

Research article

Empirical evidence for economic viability of direct seeded rice in peninsular India: An action-based research

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ARTICLE INFO

Keywords:

Impact assessment
Economic analysis
Puddled transplant rice
Direct-seeded rice (DSR)
Dry DSR
Wet DSR
Propensity score matching (PSM) approach
Peninsular India

ABSTRACT

Purpose: This study identified critical constraints in technology adoption for Direct Seeded Rice (DSR) compared with puddled transplanted rice (PTR) practices. We present the impact of DSR technology adoption on paddy yield, income generation, and cost incurred on various farm operations. Furthermore, the study investigates whether a dry DSR practice provides more economic and production benefits than a wet DSR.

Methodology: We used a multi-stage sampling (from state to district-to-village-to-farmers) and conducted a face-to-face questionnaire survey to collect primary farm-level data. We collected 669 farm and household-level data and analyzed the impact of DSR and dry DSR adoption over PTR and wet DSR, respectively. Initially, the study employed probit regression analysis to identify the DSR adoption determinants. Subsequently, using the Propensity Score Matching approach, the study measures the impact of DSR adoption over PTR in terms of yield, income, and cost management. Finally, using the PSM approach, the study estimated the impact of dry DSR adoption over wet DSR.

Findings: Probit estimates suggest that variables like education, membership in farmers' organizations, farm experience, institutional credit, crop insurance, off-farm income, and smartphone and television ownership positively regulate DSR adoption. The impact assessment analysis reveals that the adoption of DSR over PTR results in marginal yield improvement. However, the cost of irrigation, land preparation, and fertilization is significantly lower in DSR, resulting in an additional income of ₹5192/acre for DSR adopters. Moreover, a comparative analysis between dry DSR and wet DSR indicates that farmers can achieve ₹2467/acre by adopting dry DSR.

Practical implications: Our research findings designate the necessity for implementing policies and strategies to promote the adoption of DSR among non-adopters. Besides economic benefits, adopting the DSR method can yield environmental benefits, improve soil health, mitigate soil erosion, and decrease water use.

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<https://doi.org/10.1016/j.heliyon.2024.e26754>

Received 24 November 2023; Received in revised form 14 February 2024; Accepted 20 February 2024

Available online 20 February 2024

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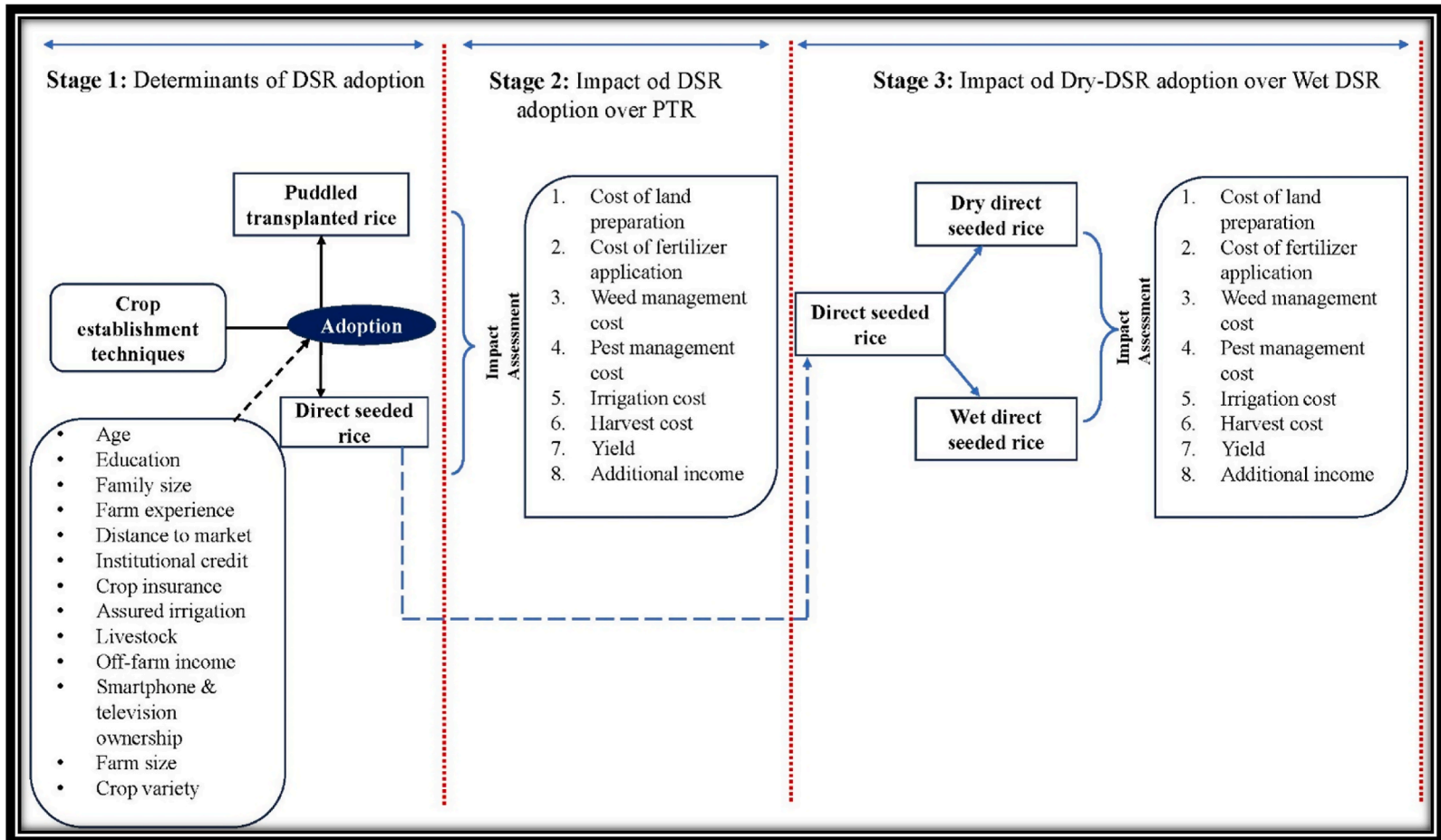


Fig. 1. Conceptual framework of the study.

1. Introduction

Rice is a staple food for more than half of the world's population [1]. South Asian countries produce and consume almost 90% of the world's rice, which amounts to 678.7 million tons, according to the FAO in 2018 and the GRSP in 2013 [2,3]. India is the second-largest producer and consumer of rice, while also ranking first in rice exports. In India, during the Kharif season, almost 55% of the total cultivated area (39.54 million hectares) is dedicated to paddy production, as per the Government of India report (GOI) in 2022 [4]. Furthermore, paddy production directly involves 57.5% of the country's farming population and contributes significantly to the agricultural gross domestic product, according to the GOI in 2020 [4]. Due to industrialization, urbanization, and crop diversification, the area under paddy cultivation has decreased worldwide. An additional 114 million tons of milled rice are required by 2035 to ensure food security, but land and water resources are scarce for further expanding paddy cultivation [5]. Sustainable rice farming methods are needed to improve productivity and farming efficiency, safeguard the environment, ensure food security, and improve rural livelihoods due to drought, rainfall variability, and resource and labor constraints.

In rural India, livelihoods are under constant strain due to various factors such as water scarcity, soil salinity, high agricultural wages, irrigation, and fertilizer costs. Efficient resource management is essential to tackle these issues [6,7]. Furthermore, with saturating yield and rocketing input prices, agriculture is becoming costly in Southeast Asia, including India [8–10]. Farmers should switch to climate-smart agriculture practices that conserve resources and increase efficiency instead of conventional practices that harm the environment [11]. However, it is predicted that one-third of Indian farmers will face water shortages by 2030. Therefore, adopting sustainable water management practices in paddy cultivation becomes imperative, reducing the strain on water resources [12].

Two standard methods for paddy production are transplanting and direct seeding. Transplanting is done in rainfed or irrigated lowland ecosystems with sufficient water available. Direct-seeded rice (DSR) is a potential water-saving technology for paddy production, which cuts land preparation time, involves direct sowing, and minimizes irrigation water requirements and soil greenhouse gas emissions [13]. Many farmers have transitioned from puddled transplanted rice (PTR) to DSR. The DSR method is primarily practiced by resource-poor farmers facing severe climatic constraints, i.e., low water table, occasional rainfall, and long dry periods that prevent rice-intensification system [14–16]. However, other paddy growers in India and other developing nations are also trying to substitute the PTR method with the less costly DSR technique [17].

DSR in paddy cultivation offers numerous benefits. For instance, it can be practiced in irrigated, rainfed, and deep-water ecosystems and has no transplantation shock, resulting in faster maturation than PTR. Dry-DSR (DDSR) and Wet-DSR (WDSR) are two classifications of DSR. The selection of the paddy establishment method depends on socioeconomic, demographic, and environmental factors. Several studies have shown that DDSR provides better yield and efficiently utilizes water under scarce irrigation water conditions. However, the adoption of DDSR is still low due to a lack of demand originating from inadequate DSR facilities, like DSR machines.

Previous studies have primarily focused on comparing the yield gain in DSR over conventional methods based on experimental studies conducted in a controlled environment. While some studies have examined the impact of various tillage and plant protection techniques along with DSR on paddy productivity and energy use, only a few have estimated the effect of DSR on paddy yield and economic performance by collecting primary data from household surveys. Furthermore, no previous study has measured the diverse impact of DDSR and WDSR on paddy yield and income.

This study aims to analyze the heterogeneous impact of dry and wet DSR on paddy productivity, revenue, and cost management. Additionally, our study aims to bridge the gaps in previous analyses presented for DSR by utilizing primary data for grain yield, additional income from DSR adoption, and estimating its impact on different cost components such as land preparation costs, irrigation costs, labor costs, and intercultural operation costs (Annexure 1). Furthermore, we present the socioeconomic and demographic constraints that play a critical role in DSR adoption, which may help the government and non-government organizations to fine-tune the existing policies for sustainable farming. We also present the results using propensity score matching, making it possible to measure the impact of DSR over the PTR establishment method.

2. Conceptual framework of the study

Fig. 1 represents the conceptual framework of the study. The entire study is divided into three stages. In the first stage, various socioeconomic and demographic variables that play a critical role in DSR adoption are identified. In the second stage, using propensity score matching, the study identified the impact of DSR adoption on the cost incurred at various operational activities, income, and crop yield. Finally, the study performs the impact analysis to measure which DSR method (Dry DSR and Wet DSR) is economically viable.

3. Methods

Adopting the DSR establishment method is a dichotomous choice of the farmer. If the net benefit from DSR adoption is higher than non-adoption, then farmers will adopt the technology. The net benefits achieved by the farmers from adoption over non-adoption is denoted as A^* (Equation (1)). If $A^* > 0$ means that farmer's net benefit from DSR adoption exceeds that of non-adoption. Nevertheless, A^* is unobservable; however, it can be presented as a function of measurable elements in the following latent variable model:

$$A^* = \beta X_i + \varepsilon_i, \quad A_i = 1[A_i^* > 0], \quad (1)$$

where A_i is a dichotomous variable that equals 1 when the household i adopted the DSR and 0 otherwise. β is the coefficient of the parameters to be measured. X_i is the vector of household and farm-related characteristics. ε_i is the error term expected to be normally distributed.

The likelihood of adopting the DSR establishment method can be presented as in equation (2):

$$\Pr(A_i = 1) = \Pr(A_i^* > 0) = \Pr(\varepsilon_i < \beta X_i) = 1 - C(-\beta X_i) \quad (2)$$

where C is the cumulative distribution function for ε_i . Regression models like logit and probit normally result from the assumptions made on the functional form of C . The adoption of DSR technology is likely to be affected by various socioeconomic and demographic characteristics, yield, and net revenue from production. To link the DSR adoption choice with the potential outcomes of adoption, considering a risk-neutral production system that maximizes net return φ , subject to competitive output and input market and a single-output technology that is quasiconcave in the vector of variable inputs, M . This may be represented as in equation (3):

$$\max \varphi = PR(M, X) - ZM \quad (3)$$

where P is the price for the output, R is the expected output level, Z is a common vector for input costs, M is the input vector, and X represents household and farm characteristics. Net return from DSR adoption can be expressed as a function of DSR adoption choice A , price of output, input variables, and household attributes as follows (Equation (4)):

$$\varphi = \varphi(A, Z, P, X) \quad (4)$$

Equations (4)–(6) indicate that the adoption choice of DSR technology, output and input prices, and household and farm characteristics may impact input demand, net return, and farm productivity.

3.1. Problem associated with impact assessment

DSR adoption may enhance the farm yield and farmers' crop income and improve their welfare. However, the variance in welfare between DSR non-adopters and adopters cannot be attributed to technology adoption. A counterfactual scenario is usually captured when experimental data is collected through randomization, eliminating the causal inference problem. On the contrary, when data are collected from a cross-sectional survey (as in the case of this study), no information on counterfactual scenarios is obtained. A possible way to mitigate this problem is to measure the direct impact of DSR adoption on outcomes differences between technology adopters and non-adopters [18].

The decision of farmers to adopt or not adopt the DSR technology may be allied with adoption benefits associated with self-selection bias. To understand the importance of self-selection bias, consider the following equation, which shows the relationship between technology choice and outcome variables.

$$S_i = \gamma_0 + \gamma_1 A_i + \gamma_2 X_i + \tau_i \quad (5)$$

In equation (5), S_i represents a vector of dependent variables, i.e., input costs, various farm operations, farm productivity, and farmers' net income, for household i . Likewise, X_i represents household and farm characteristics and τ_i is the error term. The selection-bias issue arises if unobservable factors influence both the error term of DSR adoption, i.e., ε_i (in equation (1)) and error term of outcome specification, i.e., τ_i , which results in a correlation of both error terms.

If the correlation between the two error terms exceeds zero, ordinary least square (OLS) regression may produce a biased estimation. Using Heckman's two-stage selection approach is one way to overcome selection bias. However, in both regression stages, it is assumed that unobserved variables are normally distributed, which may not be possible every time. Using the instrumental variable (IV) approach is another way to control the selection bias. However, the major drawback of the model is that it requires an instrumental variable in the treatment equation to serve as an instrument in specifying the outcome equation. Furthermore, OLS and IV techniques commonly assume a linear functional form, implying that the coefficients on the control variables are expected to be comparable for adopters and non-adopters. However, Jalan & Ravallion and Mendola mentioned that this assumption seems improbable to be valid [19,20].

Difference-in-difference matching estimator is another way to avoid selection bias where it allows temporally invariant differences in outcomes between adopters and non-adopters [21]. Unfortunately, it is valid when panel data is available. In the absence of panel data, the fixed effect model performs statistical matching to address the issue of selection bias [22]. It makes pairs between adopters and non-adopters comparable regarding observable characteristics [23].

3.2. Propensity score matching approach

The propensity score matching (PSM) method has the potential to provide an unbiased assessment of the treatment impact when the outcomes are independent of the assignment into treatment, given the pre-treatment baseline covariates. The PSM method primarily measures the treatment effect for the treated population, which can be presented as in equation (6):

$$\vartheta|_{i=1} = H(\vartheta|A=1) - H(S_1|A=1) - H(S_0|A=1) \quad (6)$$

where ϑ is the average treatment effect on treated (ATT), S_1 shows the outcomes' value of the new technology adopters and S_0 is the

value of same variable for non-adopters. However, we do not measure $H(S_0|I = 1)$. Rather, we measure the difference (θ^e) between $H(S_1|I = 1)$ and $H(S_0|I = 1)$. Hence, θ^e acts as a potential bias estimator.

Without experimental data and/or panel data, the PSM model can overcome the sample selection bias [23]. For this, the PSM model uses conditional probability that the farmers adopt DSR technology based on pre-adoption characteristics [24]. The PSM model uses the unconfoundedness assumption (i.e., also known as conditional independence assumption) to produce the condition of a randomized experiment that suggests that once D is controlled for, DSR technology adoption is random and uncorrelated with the outcome variables. Then, PSM can be expressed as equation (7),

$$p(D) = \Pr\{A = 1|D\} = H\{A|D\} \quad (7)$$

where $A = \{0, 1\}$ is the adoption indicator, and D is the vector of pre-adoption characteristics. The conditional distribution of D , in given $p(D)$ is similar in both clusters of DSR adopters and non-adopters.

PSM approach does not require functional form assumption, specifying the association between outcomes and predictors of outcomes. The assumption of unconfoundedness is the major drawback of the PSM method. Systemic differences may still exist between the outcomes of non-adopters and adopters even after conditioning, as selection relies on unmeasured baseline characteristics [21]. Still, the PSM approach provides a specification check to remove biases higher than average.

After measuring the propensity score (PS), the ATT can be measured as in equation (8):

$$\theta = H\{(S_1 - S_0|A = 1)\} = H\{H\{S_1 - S_0|A = 1, p(D)\}\} = H\{H\{S_1|A = 1, p(D)\} - H\{S_0|A = 0, p(D)\} | = 0\} \quad (8)$$

Several matching techniques can be used to match the adopters with non-adopters of similar PS. This study employs nearest neighbor matching (NNM), kernel-based matching, and radius matching to check the robustness of the outcome.

3.3. Study area and sample size

India is the second largest producer of paddy globally. The eastern and southern peninsular states in India are among the leading producers of paddy. The predominant cropping systems in these areas constitute the paddy-paddy system. Among the peninsular Indian states, Telangana is one of the largest producers of paddy. The area under paddy crop is 17.5 lakh hectares. Among the state's ten major paddy-producing districts, Nalgonda stands first for the area under paddy production (21% of the total) and paddy produce (1068828 tons, i.e., 21% of the total) [25]. About 98% of the Nalgonda farmers followed rice monocropping for both seasons, and nearly 90% have irrigation facilities. Hence, we purposively selected this district as the study area (Fig. 2). The district also represents agroecological zones of peninsular India having heavy clayey soils of vertisol order [26].

According to Census (2011), the district's population was 34,88,809 [27]. Out of the total, the number of farmers who owned land and were directly involved in agriculture was 3,12,130. We employed the Bartlett et al. sample size calculation formula (Equation (9)) to calculate an adequate sample size for the study [28]:

$$n = \frac{\frac{Z^2 pq}{d^2}}{1 + \frac{1}{N} \left[\frac{Z^2 pq}{d^2} - 1 \right]} \quad (9)$$

where N = Size of the population (312130), n = size of the sample population; Z = confidence interval at 95% ($Z = 1.96$); d = error at 5% ($d = 0.05$); p = proportion of target population ($p = 0.5$); and $q = 1 - p$ ($q = 0.5$). We found that 384 household data were sufficient

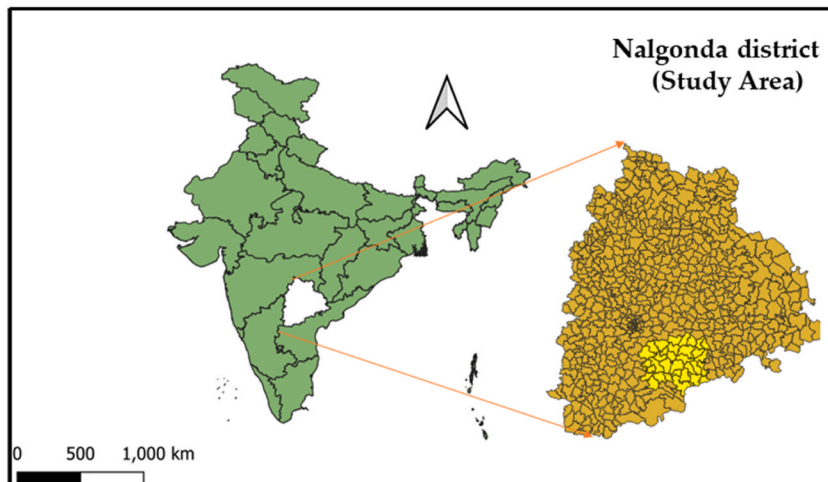


Fig. 2. Study area used in this study.

for this study. However, we surveyed 669 households from 20 blocks of Nalgonda district. Of the 669 households, 577 farmers adopted the DSR method, while 92 farmers followed the conventional (PTR) method for paddy cultivation.

4. Results and discussion

4.1. Descriptive statistics

The descriptive statistics in Table 1 show that DSR adopters differ significantly from non-DSR adopters regarding land preparation, fertilizer application, weed management, pest management, irrigation, and harvest cost. According to our analysis, establishing DSR may simplify the package of practices required for paddy production, as predicted way back by Serrano in 1975. This could increase farmers' income, especially since the rising cultivation costs in the coming years may force more farmers to adopt the DSR method for paddy cultivation. The land preparation cost for DSR adopters is 22.6% less than for non-DSR adopters. Similarly, fertilizer costs, pest management costs, irrigation costs, and harvest costs are also significantly lower compared to non-DSR adopters. However, the weed management cost is 12% higher for DSR adopters. This result agrees with Eskandari & Attar, mentioning that total energy consumption was significantly higher in transplanted rice, while herbicide usage was higher in the DSR system [29]. Moreover, the yield and additional income due to DSR adoption are 7.69% and 44.3% higher than non-DSR adopters. This result is congruent with a report from a systematic review that indicates that paddy productivity can be improved by 3.1% in the case of DSR adoption and 0.7% if PTR farmers shift to the DSR method [30]. Furthermore, the economic benefits identified through this study support Singh et al. mentioning that in DSR, integrated use of stale seedbed, shallow tillage, and sequential application of herbicides has the potential to improve the paddy yield by 2.1–2.5 t ha⁻¹ and economic return by \$ 1310 ha⁻¹ [16].

This study uses 17 independent variables as baseline covariates to measure the propensity score. Out of these 17 variables, the mean of 7 variables differs significantly among DSR adopters and non-adopters. Table 1 shows that 50% of the DSR adopters are members of farmers' organizations and accept institutional credit and crop insurance to protect the farmer from adverse climatic conditions. However, 77% of non-DSR adopters have assured irrigation, while only 54% of DSR adopters have the same facility. Smartphone and television ownership are also higher among the DSR adopters than non-adopters. Moreover, 48% of DSR adopters also have additional off-farm income, while 38% of non-DSR adopters are involved in off-farm income. This demonstrates that technology beyond agriculture also significantly impacts adoption of new agricultural technologies, acting as a catalyst for behavioral change among farmers [31].

4.2. Determinants for direct seeded rice adoption

A standard probit model is used to determine the constraints of DSR technology adoption. Table 2 represents the outcomes of probit estimation. The analysis reveals a statistically significant inverse correlation between age and the adoption of the DSR technique. With

Table 1
Difference in characteristics of DSR adopters and non-adopters.

Variable	DSR-adopters		D.S.R. non-adopters		Mean difference test
	Mean	Standard deviation	Mean	Standard deviation	
Cost of land preparation (₹/per acre)	5432	73	7018	97	0.001
Cost of fertilizer application (₹/per acre)	2463	43	3603	427	0.001
Weed management cost (₹/per acre)	1002	29	781	83	0.001
Pest management cost (₹/per acre)	721	25	2272	49	0.001
Irrigation cost (₹/per acre)	3699	90	5677	29	0.001
Harvest cost (₹/per acre)	2094	19	2834	27	0.001
Yield (t/per acre)	2.80	0.33	2.60	0.19	0.001
Additional income (₹/per acre)	44950	873	31161	708	0.001
Age of the farmer	48.06	6.92	50.54	8.02	0.196
Education level	3.11	0.56	2.91	0.45	0.371
Marital status	1.58	0.57	1.50	0.50	0.193
Family size	3.98	1.42	4.15	1.62	0.294
Membership in farmer organization	0.50	0.11	0.40	0.19	0.069
Farm experience	30.02	16.87	29.81	15.78	0.914
Distance to market	3.76	1.96	3.95	2.12	0.397
Distance to main road	1.96	0.83	2.04	0.75	0.394
Institutional credit	0.51	0.08	0.26	0.04	0.001
Crop insurance	0.53	0.09	0.26	0.04	0.001
Assured irrigation	0.54	0.19	0.77	0.12	0.001
Livestock	0.49	0.18	0.52	0.15	0.537
Off-farm income	0.48	0.13	0.38	0.18	0.075
Smartphone ownership	0.47	0.19	0.32	0.16	0.006
Television ownership	0.51	0.11	0.39	0.09	0.038
Farm size	8.89	2.01	8.71	2.09	0.812
Crop variety	1.24	0.60	1.29	0.58	0.482

Source: Authors' calculations using the survey data.

Table 2
Determinants of DSR adoption: a probit analysis.

Variables	Coefficient	Marginal effect	Standard error
Age of the farmer	−0.17**	0.12	0.04
Education level	0.29***	0.18	0.03
Marital status	0.13	0.04	0.03
Family size	0.11	0.05	0.04
Membership in farmer organization	0.30	0.16	0.06
Farm experience	0.12	0.07	0.05
Distance to market	−0.16	0.09	0.05
Distance to main road	−0.08	0.05	0.06
Crop loan	0.24***	0.16	0.04
Crop insurance	0.31***	0.19	0.06
Assured irrigation	−0.23***	0.11	0.02
Livestock	−0.05	0.009	0.03
Off-farm income	0.08	0.05	0.02
Smartphone ownership	0.23**	0.13	0.03
Television ownership	0.28***	0.19	0.06
Farm size	0.17*	0.09	0.05
Crop variety	−0.06	0.03	0.02

* = significant at 10%; ** = significant at 5%; *** = significant at 1%.

Source: Authors' calculations using the survey data.

a 1-year increase in the average age of the sample population, the chance of DSR adoption decreases by 0.12%. This finding is similar to the earlier outcome [32]. This suggests that younger farmers are more inclined to embrace DSR technology than their older counterparts. One possible explanation for this phenomenon is that younger farmers are more enthusiastic about adopting novel technology. In contrast, elderly farmers tend to adhere to traditional rice cultivation methods and are reluctant to venture beyond their comfort zone in embracing new technological advancements. This outcome is similar to the findings of [33,34]. However, Sodjinou et al. reported that farmers' age positively influences the adoption of new farm practices [35].

Education has a pivotal influence on technology acceptance, as evidenced by a positive and statistically significant correlation between education levels and the adoption of DSR technology. Results show that with a one-year increase in education level, the likelihood of DSR adoption improves by 0.18%. Farmers who have received education know the possible impact of new technology on crop production and financial returns. As a result, the household head's educational attainment tends to positively affect the decision to adopt new technologies, such as direct rice seeding. This finding is similar to the earlier reported outcomes [36–38]. Educated farmers are typically better able to adapt to new challenges and employ new technologies [39,40].

The coefficient associated with the membership in the farmers' organization variable exhibits a positive and statistically significant relationship, indicating a positive association between farmers' organization membership and technology adoption. The increase in organization membership by 10% improves the probability of DSR adoption by 1.4%. This outcome is in the same line with Tura et al. [41]. Membership in a farmer-based organization positively correlates with a higher probability of embracing agricultural innovations. Conley and Udry have demonstrated that extension services and farmers' organizations are conduits for disseminating knowledge among producers [42,43]. The findings align with the results reported by different researchers [44–47].

Utilizing information and communication technology enhances the likelihood of adopting agricultural innovations [40]. Producers with a television and/or smartphone exhibit a higher propensity to embrace agricultural innovations. Information and communication technology (ICT) enables farmers to access a wide range of information about various agricultural technologies, improving the chance of adoption [48]. Similar outcomes are obtained in this study, where smartphone and television ownership farmers have a better chance of adopting DSR technology.

The study represents a favorable correlation between the availability of institutional loans and the probability of adopting agricultural technology. Results show that a 1% improvement in institutional credit adoption enhances the chance of DSR adoption by 0.16%. This finding is similar to Tura et al. and Idrisa [36,41]. The adoption of agriculture technology is more likely among farmers who have acquired institutional credit. According to Mdemu et al. in Tanzania and Nonvide et al. in Benin, a significant limitation in technology adoption is the absence of access to formal finance [40,49]. The authors reported that the availability of finance potentially enhances the purchasing of farm inputs and the adoption of new technology in agriculture.

Farmers possess a variety of alternatives when it comes to managing agricultural hazards, and it is common for them to employ many risk management strategies concurrently. Adopting a particular risk management tool favors embracing additional risk management tools. The results indicate that improvement in adopting crop insurance by 1% positively impacts adopting other risk management techniques like DSR by 0.19%. Moreover, farmers adopting DSR over conventional PTR also assume that if crop yield gets hampered due to their inefficiency in practicing new technology, crop insurance will provide an additional shield against the loss.

The results in Table 2 also indicate that landholding size positively influences DSR adoption. A 1% improvement in land size from the mean increases the likelihood of DSR adoption by 0.09%. This means farmers with large farm sizes are more interested in DSR adoption. This finding is similar to the findings of past studies [41,50–53]. Perhaps smallholder thinks that if they lose their average yield due to adopting new technology, they cannot achieve food security and expected income. In contrast, large holders allocate their land under both interventions (DSR and PTR). With a relatively large farm size, they are confident that even if yield decreases due to DSR adoption, they can compensate for their income and ensure food security with PTR.

Unlike landholding size, assured irrigation negatively influences the adoption of DSR technology. It means farmers having assured irrigation opt for PTR. DSR is primarily a water-saving paddy production system that reduces the methane emission from paddy fields and enriches soil health. However, farmers with assured irrigation are rarely informed about flood irrigation's soil and environmental ill effects [39,44,54,55]. Also, in the study area, the government provides electricity at a subsidized rate for the farmers, which further motivates the farmers to use flood irrigation.

4.3. Matching quality of the PSM approach

The propensity score ranges from merely zero (0.020) to almost one (0.999) (Fig. 3). The mean propensity score is 0.882. Households adopting DSR practice have a mean propensity score of 0.938 (minimum 0.062; maximum 0.999) with a standard deviation of 0.134. Similarly, farmers without DSR adoption consist of a mean propensity score of 0.067 (minimum 0.020; maximum 0.959) with a standard deviation of 0.122. The estimated propensity score distribution reveals that the common support area with and without DSR adoption expands from 0.120 to 0.999, indicating enough common support area to perform PSM. The remaining households with a propensity score outside this common support area are excluded from the analysis.

The primary objective of the Propensity Score Matching (PSM) method is to achieve covariate balance both before and after the matching process. Table 3 displays the covariate balancing indicators before and after the matching process. Table 3 presents the results of several balancing tests utilized in this study. These tests include the assessment of median absolute bias before and after matching, the evaluation of pseudo R^2 before and after matching, and the determination of the p-value of joint significance of variables before and after matching. The median absolute bias is relatively high prior to matching, falling within the range of 27.16–19.54. However, the median absolute bias demonstrates a notable decrease following the matching process, falling within the range of 11.24–18.36. This suggests that a significant reduction in bias has been achieved by matching. The outcomes demonstrate a satisfactory bias reduction, ranging from 72.89% to 57.33%. The pseudo- R^2 has a very high value prior to matching for the nearest neighbor matching (NNM), kernel-based matching (KBM), and radius matching methods. The pseudo- R^2 value has a relatively low magnitude following the matching process, suggesting a substantial resemblance between the adopters and non-adopters. Similarly, it is imperative to assess the collective significance of variables prior to matching and to reject it after matching if there is no discernible distinction between adopters and non-adopters. Fig. 3 also displays the signs of covariate balancing.

4.4. Impact of DSR-practice adoption on cost incurred in various farm practices, paddy productivity, and income

The impact of DSR technology is measured using the PSM approach, and we have presented the outcomes in Table 4. We have applied three different matching algorithms, i.e., nearest neighbor matching (NNM), kernel-based matching (KBM), and radius matching (RM), to measure the average treatment effect on treated (ATT), i.e., the difference in the outcome of the DSR adopters and non-adopters. The impact of DSR adoption is significant and positive in the case of NNM, KBM, and RM, indicating that DSR adopters are getting an additional paddy yield of 0.042t/acre to 0.085t/acre. This may be because the DSR technique helps alleviate water scarcity by improving soil physical properties and slowing organic matter loss [56]. The cost of land preparation for DSR adopters is significantly lower by ₹1605/acre to ₹1643/acre due to avoidance of puddling and nursery preparation, as indicated by the negative and significant results at a 1% significance level. Likewise, adopters of DSR experience reduced fertilizer and pest management costs of ₹1090/acre and ₹590/acre, respectively, due to improved nutrient efficiency with split application compared to PTR [57].

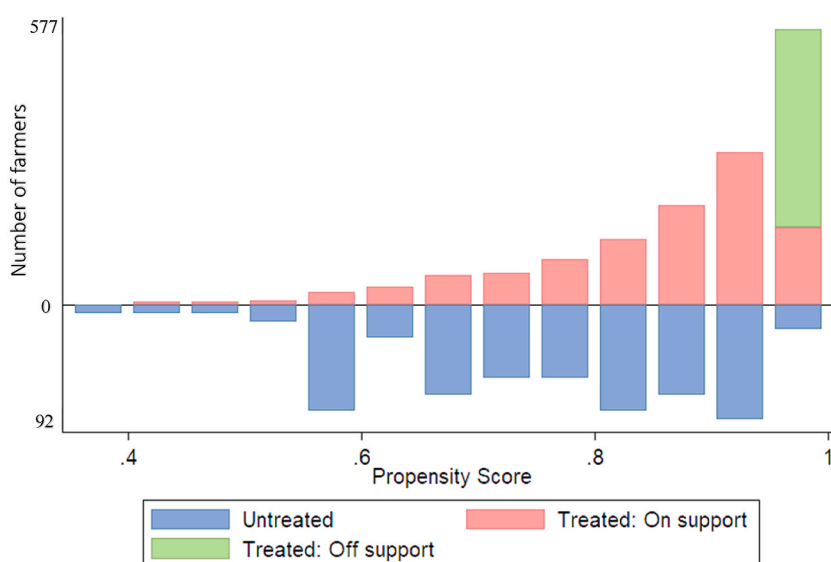


Fig. 3. Covariate balancing and common support area.

Table 3
Covariate balancing test before and after matching.

Matching algorithm	Outcome	Median absolute bias (before matching)	Median absolute bias (after matching)	(Total) % bias reduction	Pseudo R2 (unmatched)	Pseudo R2 (matched)	p-Value of LR (unmatched)	p-Value of LR (matched)
NNM	Cost of land preparation	23.41	15.95	68.12	0.366	0.003	0.053	0.633
NNM	Cost of fertilizer application	22.47	14.28	63.54	0.349	0.006	0.049	0.845
NNM	Weed management cost	21.46	15.64	72.89	0.327	0.004	0.041	0.765
NNM	Pest management cost	21.38	15.21	71.15	0.427	0.003	0.038	0.692
NNM	Irrigation cost	24.27	14.47	59.64	0.412	0.003	0.055	0.711
NNM	Harvest cost	22.17	14.28	64.39	0.398	0.007	0.062	0.734
NNM	Yield	25.62	15.85	61.88	0.371	0.004	0.046	0.778
NNM	Crop income	27.16	18.33	67.49	0.325	0.006	0.039	0.811
KBM	Cost of land preparation	22.49	15.03	66.81	0.336	0.005	0.058	0.655
KBM	Cost of fertilizer application	21.78	14.89	68.37	0.374	0.003	0.049	0.579
KBM	Weed management cost	20.73	13.71	66.13	0.399	0.008	0.044	0.616
KBM	Pest management cost	24.55	15.27	62.18	0.368	0.003	0.041	0.558
KBM	Irrigation cost	23.17	15.64	67.51	0.371	0.005	0.037	0.721
KBM	Harvest cost	25.73	18.36	71.36	0.411	0.004	0.039	0.792
KBM	Yield	22.46	15.52	69.11	0.427	0.006	0.046	0.613
KBM	Additional income	19.56	12.16	62.19	0.409	0.002	0.051	0.564
RM	Cost of land preparation	22.94	14.26	62.15	0.392	0.004	0.033	0.589
RM	Cost of fertilizer application	25.17	17.16	68.19	0.377	0.003	0.042	0.533
RM	Weed management cost	21.49	14.43	67.13	0.354	0.007	0.037	0.456
RM	Pest management cost	23.91	14.05	58.76	0.298	0.005	0.048	0.433
RM	Irrigation cost	22	13.84	62.91	0.318	0.004	0.050	0.563
RM	Harvest cost	23.93	15.60	65.18	0.359	0.003	0.040	0.447
RM	Yield	19.54	11.24	57.53	0.339	0.005	0.045	0.465
RM	Additional income	21.28	15.18	71.34	0.382	0.006	0.049	0.556

Source: Authors' calculations using the survey data.

Table 4
Impact of DSR-practice adoption on cost incurred in various farm practices, paddy productivity, and income.

Variable	Treatment variable: DSR adoption					
	Nearest-neighbor matching		Kernel-based matching (0.06)		Radius matching (0.05)	
	ATT (SE)	r-bound	ATT (SE)	r-bound	ATT (SE)	r-bound
Cost of land preparation (₹/per acre)	−1605*** (44.16)	1.7–1.8	−1633*** (54.37)	1.5–1.6	−1643*** (38.46)	1.7–1.8
Cost of fertilizer application (₹/per acre)	−1045*** (150.88)	1.5–1.6	−1116*** (60.75)	1.3–1.4	−1109*** (48.93)	1.4–1.5
Weed management cost (₹/per acre)	390** (61.38)	1.8–1.9	222** (87.49)	1.6–1.7	179*** (71.53)	1.9–2.0
Pest management cost (₹/per acre)	−623*** (15.85)	1.9–2.0	−580*** (25.26)	1.8–1.9	−568*** (15.90)	2.1–2.2
Irrigation cost (₹/per acre)	−2067*** (145.45)	1.6–1.7	−2022*** (78.44)	1.7–1.8	−2002*** (148.34)	1.6–1.7
Harvest cost (₹/per acre)	−182 (0.033)	1.6–1.7	−181 (0.025)	1.5–1.6	−192 (0.028)	1.8–1.9
Yield (t/per acre)	0.085** (0.003)	1.3–1.4	0.075** (0.003)	1.5–1.6	0.042* (0.002)	1.4–1.5
Additional income (₹/per acre)	5187 (123.46)	1.5–1.6	5289 (119.09)	1.4–1.5	5099 (146.38)	1.8–1.9

*** = Significant at 1%; ** = Significant at 5%; * = Significant at 10%.

Source: Authors' calculations using the survey data.

Furthermore, by adopting the DSR method, farmers can save between ₹2000–2067 per acre on irrigation costs due to reduced water requirements. However, DSR fields tend to have a higher weed intensity, requiring more herbicides to control. This leads to a higher cost of weed management, ranging from ₹179–390 per acre for those who adopt DSR technology compared to those who do not.

The overall cost of production for DSR technology is minimal. As a result, the additional income gain from paddy production using DSR technology is ₹5099–5289/acre. DSR adopters achieve higher income with minimum land preparation investment and reduced irrigation requirements. The rise in farm income is a huge incentive for farmers to adopt DSR technology in paddy farming. Besides the financial benefits, DSR adoption promotes sustainable farming practices that enhance soil health and encourage the growth of beneficial microorganisms. This, in turn, supports regenerative agriculture. Table 4 presents the critical threshold of hidden bias in this study. If an unobserved independent variable has the potential to impact both DSR adoption and outcome variables, there is a possibility of unobserved heterogeneity arising, which might potentially modify the importance of the influence [58,59]. Determining the extent of hidden bias in non-experimental studies poses challenges due to the absence of a suitable assessment instrument. Rosenbaum proposed a viable solution in 2002 [60]. Researchers can assess the extent to which unobserved exogenous factors impact the significance of the estimate by employing the Rosenbaum-bounds-sensitivity calculation [61,62].

The findings presented in Table 4 indicate that each ATT value is linked to a corresponding τ -bound value. This value indicates a significant gamma level at which one might justify the causal inference of DSR technology adoption. For example, the gamma value for irrigation cost is 1.7–1.8, which means that if farmers have the same vectors of baseline covariates in their odds of DSR adoption with a factor of 70–80%, the positive impact of DSR adoption on irrigation cost saving, may be questioned. It means that the strength of hidden bias must be high enough to alter the findings in Table 4. Additionally, such high gamma values associated with the outcomes indicate that the study considers most exogenous factors as baseline covariates that may influence the treatment and dependent variables.

4.5. Impact of dry DSR-practice adoption on cost incurred in various farm practices, paddy productivity, and income

We present the cost comparison between dry and wet DSR adoption and the impact on farm operations, yield, and crop income in Table 5. The result shows that adopting dry DSR marks significantly lower land preparation and irrigation costs (₹1195/acre and ₹880/acre) than wet DSR. However, wet DSR is still an alternative approach to crop establishment if the monsoon gets delayed in rainfed areas. It can conserve irrigation water when coupled with effective water management techniques.

Nevertheless, both methods eliminate the need for puddling, reducing the overall water need and shortening the land preparation period [13,63]. Although there is no significant difference in weed and pest management costs between dry and wet DSR, dry DSR still indicated a better yield of 0.052t/acre than wet DSR in heavy soils. Saving on land preparation and irrigation costs and better yield achievement result in an additional income of ₹2467/acre for dry DSR adopters than wet DSR farmers. The range of gamma values associated with each outcome in Table 5 indicates that hidden bias arising from counterfactuals that can potentially influence both the treatment and dependent variables is considered during the propensity score calculation.

5. Conclusion

Rice is a widely grown crop that requires many resources, but farmers are moving towards sustainable methods like DSR due to unpredictable rainfall, labor shortages, and resource limitations. DSR is a feasible and cost-effective alternative to traditional rice cultivation methods like PTR. In India, farmers are shifting to the more modern and efficient DSR method. Despite its benefits, only a few farmers have adopted DSR over PTR. This study aims to identify the critical determinants of DSR adoption and its impact on farmers' yield, income, and costs in different farm operations. It also compares the effect of dry DSR adoption over wet DSR in terms of yield and economic welfare, filling a research gap in identifying the best-suited DSR method for farmers in peninsular India. The study found that factors such as farmers' education, institutional credit, off-farm income, and smartphone ownership positively impact DSR technology adoption. However, farmers' age and irrigation availability restrict DSR adoption. DSR adopters have lower land

Table 5
Impact of DSR-practice adoption on cost incurred in various farm practices, paddy productivity, and income.

Variable	Treatment variable: Dry-DSR (DDSR) adoption					
	Nearest-neighbor matching		Kernel-based matching (0.06)		Radius matching (0.05)	
	ATT (SE)	r-bound	ATT (SE)	r-bound	ATT (SE)	r-bound
Cost of land preparation (₹/per acre)	−1195*** (46.74)	1.6–1.7	−1193*** (26.41)	1.7–1.8	−1197*** (29.48)	1.6–1.7
Cost of fertilizer application (₹/per acre)	−5.01 (4.724)	1.3–1.4	−7.59 (4.47)	1.5–1.6	−8.32 (3.86)	1.4–1.5
Weed management cost (₹/per acre)	9.482 (25.01)	1.6–1.7	5.59 (24.63)	1.5–1.6	7.48 (17.17)	1.8–1.9
Pest management cost (₹/per acre)	−37.16 (14.09)	1.5–1.6	−39.18 (11.18)	1.4–1.5	−40.09 (10.50)	1.8–1.9
Irrigation cost (₹/per acre)	−886*** (26.05)	1.7–1.8	−876*** (18.76)	1.5–1.6	−879*** (18.02)	1.7–1.8
Harvest cost (₹/per acre)	−75 (15.81)	1.8–1.9	−69 (9.46)	1.6–1.7	−68 (9.87)	1.9–2.0
Yield (t/per acre)	0.044 (0.04)	1.5–1.6	0.052** (0.03)	1.3–1.4	0.052** (0.02)	1.4–1.5
Additional income (₹/per acre)	2457*** (348)	1.9–2.0	2473*** (282)	1.8–1.9	2470*** (258)	2.1–2.2

*** = Significant at 1%; ** = Significant at 5%; * = Significant at 10%.

Source: Authors' calculations using the survey data.

preparation, fertilizer application, pest management, and irrigation costs than PTR adopters. Adopting DSR technology can save a paddy farmer ₹5192 per acre over PTR. Land preparation and irrigation costs are significantly lower for dry DSR adopters than for wet DSR farmers, bringing an additional crop income of ₹2467 per acre for dry DSR farmers.

There are two alternative ways to eliminate the risk of adopting DSR and engage wider farming communities under D.S.R. First, the central government must promote clustering and cooperative approaches to engage sizable and suitable areas under DSR implementation. Second, state and central government and non-governmental organizations need to provide training on DSR agronomy and other management practices (including weedicide and pesticide spraying, nutrient management, and irrigation) to up-skill the farmers sufficiently to practice DSR in their conventional fields. Also, the policymakers need to develop incentive structures to promote the uptake of the DSR method. Policies designed to enhance the adoption of DSR should prioritize the development of operator capabilities in weed control through comprehensive training on optimal management approaches. Adopting the DSR method by rice farmers can yield environmental benefits, such as less tillage or soil disturbance, mitigation of soil erosion, and decreased water use. Implementing soil and water conservation technologies in DSR would enhance yield and contribute to food security, hence supporting the *National Food Security Mission*. Sustainable paddy production will align with government policies such as *Sustainable Livelihoods*, *Sustainable Land Management*, *Soil Moisture and Nutrient Improvement*, *Improved Agriculture/Crop Land Management*, *Cropland and Grassland Land-use Conversions*, and *Soil Protection and Conservation*. Adhering to DSR practices can be a highly effective method for preserving and safeguarding soil biodiversity. Furthermore, this practice can contribute to broader climate policies, such as achieving *net zero emissions*, and support other government economic goals, such as *Doubling Farmers' Income*.

There are a few limitations of the study; the study was conducted in a representative area of peninsular India, i.e., Telangana state, and may be replicated in various agroecological conditions to measure DSR's suitability over PTR. Moreover, this study only concentrates on the economic benefits of DSR adoption. However, future studies could focus on environmental outcomes and soil characteristics that benefit societies at scale.

Ethics declarations

- This study was reviewed and approved by Dr. Reddy's Foundation, with the approval number: DRF/ACE-MITRA/2022. The approval letter is attached as an annexure.
- All participants/farmers (or their proxies/legal guardians) provided informed consent to participate in the study/program.
- Informed consent from participants/farmers (or their proxies/legal guardians) for this publication was not required as this study did not use any of their anonymized case details and images.

Data availability statement

All data required to support the results and conclusion of this study are available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Shiladitya Dey: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Kumar Abhishek:** Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Suman Saraswathibatla:** Supervision, Resources, Project administration. **Piyush Kumar Singh:** Writing – review & editing, Conceptualization. **Prithvi Ram Bommaraboyina:** Writing – review & editing, Conceptualization. **Abhishek Raj:** Writing – review & editing, Conceptualization. **Hamika Kaliki:** Writing – review & editing. **Abhishek Kumar Choubey:** Writing – review & editing. **Hari Babu Rongali:** Writing – review & editing. **Aruna Upamaka:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We acknowledge the support of our field team for collecting primary data to support this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.heliyon.2024.e26754>.

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