw yield, panicle length, panicle weight, grains per panicle, chaffy grains per panicle, and 1000-grain weight (test weight) were recorded. The collected data were analysed using SPSS to elucidate the treatment effects (method of crop establishment, fertilizer doses and varieties) as well as their interaction. Treatment means were compared using least significant difference (LSD) at 0.05 level of significance ($p \leq 0.05$).

Results and Discussion

On an average, the plant height significantly differed within the establishment methods, and the highest value was found in TPR (81 cm) followed by WDSR (72 cm), however, difference between plant height in WDSR and aerobic was non-significant (Table1), which may be attributed to proper crop spacing (both plant to plant and row to row). That reduces competition among the plants and additionally, the puddled conditions likely facilitated deeper root penetration, resulting in improved nutrient uptake and plant growth (Mahajan *et al.,* 2004; Hardev *et al.,* 2014). In WDSR and aerobic conditions, suitable proper environment for rice growth may not be achieved as compared to transplanted condition as rice is well suited crop of puddled and submerged condition hence, transplanted rice received proper growing environment. Fertilizer management did not significantly influence the plant height; however, mean plant height differed significantly among varieties, ranging from 60.1 cm (CR Dhan 801) to 83.2 cm (Sahbhagidhan), reflecting inherent genetic variability (Table 1). Yield attributes; panicles m^{-2}, test weight and grains per panicle were significantly higher (178, 25.2 g and 93) in the third year compared to the preceding two years (Table 1), attributable to more favourable and timely rainfall (Fig. 1).

This underscores the critical importance of adequate and well-distributed rainfall for productivity in rainfed ecosystems. Among the establishment methods, transplanting recorded higher values of yield attributing parameters viz. number of

Table 1: Effect ofcrop establishment methods, fertilizer management and varieties over the three years on yield and yield attributes of rice

	Plant height (cm)	No. of panicle m^{-2}	Test weight (g)	No. of grains $panicle^{-1}$	Chaff $panicle^{-1}$	Panicle length (cm)	Panicle weight (g)	Days to 50% flowering	Fertility (%)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
Year											
2019	74.8^{a}	143^{b}	24.7^{b}	92^{a}	18^{b}	21.7	2.39^{a}	85^{b}	84.3^{a}	2.98^{b}	4.87^{b}
2020	72.7^{b}	105^{c}	24.3^{c}	82^{b}	19^{a}	21.6	2.27^{b}	79^{c}	81.0^{b}	1.92^{c}	2.97^{c}
2021	74.1^{a}	178^{a}	25.2^{a}	93^{a}	17^{b}	21.6	2.36^{ab}	86^{a}	84.7^{a}	3.85^{a}	6.29^{a}
						NS					
Establishment Method											
TPR	81.0^{a}	180^{a}	24.8^{a}	106^{a}	20^{a}	22.6^{a}	2.66^{a}	82^{c}	84.4^{a}	4.20^{a}	6.61^{a}
WDSR	72.0^{b}	118^{c}	24.8^{a}	84^{b}	15^{b}	21.4^{b}	2.26^{b}	84^{a}	84.7^{a}	2.33^{b}	3.87^{b}
Aerobic	68.6^{c}	128^{b}	24.5^{b}	77^{c}	19^{a}	20.9^{c}	2.10^{c}	83^{b}	80.9^{b}	2.22^{c}	3.65^{c}
Nutrient Management											
F1	71.5	142^{b}	24.5^{b}	87^{b}	17	21.0^{b}	2.19^{b}	84^{a}	83.2	2.85^{b}	4.49^{b}
F2	75.5	129^{c}	25.0^{a}	92^{a}	18	22.0^{a}	2.45^{a}	83^{b}	83.6	2.75^{c}	4.65^{b}
F3	74.5	155^{a}	24.6^{b}	88^{b}	18	21.9^{a}	2.39^{a}	84^{a}	83.2	3.14^{a}	4.99^{a}
	NS				NS				NS		
Rice Varieties											
Sahbhagidhan	83.2^{a}	135^{c}	25.0^{c}	86^{d}	14^{c}	21.6^{b}	2.07^{b}	76^{e}	85.6^{a}	2.77^{bc}	4.28^{d}
IR64 Drt1	75.1^{c}	170^{a}	28.3^{a}	66^{e}	12^{d}	21.3^{bc}	2.05^{b}	81^{d}	84.5^{a}	3.10^{a}	4.93^{ab}
CR Dhan 801	60.1^{e}	149^{b}	21.2^{e}	89^{c}	15^{c}	20.2^{d}	2.07^{b}	86^{b}	85.5^{a}	2.72^{c}	4.58^{c}
DRR Dhan 44	81.3^{b}	127^{c}	25.9^{b}	95^{b}	22^{b}	23.9^{a}	2.75^{a}	84^{c}	80.3^{b}	2.88^{b}	4.71^{bc}
PA 6444 Gold	69.5^{d}	129^{c}	23.0^{d}	108^{a}	26^{a}	21.1^{c}	2.77^{a}	90^{a}	80.8^{b}	3.11^{a}	5.06^{a}

panicles m^{-2} (180), test weight (24.8g) and grains per panicle (106), followed by WDSR (118, 24.8g and 84 respectively) and aerobic (128, 24.5g and 77, respectively) (Table 1), as proper growth environment in transplanted condition encourages more efficient utilization of available resources and improved translocation of photosynthates from the source to the sink. It is well understood that, rice cultivation in India predominantly relies on transplanted conditions, which provide a controlled environment for optimal growth and development, as most existing varieties were systematically bred and evaluated under conventional puddled transplanted rice (PTR) systems (Paswan *et al*., 2023).

Among the fertilizer management options, plant height at maturity did not differ significantly, however, the yield attributing parameters such as test weight, grains per panicle were found superior under F2 (25 g and 92), followed by F3 and F1; although the number of panicles per m^2 was significantly higher in F3 (155), followed by F1 (142) (Table 1). Higher yield attributing parameters observed at higher dose of fertilizers may be due to more amount of essential nutrient supplied and extended availability of nutrients especially, nitrogen likely contributed to the production of a greater number of effective tillers and yield attributes. Enhanced availability of nutrients, especially nitrogen to the crop led to an increase in leaf area index, which facilitated more photosynthetically active organs, leading to higher production and accumulation of assimilates, expressing in terms of better yield attributing parameters (Vishwakarma *et al.,* 2016; Ghoneim *et al.,* 2018). These findings also corroborate with previous studies conducted by Thind *et al.* (2017). Among the varieties, IR64 Drt1 (V2) recorded the highest panicle number m^{-2} and test weight, while PA 6444 Gold (V5) had the highest grains per panicle, followed by DRR Dhan 44 (V4). IR64 Drt1 also recorded the lowest number of unfilled grains per panicle (12), followed by Sahbhagidhan (14) (Table 1). Varietal differences in yield attributes and chaffy grains reflect inherent genetic character and the variability are dependent on many factors, e.g. genotypes, agronomic management and G x E interaction etc. Crop yield resulted from the complex interplay between growth acquired during the vegetative phase and the yield attributes.

TPR recorded the highest mean grain yield (4.20 t ha^{-1}), followed by WDSR (2.33 t ha^{-1}) and AR (2.22 t ha^{-1}), though yields under WDSR and AR, while statistically different, were numerically close (Table 1). It is well understood that rice grow better in puddled and transplanted condition which provide more favourable environment for crop growth. One of the reasons for higher grain yield in TPR compared to WDSR and aerobic was the presence of higher panicle number and grains per panicle (Xu *et al.,* 2019), which might be due to higher availability of nutrients, light, and moisture in TPR as it reduced percolation losses and promote better anchorage of roots. On the other hand, the lower yield in aerobic may be due to water loss through seepage and percolation, as well as nutrient loss through leaching (Singh *et al.,* 2015; Kumar and Batra, 2017; Mauriya *et al.,* 2019). On an average, higher dose of fertilizer (F3) resulted in more yield (3.14 t ha^{-1}) followed by F1 and F2, where low dose of nutrient was provided (Table 1). Among the variety, the mean yield of hybrid (V5) was highest (3.11 t ha^{-1}) which was at par with the HYV (V2) whereas, the performance of other varieties was at par (Table 1).

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Table 2: Interactive effect of fertilizer management, crop establishment methods and year on grain yield (t ha^{-1}) of rice

	Year (Y)												M X F		
	2019 (Y1)				2020 (Y2)				2021 (Y3)						
	Fertilizer management (F)			M X Y	Fertilizer management (F)			M X Y	Fertilizer management (F)			M X Y			
	F1	F2	F3		F1	F2	F3		F1	F2	F3		F1	F2	F3
M1	4.25	4.13	5.03	4.47	3.35	2.89	3.33	3.19	4.58	4.75	5.47	4.93	4.06	3.92	4.61
M2	2.03	2.36	2.63	2.34	1.19	1.22	1.54	1.32	3.36	3.18	3.47	3.34	2.19	2.25	2.55
M3	2.07	2.04	2.24	2.12	1.41	1.05	1.34	1.27	3.42	3.16	3.23	3.27	2.30	2.09	2.27
F X Y	2.79	2.84	3.30		1.98	1.72	2.07		3.79	3.70	4.06				
CD ($p \leq 0.05$)	M X Y = 0.14; M X F = 0.14; F X Y = 0.14; M X F X Y = 0.25														

Table 3: Interactive effect of crop establishment methods, year and varieties on grain yield (t ha^{-1}) of rice

	Year (Y)												M X V		
	2019 (Y1)				2020 (Y2)				2021 (Y3)						
	Method (M)			V X Y	Method (M)			V X Y	Method (M)			V X Y			
	M1	M2	M3		M1	M2	M3		M1	M2	M3		M1	M2	M3
V1	4.07	2.31	1.89	2.76	2.95	1.20	1.14	1.76	4.69	3.48	3.24	3.80	3.90	2.33	2.09
V2	4.96	2.38	1.85	3.06	3.71	1.44	1.17	2.11	5.25	3.62	3.52	4.13	4.64	2.48	2.18
V3	4.68	1.86	1.84	2.79	3.43	1.11	1.20	1.91	4.81	2.82	2.71	3.45	4.31	1.93	1.91
V4	3.56	2.67	3.04	3.09	2.34	1.43	1.54	1.77	4.29	3.45	3.59	3.78	3.40	2.52	2.72
V5	5.07	2.49	1.99	3.18	3.52	1.41	1.27	2.07	5.62	3.31	3.29	4.08	4.74	2.40	2.18
M X Y	4.47	2.34	2.12		3.19	1.32	1.27		4.93	3.34	3.27				
CD ($p \leq 0.05$)	V X Y = 0.19; M X V = 0.19; M X Y = 0.14; M X V X Y = 0.32														

It showed that, average productivity of IR64 Drt 1 is comparable to that of the hybrid, hence in this drought prone rainfed area; there is a scope to sustain rice productivity from HYVs (Table 1).

Grain yield of rice is highly affected by the interaction of crop establishment method, varieties as well as fertilizer application. Irrespective of varieties, the interactive effect of method of establishment and fertilizer dose, was found significant and highest yield was recorded in M1 F3 (4.61 t ha^{-1}) and lowest in M3 F2 (2.09 t ha^{-1}) (Table 2). M1 was superior across the fertilizer management, whereas M2 and M3 significantly differed in case of F2 and F3, however did not follow any specific trend. F1 and F2 were more or less at par across the method of establishment (Table 2). Interaction of method of establishment and varieties were found significant and across the variety, the highest yield was recorded in M1 followed by M2 and M3, except for variety V4 (Table 3). As compared to Hybrid (V5), the yield of V2 is at par across the method of establishment. In comparison to other HYVs, the percentage yield reduction was higher in case of V5 when the method of establishment was changed from M1 to M2/M3 (Table 3). Different varieties performed differentially under different crop establishment methods, however, the yield of drought-tolerant high-yielding variety IR64 Drt1 remained statistically at par across the methods of establishment, indicating consistent performance of HYV under different methods. Its mean grain yield under TPR (4.64 t ha^{-1}; Table 3) declined by only about approximately by 46% only under WDSR (2.48 t ha^{-1}) and about 53% under aerobic condition (2.18 t ha^{-1}), whereas hybrid PA 6444 Gold (V5) suffered a yield reduction of approximately 50% from TPR (4.74 t ha^{-1}) to WDSR (2.40 t ha^{-1}) and 54% to aerobic (2.18 t ha^{-1}). Crucially, IR64 Drt1's absolute yield under WDSR (2.48 t ha^{-1}) was statistically at par with the hybrid under same method (2.40 t ha^{-1}), and yield under aerobic (2.18 t ha^{-1}) was comparable to hybrid under aerobic (2.18 t ha^{-1}), indicating that the yield penalty for shifting from TPR was proportionally similar for both genotypes, but the inherent yield advantage of hybrid in TPR was largely lost under DSR and aerobic conditions.

Interaction of variety × method × year (Table 3) further reveals that varietal rankings are not entirely stable across seasons. In the favourable rainfall year 2021, the hybrid (V5) achieved its highest yields, particularly under TPR (5.62 t ha^{-1}; Table 3). However, in the drought year 2020, the yield of all varieties collapsed across methods, with IR64 Drt1 still maintaining a relative advantage in WDSR (1.44 t ha^{-1}). Therefore, in case of rainfall uncertainty and potential delays in transplanting, HYVs may be a more reliable option than hybrids due to their comparatively greater stability and adaptability.

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Table 4: Interactive effect of fertilizer management, year and varieties on grain yield (t ha^{-1}) of rice

	Year (Y)												F X V		
	2019 (Y1)				2020 (Y2)				2021 (Y3)						
	Fertilizer management (F)			V X Y	Fertilizer management (F)			V X Y	Fertilizer management (F)			V X Y			
	F1	F2	F3		F1	F2	F3		F1	F2	F3		F1	F2	F3
V1	2.82	2.53	2.92	2.76	1.93	1.52	1.84	1.76	3.99	3.45	3.97	3.80	2.92	2.50	2.91
V2	2.86	2.82	3.50	3.06	2.08	1.88	2.36	2.11	4.36	3.73	4.29	4.13	3.10	2.81	3.39
V3	2.61	2.71	3.06	2.79	2.08	1.62	2.03	1.91	3.13	3.64	3.57	3.45	2.61	2.66	2.89
V4	2.93	2.79	3.54	3.09	1.74	1.53	2.04	1.77	3.69	3.38	4.27	3.78	2.78	2.57	3.29
V5	2.71	3.36	3.47	3.18	2.08	2.05	2.07	2.07	3.76	4.27	4.20	4.08	2.85	3.23	3.25
F X Y	2.79	2.84	3.30		1.98	1.72	2.07		3.79	3.70	4.06				
CD (p ≤ 0.05)	V X Y = 0.19; F X V = 0.19; F X Y = 0.14; F X V X Y = 0.32														

Table 5: Interactive effect of fertilizer management, crop establishment methods and varieties on grain yield (t ha^{-1}) of rice

	Method (M)												F X V		
	M1				M2				M3						
	Fertilizer management (F)			V X M	Fertilizer management (F)			V X M	Fertilizer management (F)			V X M			
	F1	F2	F3		F1	F2	F3		F1	F2	F3		F1	F2	F3
V1	4.00	3.70	4.01	3.90	2.51	2.01	2.46	2.33	2.24	1.79	2.25	2.09	2.92	2.50	2.91
V2	4.44	4.46	5.01	4.64	2.62	2.14	2.67	2.48	2.25	1.82	2.48	2.18	3.10	2.81	3.39
V3	4.07	4.10	4.75	4.31	1.64	2.10	2.05	1.93	2.11	1.77	1.86	1.91	2.61	2.66	2.89
V4	3.35	2.95	3.90	3.40	2.13	2.17	3.25	2.52	2.87	2.59	2.71	2.72	2.78	2.57	3.29
V5	4.45	4.39	5.38	4.74	2.07	2.84	2.30	2.40	2.03	2.46	2.07	2.18	2.85	3.23	3.25
F X M	4.06	3.92	4.61		2.19	2.25	2.55		2.30	2.09	2.27				
CD (p ≤ 0.05)	V X M = 0.19; F X V = 0.19; F X M = 0.14; F X M X V = 0.32														

Interactive effect of fertilizer and variety are also significant for grain yield (Table 4 and 5). A notable finding is the contrasting response to split application between F1 (three splits: ½, ¼, ¼) and F2 (two splits: ⅔, ⅓) at the same total RDF rate.

The consistently lower yield under F2 across most methods and variety combinations (Tables 4 and 5) indicate that the timing and proportion of nitrogen application exert a critical influence on yield under rainfed conditions. The three-split application (F1) likely provided a more temporally aligned supply of nitrogen with crop demand peaks; particularly at tillering and panicle initiation whereas the two-split schedule (F2), with a heavier basal dose, may have subjected a larger proportion of applied nitrogen to losses through volatilization (under aerobic soil conditions) or denitrification (under saturated conditions following rainfall events). Higher dose of fertilizer leads to significant enhancement in yield and the response was more significant in case of hybrid. Singh *et al.* (2014) also reported increase in grain yield of rice in response to elevated nitrogen application up to 100 kg N ha^{-1} along with improvement in nitrogen use efficiency. However, decreased nitrogen use efficiency at higher nitrogen rates has also been reported (Timsina *et al.,* 2001; Mae *et al.,* 2006).

Economic viability is a decisive factor for technology adoption, hence; suitability of variety and method for rice production cannot be determined based on the grain yield alone. As shown in Table 6, the highest gross returns and net returns in terms of Indian currency of Rs. 87,055 ha^{-1} and Rs. 44,884 ha^{-1}, and benefit–cost ratio (1.06) was observed from transplanted rice mean over the years across the nutrient management and varieties. Net return obtained from TPR was 3.8 times higher over WDSR and aerobic rice. Higher dose of fertilizer (F3) resulted in the highest value of B:C (0.67) followed by F1 (0.57) and F2 (0.54).

Among the varieties, the average net return as well as B:C ratio of IR 64drt1 (V2) was highest (Rs. 27,001 ha^{-1} and 0.72, respectively), followed by Hybrid (V5) and DRR Dhan 44 (V4). In transplanted rice average over the three years, highest net return and B:C ratio was incurred with the Hybrid in F3 (Rs. 64,790 ha^{-1} and 1.45), whereas, in WDSR and aerobic rice highest net return and B:C was with DRR Dhan 44 in F3 (Rs. 30,418 ha^{-1} and 0.81) and F1 (Rs. 25,277 ha^{-1} and 0.74), respectively (Table 7,8). Singh *et al.* (2018) also reported that transplanting of rice fetched higher net return and benefit -cost ratio compared to aerobic rice and semi-dry rice cultivation at Ranchi. The overall lower profitability of

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Table 6: Effect of crop establishment methods, nutrient management and varieties on economics of rice cultivation

	Cost of cultivation (Rs.)	Gross return (Rs.)	Net return (Rs)	B:C
Year				
2019	36566	60101	23536	0.64
2020	36675	39645	2971	0.08
2021	41060	82492	41433	1.01
Establishment Method				
TPR	42171	87055	44884	1.06
WDSR	37014	48770	11755	0.32
Aerobic	35114	46415	11300	0.32
Nutrient Management				
F1	37672	59282	21610	0.57
F2	37402	57620	20219	0.54
F3	39226	65337	26111	0.67
Rice Variety				
Sahbhagidhan	37510	57603	20093	0.54
IR64 Drt1	37510	64511	27001	0.72
CR Dhan 801	37510	56803	19293	0.51
DRR Dhan 44	37510	60034	22524	0.60
PA 6444 Gold	40460	64794	24334	0.60

Table 7: Interactive effect of crop establishment methods, nutrient management and varieties on net return (Rupees) of rice production

Varieties	**Methods**											
	M1				**M2**				**M3**			
	Fertilizer management				**Fertilizer management**				**Fertilizer management**			
	F1	F2	F3	Mean	F1	F2	F3	Mean	F1	F2	F3	Mean
Sahbhagidhan	41571	36367	39502	39147	16125	6074	14097	12099	12483	3640	10928	9017
IR64 Drt1	50598	51075	60923	54198	18203	9374	18143	15240	13564	4712	16420	11565
CR Dhan 801	42013	45083	56208	47768	-1155	8519	5834	4399	10062	3694	3355	5704
DRR Dhan 44	28716	20669	38080	29155	8590	9590	30418	16199	25277	20397	20945	22206
PA 6444 Gold	48737	48963	64790	54163	3991	20992	7516	10833	5394	14160	4439	7998
Mean	42327	40431	51900		9151	10909	15202		13356	9321	11217	

Table 8: Interactive effect of crop establishment methods, nutrient management and varieties on benefit-cost ratio of rice production

Varieties	**Method**											
	M1				**M2**				**M3**			
	Fertilizer management				**Fertilizer management**				**Fertilizer management**			
	F1	F2	F3	Mean	F1	F2	F3	Mean	F1	F2	F3	Mean
Sahbhagidhan	1.00	0.88	0.92	0.94	0.45	0.17	0.38	0.33	0.37	0.11	0.31	0.26
IR64 Drt1	1.22	1.24	1.42	1.29	0.51	0.26	0.48	0.42	0.40	0.14	0.46	0.33
CR Dhan 801	1.02	1.10	1.31	1.14	-0.03	0.24	0.16	0.12	0.30	0.11	0.09	0.17
DRR Dhan 44	0.69	0.50	0.89	0.69	0.24	0.27	0.81	0.44	0.74	0.60	0.59	0.65
PA 6444 Gold	1.13	1.14	1.45	1.24	0.10	0.54	0.18	0.27	0.14	0.38	0.11	0.21
Mean	1.01	0.97	1.20		0.25	0.30	0.40		0.39	0.27	0.31	

WDSR and AR relative to TPR was primarily due to poor and uneven crop establishment and challenges in weed management, which is the main constraint limiting direct-seeded rice productivity (Xu *et al.,* 2019; Chakraborty *et al.,* 2017). Additionally, most rice varieties, particularly hybrids, are bred for transplanted systems (Tuong and Bouman, 2003), amplifying yield penalties when shifted to DSR. Dry direct seeding further risks suboptimal establishment during early-season dry spells

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(Haefele and Bouman, 2009). The reduced water demand for establishment enables earlier planting and harvesting, making DSR potentially capable of yielding more than TPR in specific water conditions (Ahmed *et al.,* 2014). These findings indicate that DSR could serve as an alternative cultivation method in rainfed regions (Xu *et al.,* 2019).

This study has specifically identified and validated three crucial components, *i.e.*, varieties, crop establishment methods and fertilizer management (rate and time of nutrient application) for sustainable rice production under rainfed drought-prone region. The findings demonstrate that these factors must be considered in an integrated manner to improve productivity and stability under moisture-stressed environments. When all these factors were evaluated together, the mean grain yield of hybrid was comparable to that of some HYVs. However, compared to the HYVs, percentage yield reduction was higher in case of hybrid when the method of establishment was shifted from transplanted to DSR or aerobic rice, indicating their relatively lower adaptability to changes in establishment method under water-limited conditions.

Hence, these results have important implications for rainfed drought prone areas, like Jharkhand where rainfall is main limiting factor which changes the soil moisture dynamics. HYVs should be preferred for cultivation over hybrids due to their comparatively greater yield stability. In addition, to minimize the risks associated with delayed transplanting under uncertain rainfall, alternative crop establishment methods such as direct-seeded rice may be adopted for sustaining rice cultivation. However, ensuring simultaneous adoption and effective management of all these factors together will be the main limitation for stake holders. Further research across multiple locations, and newer varietal combinations particularly climate-resilient rice varieties would help to strengthen the recommendations and improve their wider applicability.

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