Direct Seeded Rice in Haryana (India) ABY Districts: Impact and Lessons for Scaling

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Executive Summary

Introduction

Rice is a staple crop in India, traditionally cultivated using the Transplanted Puddled Rice (TPR) method. This traditional method, while effective and very popular amongst farmers, is highly labour, water, and energy-intensive, that leads to significant groundwater depletion and higher energy usage in pumping groundwater. In response to these challenges, the Direct Seeded Rice (DSR) method has been introduced as a more sustainable alternative. DSR involves sowing seeds directly into the field, eliminating the need for growing and transplanting seedlings. This method, tested in various field trials, promises to have several benefits, including water savings, reduced labour and production costs, higher economic returns, and lower methane emissions. However, the success in farmer fields when adopted at scale outside trials remains to be analysed critically.

In that context, this study was commissioned through a MoU with National Project Management Unit (NPMU), Atal Bhujal Yojana (ABY). ABY, also known as Atal Jal, is a central sector scheme aimed at sustainable groundwater management with community participation. Launched in December 2019, ABY focuses on improving groundwater management in water-stressed areas across seven states, including Haryana. The adoption of DSR in Haryana has been gradual but promising. The area under rice cultivation in the state has increased significantly over the years, with initial efforts to introduce DSR beginning around 2009. The state government has played a crucial role in promoting DSR by offering financial incentives to farmers. In 2022, an incentive of INR 4000 per acre[1] was introduced to encourage farmers to adopt DSR. Given its uptake in Haryana, the objective of this study is to assess the socio-economic and environmental benefits of DSR, identify the challenges, and offer recommendations for scaling up this technology in Haryana and other regions.

The study employed a multi-faceted approach including qualitative surveys with stakeholders, focus group discussions, field visits, and a large-scale quantitative survey (sample size is 809) of DSR and TPR farmers across selected districts in Haryana to assess the impact of DSR. These farmer-level sources were complemented by water flow meter data analysis and remote sensing analysis.

Key Findings

One of the important findings of this study is the water-saving potential of DSR. Based on recall data on irrigation water application, we found that DSR plots had 20% less hours of irrigation on average, with consistent results across all the districts surveyed. This reduction in irrigation hours translates into significant reduction in estimated water application for DSR (consistent under different versions but the percentage difference varies) minimum 13-14% to 19-22%. This result was confirmed through the water flow meter data analysis that showed on average (excluding one district i.e. Sirsa[2]) water application is 20% lower for DSR plots. This significant reduction in water usage can help control the declining water table in Haryana and have a cascading effect on the state's water resources.

These field observations also align with the average percentage difference of 5-7% observed through satellite data from Landsat in Actual Evapotranspiration (AET) values during the Kharif season between TPR and DSR systems. Difference in AET values is lower compared to differences in irrigation water

[1] I USD = about INR 80 (2022)

[2] Since in Sirsa, canal irrigation accounts for 80% of irrigation need, groundwater use is far lower to compare using water flow meter (WFM) data that only captures groundwater.

application, because of inefficiencies in irrigation application. The remote-sensing analysis also highlights the successful application of satellite data and drones in calculating evapotranspiration rates and classification of DSR and TPR sites. These technologies can provide valuable analytical tool to monitor DSR uptake and its impact. In terms of monitoring, while establishing water flow meters to measure irrigation water application is a much-needed step for assessing the actual water saving in DSR over TPR, but the present set-up of water measurement still requires few modifications. In particular, there is a need to measure canal water especially in western Zone of Haryana for which Parshall flumes may be installed at appropriate places.

DSR adoption also reduced total labour use by 18%, with a significant decline in female labour participation. Although women are more involved in weeding, the reduction in labour required for sowing more than offsets this increase. Moreover, the peak demand during transplanting is flattened over a longer period as weeding is undertaken at different time intervals. The enhanced profitability and lower labour demand makes DSR an attractive option for farmers, particularly in regions where water efficiency and labour shortages are key concerns.

At the farmer level, we find that land-preparation, sowing/transplanting (including nursery) and irrigation costs are significantly lower for DSR plots; but there is also a significant increase in cost of fertilizers, pest/disease control, weed management, and harvesting. We find no significant difference in the total cost of cultivation, even after accounting for the varietal differences. Reduced cost of cultivation often claimed in the past studies is however not emerging from this study. It looks that recent change in the technology making laser land levelling an essential component has flattened the cost differential but may have added to water saving and yield. Overall, there was around 3% yield penalty in DSR, but when comparing across same paddy variety no significant difference in yield was observed, except in Pusa Basmati 1692, where DSR exhibited a lower yield (statistically significant), likely due to its higher susceptibility to weather fluctuations.

Despite almost similar costs and yields, DSR resulted in significantly higher net returns (except for Pusa Basmati 1692) due to the higher market price linked to better grain quality factors, lower breakage rates during milling and reduced chalkiness. On an average, net returns for DSR were almost 22% higher. It is crucial to make farmers aware of this advantage to refrain them from mixing DSR paddy with TPR paddy, which could negate the price benefit.

However, in terms of agronomic practices, weed management remains the most significant barrier to DSR adoption, with 56% of farmers reporting it as a major challenge. This is followed by concerns about yield penalties (12%) and diseases/pests (9%). Interestingly, fewer adopters are applying herbicides at the correct doses, and there is a tendency among adopters to overdose herbicide applications, especially during post-emergence period. However, these higher doses of herbicide application do not lead to significant increase in yield, indicating scope for optimization. DSR plots also recorded higher seed rate and fertilizer use, particularly MOP, Zinc, and Iron as compared to TPR. Varying doses of nutrient fertilization do not significantly alter yield, suggesting scope for optimizing fertilizer use to reduce cultivation costs. Similarly, the yields remain nearly the same even if the seed rate is slightly lower, suggesting potential to optimize this further. These findings indicate that there are several opportunities to bring down the cost of cultivation in DSR. Some cost-cutting strategies can include optimum seed rates, infrequent irrigations, minimal tillage, and reduced fertilizer and herbicide use. Stakeholders need to be made aware of these issues through training and awareness campaigns.

Recommendations

DSR technology has significant potential for water saving, with improved economic returns for farmers and a reduced burden on female labour engagement. The observed reduction in groundwater usage by 15-20%, also implies decrease in government electricity subsidies (INR 1260/acre) and reduced methane and greenhouse gas emissions from decreased pumping. However, several challenges need to be addressed to scale up DSR adoption effectively, including economic constraints, agronomic challenges, agronomic barriers, cultural and behavioural aspects, and farmers' concerns about market yield and risks.

One major limiting factor is the high initial cost of DSR machinery, particularly for small and marginal farmers who lack the financial capacity and risk tolerance to invest in such technology. While current subsidy rates for DSR equipment are reasonable, additional funding is needed to meet the growing demand. Along with that, public-private partnerships should be encouraged to develop cost-effective, region-specific DSR machinery and hiring services.

Additionally, high weed pressure in DSR plots necessitates costly and complex integrated weed management, while the absence of herbicide-resistant rice varieties further complicates adoption. Strengthening training in weed management and optimal fertilizer application is needed that can further reduce costs for farmers and improve yields. Our results also show that optimizing seed rates and fertilizer application, along with conservation tillage and laser levelling practices, can improve farmers' yields and returns. Hence, increased investment in R&D is crucial. Particularly for developing DSR-conducive rice varieties and cost-effective weed management protocols. Dedicated funds should be allocated to agricultural universities and research organizations with these objectives. Along with that, regular workshops and training sessions on DSR's technical aspects, with increased support for Krishi Vigyan Kendras (KVKs), are crucial for capacity building.

DSR's vulnerability to untimely rainfall and the need for customized fertilizer strategies make it a risky choice, discouraging adoption. Moreover, farmers' reluctance to shift from familiar traditional practices and concerns over unstable yields and fluctuating market prices, especially for Basmati rice, add to the uncertainty, making it difficult for farmers to fully commit to DSR. Hence DSR adoption can remain restricted among larger farmers able to take risks and only in areas with low rainfall with long-duration varieties, necessitating high irrigation demand with low supply. So attractive incentives are essential for DSR adoption and innovative measures like linking incentives to energy use, combined with schemes like "Pani Bachao Paisa Kamao," can be considered. Along with that, collaborations with NGOs and farmer groups can support grassroots adoption, with early adopters guiding others and Farmer Producer Organizations (FPOs) pooling resources for equipment, market access, and spreading DSR knowledge. Establishing a one-stop system where small and marginal farmers can access seeds, herbicides, fertilizers, and machines, along with early procurement and guaranteed prices for DSR varieties, can strengthen market linkages and procurement support. Finally, setting up a data monitoring cell to track adoption rates and assess DSR's impact on water conservation, yield, and economic benefits will help identify future challenges and provide necessary inputs for policy adjustments in time.

In summary, while DSR presents a promising alternative to traditional rice cultivation methods, especially in water-stressed areas under ABY, its successful scaling requires a multi-faceted approach with concerted efforts from all stakeholders, including farmers, researchers, policymakers, and the private sector. By addressing the identified challenges and leveraging the observed benefits, DSR can contribute significantly to mitigate the groundwater depletion issues targeted by ABY, thereby supporting the scheme's broader mission of sustainable groundwater management.

1. Introduction

Rice is a major cereal crop in India, grown under vastly varying agro-climatic conditions. Until about a decade and a half ago, the crop was commonly cultivated by transplanting seedlings into puddled soil (TPR). Rice crop was typically followed by another cereal crop, mostly wheat, in the Rabi season, known as the Rice-Wheat Cropping System (RWCS).

However, the profitability and sustainability of this system have been increasingly threatened because of its labour, water, and energy-intensive nature. The growing scarcity of these resources, exacerbated by the resource-intensive practices introduced during the green revolution, led to alarmingly high rates of groundwater depletion. Additionally, the physical deterioration of soils negatively impacted the performance of the wheat crop. Besides, adverse environmental consequences, particularly high greenhouse gas emissions, and climate vulnerabilities necessitated a shift from puddled transplanting to direct seeding of rice (DSR) in irrigated rice ecosystems.

The shift to DSR has been reported to offer multiple benefits, including significant savings in irrigation water, reduced labour and production costs, higher net economic returns, and lower methane emissions without any yield penalty or even higher yields. However, these results have not been uniformly achieved by farmers transitioning from TPR to DSR. The primary reason for this inconsistency might be due to the failure of the farming community to implement the complete package of DSR. As a result, several unforeseen challenges emerged, such as the development of herbicide-resistant weeds, the emergence of new weed species, the proliferation of weedy rice, increasing soil-borne pathogens like nematodes, and issues related to water and nutrient management.

These emerging challenges, coupled with farmers' limited experience with DSR, impacted rice productivity under this system. In this report, we analyse the status of DSR adoption in Haryana, exploring various barriers to its widespread adoption, and outline key policy measures and institutional support required to popularize and scale up this technology in the state of Haryana and beyond.

Historical background of DSR in Haryana

Rice is a major crop of Haryana. Area under this crop increased from 0.192 to 1.661 million ha during 1966-67 to 2022-23. The rice production increased from 0.223 to 4.523 million tonnes. Rice cultivation with the TPR system of production is highly inefficient in water use causing major drain on the surface and groundwater resources of the state. Gupta et al. (2002) estimated that rice in Haryana on average consumes 1560 mm of water, although it may vary from one kind of soil to another being higher in light than heavy textured soils. Since inadequate rainfall and unsure supplies of canal water failed to meet the water requirement of rice crop, there has been an unprecedented increase in groundwater extraction structures from 27957 tube wells in 1966-67 to 0.8 million tube wells (0.2 million diesel and 0.5 million electric pump sets) in 2022-23. Resulting depletion in the groundwater table is a major cause of concern in 14 of the 22 districts of Haryana with Ambala, Kurukshetra, Kaithal, Karnal and Panipat being the worst affected. Anticipated grim water scenario in agriculture together with the inefficient TPR production system warranted the exploration of alternative rice production methods, which are more efficient in water use.

Cereal Systems Initiative for South Asia (CSISA) Haryana hub, in association with various Krishi Vigyan Kendras (KVKs) under the aegis of CCS Haryana Agricultural University, Hisar attempted to introduce direct-seeded rice (DSR) technology in the state around 2009. Initially, an area of about 226 hectares was covered across 79 demonstrations, which increased to 1,614 hectares in 1,074 demonstrations by 2012 (Kamboj et al., 2012). This experience, along with efforts by other organizations, led to the development of a package of practices for the DSR system of rice cultivation. CCS Haryana Agricultural University, Hisar, first published this package in its compilation of Package of Practices for Kharif Crops in 2012. The total area under DSR in the state increased to 30,000 acres in 2016 and 33,000 acres in 2017 but declined to 16,500 acres in 2018. This decline may have been due to farmers' reluctance to continue with the practice, driven by challenges such as poor germination, uneven crop stands, high weed infestation, and yield penalties—all resulting from a lack of knowledge about aerobic rice cultivation. However, given the inherent benefits of the technology and increasing support extended by the state government, DSR has regained momentum, showing an upward trend since 2021.

The State government, in 2021, started an incentive scheme in select districts offering INR 5,000 per acre for farmers to adopt direct-seeded rice (DSR) instead of transplanted rice (TPR). In 2022, the incentive was introduced for the whole state at INR 4000[3] per acre for DSR adopting farmers. At the same time, labour shortages emerged as another major driver of the shift from TPR to DSR, as the labour requirement for transplanting is about 5–10 times higher than for direct seeding. Labour shortages, especially during peak demand in the rice transplanting season, combined with a sharp increase in wages, escalated production costs, and significantly reduced net income from rice cultivation. Another likely reason for the shift towards DSR is that harvesting in DSR occurs 7–14 days earlier than in TPR. This extends the short window typically encountered between the rice harvest and the sowing of the next crop. The additional time allows farmers to manage rice straw more effectively. In the long run, this could also help reduce the practice of burning paddy straw, which negatively impacts soil quality and pollutes the environment. Puddling, an essential component of TPR, also leads to the complete breakdown of soil aggregates, destruction of macropores, and the formation of a hard pan at shallow depths. This adversely affects the yields of succeeding non-rice crops, especially wheat. Moreover, increased energy consumption associated with groundwater pumping and the accelerated wear and tear of agricultural equipment, including tractors, strains farmers' finances. These factors further contributed to the growing interest in DSR, which avoids the need for puddling. Finally, increasing quality consciousness amongst the masses has driven interest in conservation tillage and the adoption of technologies that reduce greenhouse gas (GHG) emissions in agriculture. This driver of change has further strengthened the case for adopting DSR in the state. As a result of these factors, the area under DSR in 2024 has expanded to a bit less than 80,000 hectares in the state.

2. Scope of Assignment

Atal Bhujal Yojana (ABY) is the Indian government's flagship scheme, focusing on community-led groundwater management to implement effective demand- and supply-side interventions to halt groundwater depletion. A key focus of the scheme is to promote water demand-side interventions for the sustainable management of groundwater through community participation. Launched in 2019, the scheme is being implemented in water-stressed blocks across seven states in India.

Haryana is one of the states where ABY is active, and in recent years, it has witnessed a rapid uptake of DSR among paddy farmers. Given this trend, it is crucial to assess the current status of DSR adoption in the state and its impact on the farmers and the environment. From that perspective, this study was

[3] I USD = about INR 80 (2022)

undertaken as part of an MOU between the International Water Management Institute and National Project Management Unit-Atal Bhujal Yojana in June 2024 to conduct a comprehensive assessment of the scope and impact of Direct Seeded Rice (DSR) adoption in Haryana under the Atal Bhujal Yojana.

The study aims to evaluate the socio-economic and environmental impacts of DSR, identify barriers to its wider adoption, and recommend strategies for scaling up DSR practices in Haryana and other Atal Bhujal states. The objectives of the study were the following -

- **Assess the socio-economic impacts** of DSR adoption at the farm and plot level, focusing on
  - Cultivation costs and yield
  - Economic viability and profitability
  - Labour dynamics, including workforce requirements and women's workload
- **Evaluate the environmental impacts** of DSR, including:
  - Water use
  - Changes in chemical use (fertilizer/pesticides)
- **Identify key barriers** to DSR adoption, such as
  - Varietal selection and seed availability
  - Access to appropriate machinery and equipment
  - Crop management challenges
  - Resilience to environmental stresses
- **Analyse market linkages and policy support** influencing DSR adoption and scalability, including the role of government incentives and subsidy programs.
- **Explore technological innovations** such as the use of **Unmanned Aerial Vehicles (UAVs)** for effective DSR monitoring and management.

The study employed a multi-pronged approach to assess various aspects, including qualitative interviews with farmers and other stakeholders, a large-scale quantitative survey of DSR and TPR farmers, analysis of flow meter data on farmers' water use, and remote sensing data. The next section provides a detailed description of these data sources used in the study.

3. Sampling and Methodology

3.1. Qualitative survey

To capture a comprehensive range of perspectives and identify key issues, a qualitative study was conducted with ABY district implementation partners between July and August 2024. Focus Group Discussions (FGDs) were organized across various villages, with an average group size of 10-15 farmers. Participants represented different adopter categories, including: i) DSR adopters who have reduced their cultivated area, ii) former adopters who have discontinued the practice, or reduced the area under DSR, iii) DSR adopters who have expanded or maintained their cultivated area, iv) late adopters, and v) TPR practitioners.

These FGDs were conducted in villages across Sirsa (2 villages), Fatehabad (3 villages), and Karnal (4 villages) districts. Discussions were followed by visits to the field where DSR was practiced. The site selection – location and farmers' details were collected from the data received from ABY- State Programme Management Unit with block name, village name, farmers' name, and their area under

DSR. Villages with more adopters were preferred however number of villages visited was more dependent on the concentration of adopter types. The discussion started with open-ended questions and continued with activities like identifying and categorizing (severity level) diseases, insect pests, and weeds observed on their farms using pictorial aids. 10 Flashcards depicting various challenges were prepared and presented to the farmers, who were then asked to rank the challenges based on their severity, drawing from their experiences with DSR practice. This exercise was carried out separately for each adopter group.

Furthermore, as part of the qualitative survey, agrochemical shops were visited to assess the availability of chemicals and understand farmers' demand. Visits were also made to district agricultural departments, in collaboration with District Implementation Partners (DIPs), to gain further insights.

3.2. Quantitative survey

A quantitative survey of paddy farmers in Haryana, including both DSR and TPR farmers, was conducted between September and October 2024. Out of the 14 districts, 36 blocks, and 1,647 Gram Panchayats (GPs) under ABY in the state, data from six districts covering 12 ABY blocks in Agro-Ecological Zones (AEZ) 1 (four districts) and Zone 2 (two districts) was shared by the ABY State Project Management Unit. Based on the shared list of beneficiaries, in Kharif 2023, the total DSR area across these six districts was 23,612 hectares, spread over 337 GPs, with approximately 7,000 farmers involved. The primary survey was conducted in four districts selected from these six ABY districts.

For the selection of the four districts from the six shared by SPMU, the two districts from Western Haryana (Agro-Ecological Zone 2), Sirsa and Fatehabad, were included. The selected districts are highlighted in the map shown in Figure 1. The remaining two districts were chosen in Agro-Ecological Zone 1 through a random selection process proportional to their DSR area in Kharif 2023. This approach ensured a geographically diverse spread of farmers for the quantitative survey. The selected districts from Agro-ecological Zone 1 were Karnal from the north and Yamunanagar from the eastern part of Haryana.

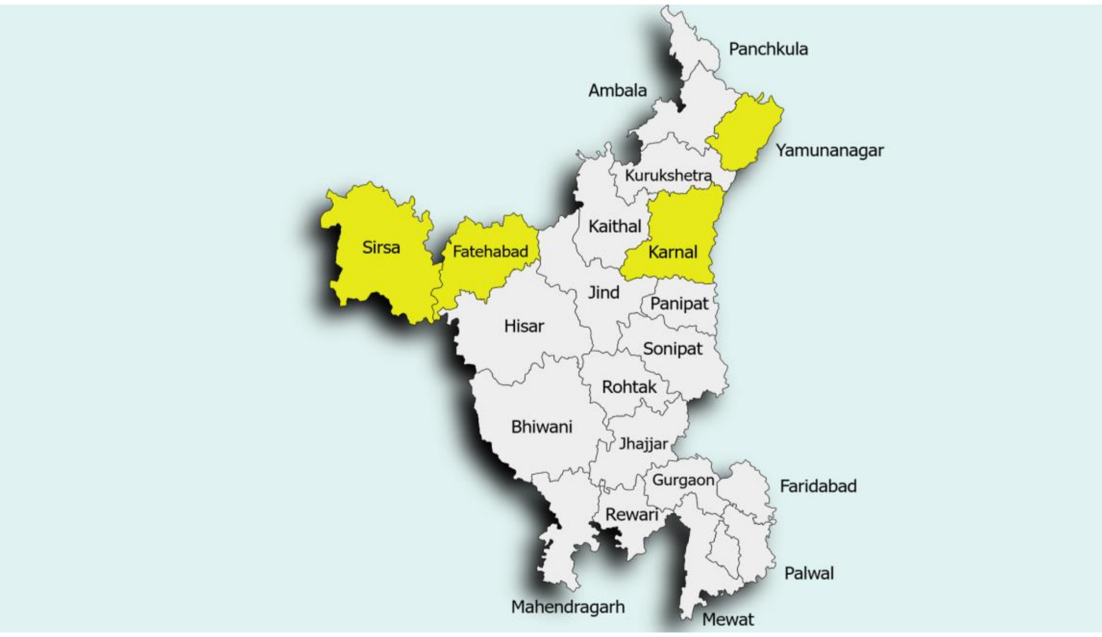

Figure 1: Map of Haryana showing districts selected for the study

Based on power calculations, a sample size of 800 farmers from 50 GPs was determined, with an equal proportion of DSR and TPR farmers. To ensure that the selected GPs had enough DSR farmers, GPs with fewer than nine DSR farmers in 2023-24 were excluded, except for three GPs that had farmers with Water Flow Meter (WFM) data, despite having fewer than nine DSR farmers.

Since most of the DSR uptake occurred in Sirsa, a proportional sampling approach for GPs across districts was not followed to ensure a more diverse district-wise representation. Instead, all GPs from Fatehabad, Karnal, and Yamunanagar were selected, making up approximately 30 GPs. The remaining 20 GPs were chosen from Sirsa, with 18 randomly selected and 2 additional GPs included based on the availability of WFM data. This approach helped achieve a balanced representation of districts within the sample.

Next, in each GP, 8 DSR farmers were randomly selected from the beneficiary list and 8 TPR farmers were chosen through a random walk. This methodology ensures a comprehensive comparison between DSR and TPR farmers across the selected districts. In total, we conducted interviews with 809 farmers, including 429 DSR and 380 TPR farmers (Table 1).

Table 1: Sample distribution across districts for the quantitative survey

Agro-Climatic Zone	**District**	**Normal monsoon (Jun-Sep) rainfall** *(in mm)*	**Proportion of Kharif paddy in NSA (%) – 2020-21**	**Proportion of irrigated area (%) – 2020-21**	**Proportion of canal irrigated area (%) – 2020-21**	**Total DSR area** *(hectare)*	**Sample farmer survey**			
							GP no. (Block no.)	**TPR**	**DSR**	**Total**
Zone2 (West Haryana)	Sirsa	210	25.5	99.0	68.9	20633	20 (2)	79	246	325
	Fatehabad	261	57.7	99.6	29.2	741	12 (1)	106	89	195
Zone 1 (NE Haryana)	Karnal	520	88.6	100	28.2	450	6 (1)	72	24	96
	Yamunanagar	898	77.4	100	1.6	716	12 (4)	123	70	193
Haryana	average/Total		42.3	99.1	34.6		50	380	429	809

Since many villages in Sirsa have nearly fully transitioned to DSR, it was decided to oversample DSR farmers in Sirsa (Figure 2). In other 3 districts, particularly in Karnal, TPR farmers were oversampled due to challenge of finding 8 DSR farmers in some areas.

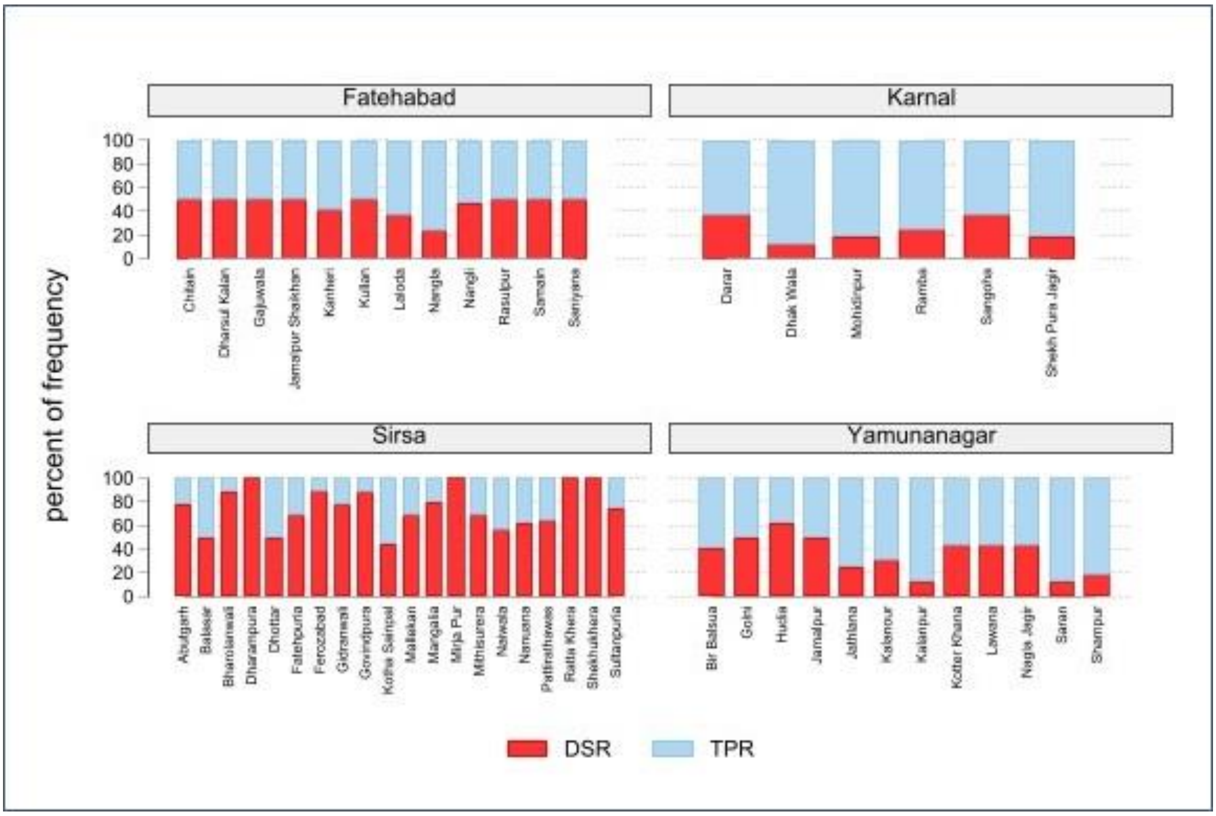

Figure 2: Proportion of DSR and TPR farmers in the sample across different villages

The farmer survey was conducted with the household head responsible for farming. The questionnaire collected detailed information on the household's cropping choices across different plots and their paddy cultivation practices in 2024, including yield and input use such as labour, fertilizer, seed, and pesticides. Data was specifically gathered for the largest plot—DSR plots for DSR farmers and TPR plots for TPR farmers—in 2024. Additionally, information on cultivation costs and irrigation usage patterns, including the number of irrigation events, hours of irrigation per event. and water depth per irrigation, was collected for both 2024 and 2023. The questionnaire also captured demographic details and farmers' perceptions of DSR.

3.3. Water Flow meter data analysis

Groundwater usage was also assessed using data from water flow meters (WFM) obtained from NPMU-ABY for four districts namely Kurukshetra, Yamunanagar, Sirsa, and Kaithal. Data were collected from 346 WFM units in 2023 and 727 WFM units in 2024. Out of the total WFM units recorded each year, only 42 in 2023 and 44 in 2024 were associated with DSR fields, while the rest corresponded to TPR fields. A thorough data quality check was performed, identifying and addressing outliers before analysis.

Groundwater consumption was calculated for each field type over the period from June 15 to October 15. The total water usage recorded by each WFM unit was divided by the corresponding irrigated area to determine water consumption per hectare. To compare water, use efficiency between DSR and TPR fields, the WFM data were averaged at the district level.

The WFM data ranged from 0 to over 160,000 m³/ha, necessitating the identification of outliers in both DSR and TPR distributions. As a first step, Inter-quartile range (IQR) method was used to identify the outliers (Figure 3). The outliers were excluded by setting a lower threshold of ≥100 m^3/ha and an upper threshold of ≤25000 m^3/ha, ensuring the reliability of the analysis.

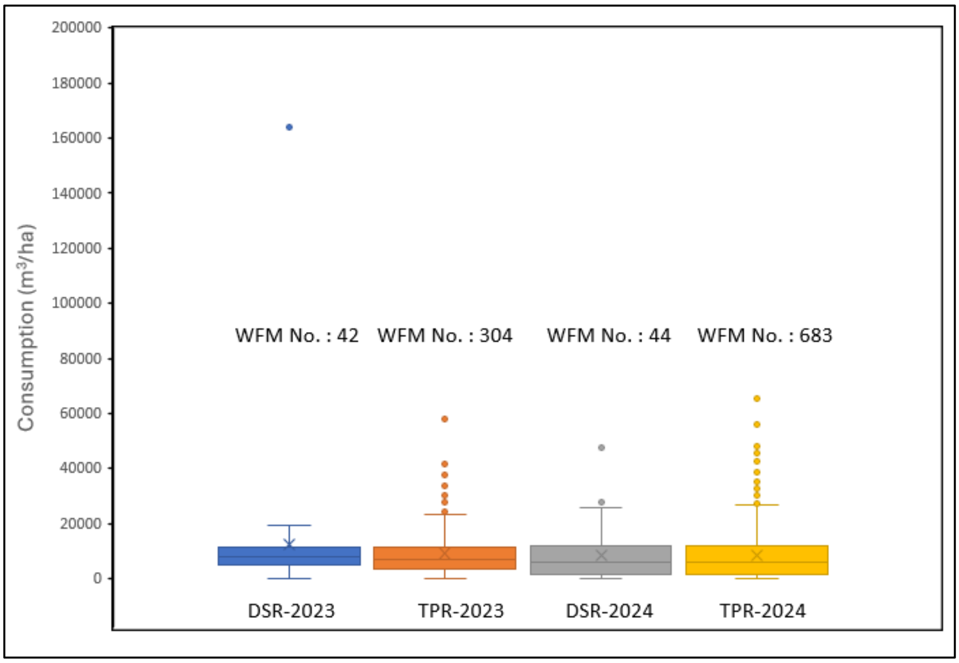

Figure 3: Box-Whisker plot of DSR and TPR dataset for 2023 and 2024

As a second step for identifying outliers, we also conducted data distribution analysis, to understand how the data points are spread across different value range and identify any patterns or anomalies. The histogram shows that most of the data fell within the applied limit, confirming that most values were within an expected range (Figure 4).

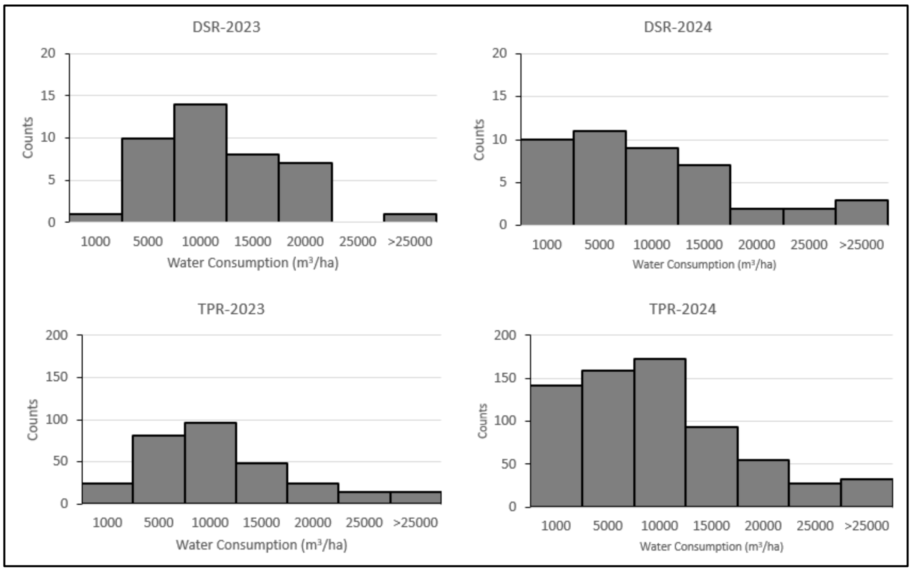

Figure 4: Histogram of water flow-meter observations for DSR and TPR plots

Lastly, we excluded well data that had been used in both DSR and TPR fields to prevent duplication and ensure a more precise classification of the dataset. This step was essential to eliminate potential bias or misrepresentation, maintaining the accuracy of the analysis and the reliability of distribution and outlier identification. After applying all the criteria, the final number of WFM units used for the study is presented in Table 2.

Table 2: Final sample of water flow-meter observations from borewells considered for the study

District	WFM No. (DSR-2023)	WFM No. (DSR-2024)	WFM No. (TPR-2023)	WFM No. (TPR-2024)
Kaithal	3	2	15	10
Kurukshetra	2	2	203	179
Sirsa	18	13	7	8
Yamunanagar	14	2	35	178

3.4. Remote sensing analysis

Remote sensing data were utilised for a comprehensive analysis of the differences between DSR and TPR areas (Figure 5). The approach included utilising Earth observation datasets, such as Landsat and Sentinel, from satellites and UAVs to ensure a comprehensive analysis. Primary objectives of the remote sensing approach were to compare evapotranspiration for DSR and TPR plots and to map the distribution of DSR and TPR areas. Actual evapotranspiration, often referred to as the actual amount of water lost from the surface through evaporation and plant transpiration, is a crucial parameter in understanding the water balance of an area. To make the analysis easier, the team used the USGS Landsat provisional Actual Evapotranspiration science product. Senay et al. (2023) outlined surface energy balance principles to calculate the latent heat flux and derive these products. The Landsat ETa science product provides a per-pixel estimate of daily water transfer from the Earth's surface to the atmosphere in units of water depth in millimetres (mm). Images were collected for the Kharif season (May-November 2024) in the Haryana state, encompassing the districts under study. Standard corrections, such as the removal of water bodies and elimination of cloud-obscured pixels, were meticulously implemented during the image processing stage. Pixel quality was enhanced by using the product's Pixel Quality Assessment layer to ensure accurate information for the study region, minimising uncertainties from satellite data. Based on the field visits and surveys conducted by the IWMI team and surveyors, the locations of the DSR and TPR farm plots were geotagged and collated. Using the geotagged location with the Landsat ETa product was used for the time series analysis.

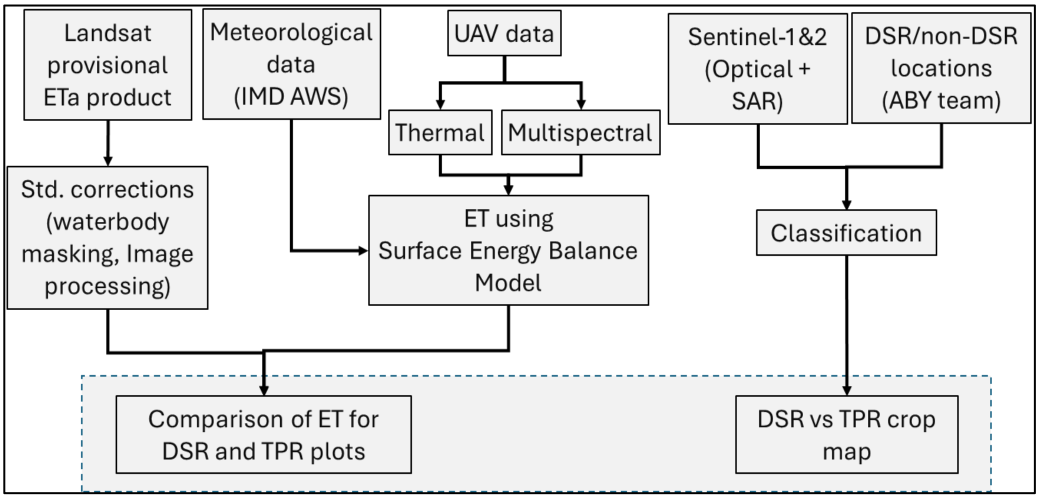

Figure 5: Overall approach for remote sensing analysis

As part of the project, the team also wanted to explore the feasibility of using Unmanned Aerial Vehicles (UAVs) for these studies (Table 3). UAVs have certain advantages over satellite datasets since they can be deployed on demand for a small area assessment while providing high-resolution imagery. UAVs can operate below clouds and in various weather conditions, ensuring continuous monitoring even when satellite imagery is obstructed. Their customisable flight plans allow targeted data collection, focusing on specific areas of interest, making them a more efficient and accurate tool for precision agriculture. In this study, a UAV was used to test the methodology of measuring evapotranspiration, for which a quadcopter was used having specifications mentioned in the table. On November 11, 2024, a survey was conducted in the Sirsa District, specifically in Dharampura and Damdama villages (Figure 6). Data collected from the UAV flights were used to create a detailed map (orthomosaic) incorporating multispectral, thermal, and elevation data using Open Drone Map and Pix4D. These datasets were then analysed to calculate instantaneous evapotranspiration using the Surface Energy Balance algorithm. Inputs for the Surface Energy Balance model included air temperature from the Automatic Weather Station of the Indian Meteorological Department[4]. Resultant outputs were high-resolution products NDVI, SAVI, LAI, LST, and ET_{inst}.

Table 3: Technical specifications of the Unmanned Aerial Vehicle (UAV) used for the study

Specification	Details
UAV Type	Quadcopter (DJI Matrice 350 Custom)
Image Bands	Multispectral – Blue, Green, Red, NIR (Near-Infrared)
Thermal Imaging	Celsius Scale
Image Resolution	~5 cm
Flight Height	100 m
Sensor Model	MicaSense Altum-PT
Spectral Bands	Blue (475±32 nm), Green (560±27 nm), Red (668±14 nm), Red Edge (717±12 nm), NIR (842±26 nm) and Thermal (8-14 µm)

[4] http://aws.imd.gov.in:8091/state.php?id=HARYANA

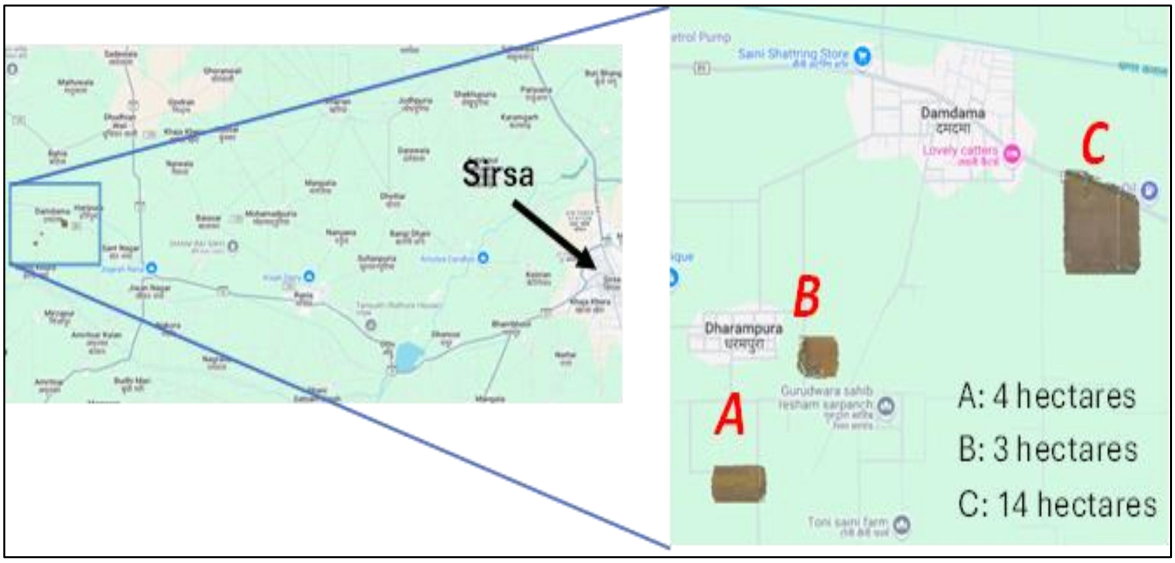

Figure 6: Location map of selected agricultural fields in Sirsa district for the UAV survey. The left panel shows broader geographic context, while the right panel zooms into 3 identified fields (A, B and C)

The study also piloted the identification of DSR farms from TPR and other crops to assess the feasibility and accuracy of the classification methodology. We applied the Random Forest algorithm, a machine learning technique, leveraging the 10-20 m spatial resolution of the European Space Agency Sentinel-1 and 2 datasets. This study used a combination of Sentinel-1 and Sentinel-2, with the former providing microwave SAR data and the latter providing optical data. Microwave datasets have an advantage over optical data since their data collection is not hindered by cloud presence and hence provides more consistent data. This is crucial for the Kharif season as it experiences high cloud cover, with approximately 80% of the region obscured by clouds. A time series dataset of 2022-2024 was used for this study. The Atal Bhujal Haryana SPMU and NPMU team provided the locations of the DSR and TPR farms. We used these points in the classification methodology after randomly splitting the training and testing data in an 80:20 ratio. The team performed a time series classification, which subsequently led to the seasonal classification of DSR and TPR farms. This analysis was carried out using Google Earth Engine.

4. Results and Discussions

4.1. Impact on groundwater irrigation application

To understand the impact of DSR adoption on irrigation water application, we used both farmer survey data based on recall on number of irrigation events, hours of irrigation per event, and depth of water application in plots along with the water flow meter data readings as received from SPMU. The results from both approaches are presented below.

Irrigation water application comparison across DSR and TPR using farmer survey recall data

Across all 4 districts, the reduction in irrigation hours for DSR plots compared to TPR plots was consistently in the range of 15-30%. On an average, DSR plots required approximately 20% fewer hours of irrigation both in 2023 and 2024, showing a significant reduction in irrigation hours compared to TPR plots. The difference narrowed slightly, with DSR plots using 16-17% fewer irrigation hours when canal-irrigated plots were excluded from the analysis (Figure 7).

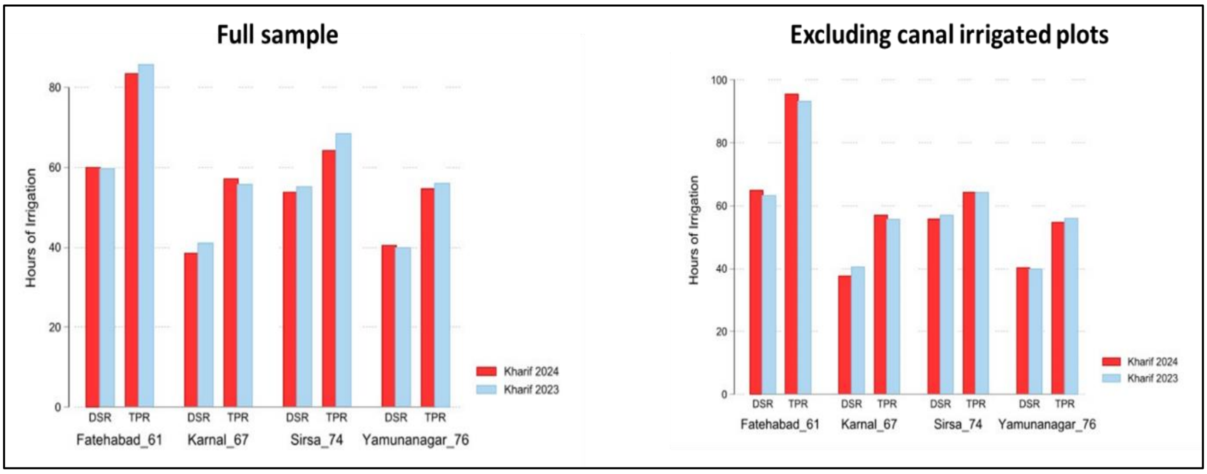

Figure 7: Total hours of irrigation across different districts for DSR and TPR plots

Significant differences in irrigation hours besides nursery preparation were observed during the early growth stages namely soil puddling and preparation stage, and the tillering and nursery stages (Table 4). Overall, on an average, DSR plots received one less irrigation compared to TPR plots, with TPR plots receiving around 19 irrigations in total. The higher difference in total hours of irrigation as compared to total number of irrigations between TPR & DSR is justified since the hours per irrigation were also higher in TPR plots compared to DSR plots.

Table 4: Total hours of irrigation across different paddy growth stages for DSR and TPR farmers

	Kharif 2023						**Kharif 2024**					
	Nursery	**Soil puddling/Soil preparation**	**Sowing/Transplanting till tillering**	**Tillering to panicle initiation**	**Panicle initiation to flowering**	**Ripening**	**Nursery**	**Soil puddling/Soil preparation**	**Sowing/Transplanting till tillering**	**Tillering to panicle initiation**	**Panicle initiation to flowering**	**Ripening**
TPR	4.3	8.6	22.3	16.0	11.1	4.6	4.4	8.7	21.9	15.6	10.3	4.2
DSR	.	4.2	17.1	15.7	11.0	4.8	.	4.0	16.8	15.6	10.7	4.9
Significance level	-	***	***	NS	**	NS	-	***	***	NS	*	***
Average	4.3	6.3	19.5	15.8	11.1	4.7	4.4	6.3	19.3	15.6	10.5	4.5

NS means non-significant. *** is for 1%, ** is for 5%, and * is for 10% level of significance respectively

To estimate the savings in irrigation volume, the data were analysed using three different approaches, with each approach having 3 different versions of dealing with extreme values. In each approach, **version 1** used full dataset as received during the survey. V**ersion2** had truncated data wherein all data reporting Q<1000 m^3/ha or Q>25000 m^3/ha were removed. V**ersion 3** had truncated data wherein all extreme values outside $\text{median} \pm 3 * iqr$[5] were removed. We present the result from all 3 approaches below.

[4] IQR is the Inter-quartile range

Approach 1:

In the first approach total water applied was calculated by multiplying the depth of water applied per irrigation event and the total number of irrigations (both data are given in Appendix A, B, C).

A significant reduction in water application for DSR plots, with a consistent decrease of 27-29% across different versions is observed (Table 5).

Table 5: Estimated volume of water used for irrigation amongst DSR and TPR farmers as per reported depth of water per irrigation and number of irrigations

	Volume (Q) of irrigation water application (m^3/ha)					
	Version 1 with full sample		**Version 2 removing values if Q<1000 | Q>25000**		**Version 3 removing extreme values if outside median±3*IQR**	
	Kharif 2023	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**
TPR	13444	13210	13217	12914	13401	13111
DSR	9502	9586	9466	9451	9502	9586
% difference and significance level	29%***	27%***	28%***	27%***	29%***	27%***
Total	11354	11347	11215	11123	11331	11294

*** is for 1% level of significance

Approach 2:

In the second approach, the depth of water application was estimated using average values of driving unit HP, total dynamic heads, and pumping hours reported in Table 4. Pumping plant efficiency, comprising motor efficiency (90%), drive efficiency (90%), and pump efficiency (50%) required for these calculations, was lumped together and taken as ~40%.

Here, too, a significant reduction in water use for DSR plots was observed, although the percentage difference varied between 13-14% (Table 6).

Table 6: Estimated volume of water used for irrigation amongst DSR and TPR farmers as per reported pumping hours and pumping efficiency

	Volume (Q) of irrigation water application (m^3/hectare)					
	Version 1 with full sample		**Version 2 removing values if Q<1000 | Q>25000**		**Version 3 removing extreme values if outside median±3*iqr**	
	Kharif 2023	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**
TPR	13123	12359	10853	10742	12161	11556
DSR	10260	10057	9375	9314	9611	9387
% difference and significance level	22%***	19%***	14%***	13%***	21%***	19%***
Total	11605	11175	10045	9989	10801	10432

*** is for 1% level of significance

Approach 3:

In the third approach, the same analysis was carried out, excluding the canal-irrigated plots from the survey data. The results remained consistent, showing a significant reduction in water application for DSR, with the percentage difference once again ranging from 13-20% (Table 7), lowest being in version 2, followed by version 3 and version 1.

Table 7: Estimated volume of water used for irrigation amongst DSR and TPR farmers as per reported depth of water per irrigation and number of irrigations, excluding canal irrigated plots

	Volume (Q) of irrigation water application (m³/hectare)					
	Version 1 with full sample		**Version 2 removing values if Q<1000 | Q>25000**		**Version 3 removing extreme values if outside median±3*iqr**	
	Kharif 2023	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**	**Kharif 2023**	**Kharif 2024**
TPR	10741	10645	9826	9666	10334	10001
DSR	8816	8541	8477	8431	8659	8448
% difference and significance level	18***	20***	14***	13***	16***	16***
Average	9871	9756	9204	9131	9572	9335

*** is for 1% level of significance

Thus, based on farmer-level recall data on irrigation water application, we find using different approaches that DSR consistently leads to lower irrigation hours and reduced water application compared to TPR. This suggests that DSR is a water-efficient alternative in farmers' fields, contributing to more sustainable groundwater use for irrigation.

Irrigation water application comparison across DSR and TPR using WFM data

Based on the WFM data, we find that DSR exhibited lower water application than TPR across all districts except Sirsa in 2023 (Figure 8). The most significant difference is observed in Kurukshetra. A similar trend is observed in 2024 (Figure 8).

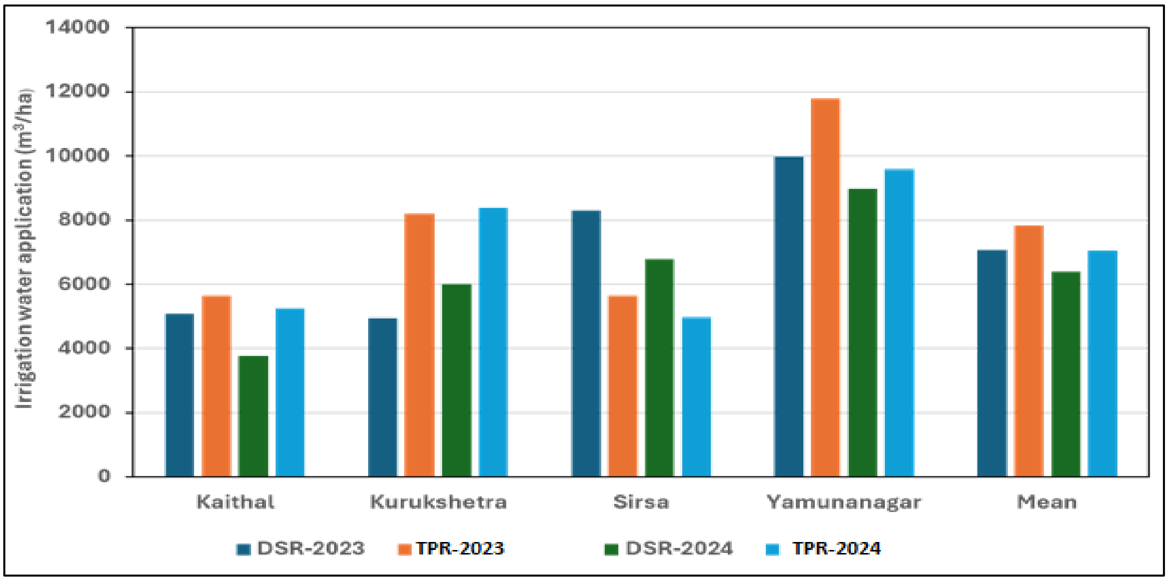

Figure 8: Average irrigation water application (m³/ha) across four districts and combined average amongst DSR and TPR plots

The higher water consumption for DSR in Sirsa compared to TPR may be attributed to the dominance (~80%) of the canal irrigation (Fig. 9a) because Sirsa is located in the arid zone where annual rainfall is less than 300 mm (Fig. 9 b) in the district. It is mainly attributed to lower water consumption recorded for transplanted rice because of surface water usage during the early growth stages. On average across all districts, water consumption for 2023 and 2024 indicates that DSR used 10% less water than TPR plots. This value increases to 20% upon the exclusion of district Sirsa, which is dominated by canal irrigation. The average water consumption for DSR and TPR in the 3 districts, excluding Sirsa, is 0.65 m and 0.81 m, respectively. Although the saving of water in DSR is quite similar to what has been obtained using other approaches, the key limitation of the WFM study is the relatively small sample size from DSR fields. It may affect the generalizability and statistical reliability of the findings.

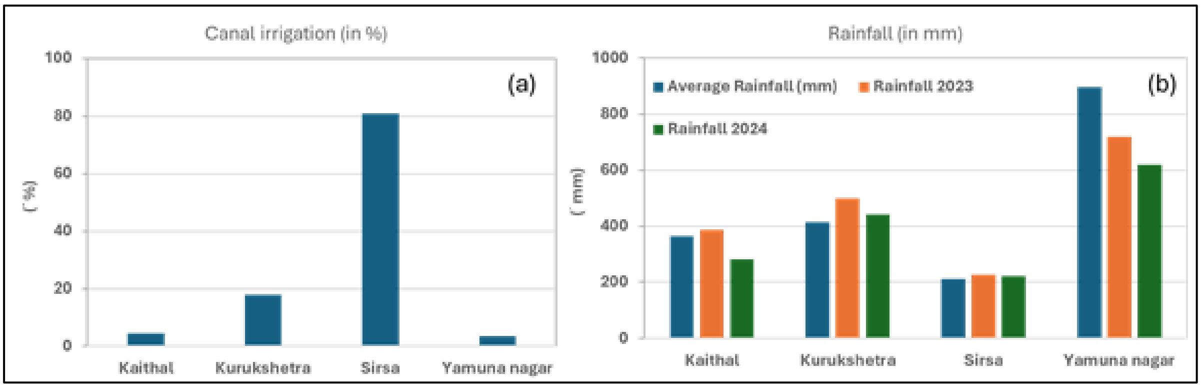

Figure 9: a) Proportion of area irrigated by canals across four districts (Data source: CGWB district reports), b) Annual rainfall and its deviation from mean for 2023 and 2024 (Data source: 2023-INDIA-WRIS, 2024 and Mean: IMD)

4.2. Impact on farmers' cost, return, and irrigation practices

To understand the impact of DSR on the cost of cultivation, the activity-wise cost of cultivation was compared for DSR and TPR plots. Significantly higher costs of fertilizers (11%), pest/disease control (27%), weed management (48%), and harvesting (14%) have been observed in DSR compared to TPR. Pests like leaf folder, stem borer, etc, increased significantly, thereby increasing the cost of pest/disease control. This could be due to their crop establishment practices and plant density. However, the cost for other activities, i.e., land preparation, sowing/transplanting (including nursery), and irrigation, had a higher cost in TPR compared to DSR. Overall, there is no significant difference in the total cost of cultivation (Table 8). Even comparing the cost of cultivation for the same variety, numerically, DSR tends to have slightly lower costs than TPR, although the difference is not statistically significant. Reduced cost of cultivation, often claimed in past studies, is not emerging from this study. It looks that recent changes in technology, making laser land levelling an essential part, have flattened the cost differential but may have added to water saving and yield.

Table 8: Activity-wise cost of cultivation (INR/acre) for DSR and TPR farmers in Kharif 2023 and 2024

Item of cost	Kharif 2023				Kharif 2024			
	TPR	DSR	% diff	Significance level	TPR	DSR	% diff	Significance level
Land preparation	3804	3227	-15%	***	3872	3309	-15%	***

Sowing/Transplanting (including nursery)	5157	2726	-47%	***	5309	2773	-48%	***
Irrigation	586	541	-8%	**	571	584	2%	**
Fertilizers	3641	4054	11%	***	3560	4149	17%	***
Pest/disease control	3568	4537	27%	***	3713	4842	30%	***
Weed management	2380	3533	48%	***	2383	3667	54%	***
Harvesting	2237	2546	14%	***	2322	2643	14%	***
Post-harvest	1125	1084	-4%	NS	1152	1121	-3%	NS
Total cost	22497	22247	-1%	NS	22882	23088	1%	NS

NS means non-significant. *** is for 1%, ** is for 5% level of significance respectively

Just to illustrate the change in activity-wise cost, it emerged that there is statistically significantly higher application of MOP, Zinc and Iron in DSR than TPR (Table 9). The higher fertilizer requirement can be attributed to high seed rate commonly used in DSR compared to traditional transplanting methods, besides the Zn and Fe availability in DSR especially in light textured soils.

Table 9: Comparison of the use of different fertilizers amongst DSR and TPR farmers

	Urea (kg/acre)	DAP (kg/acre)	NPK (kg/acre)	MOP (kg/acre)	Zinc (kg/acre)	Iron (kg/acre)	Green manure (Kg/acre)	Farm yard manure (tonnes/acre)	Vermi compost (kg/acre)
TPR	133	40	4	20	5	2	100	5.2	0
DSR	136	41	4	24	6	5	200	4.6	1
Significance level	NS	NS	NS	***	**	***	NS	NS	***
Average	134	41	4	22	5	3	100	4.9	1

NS means non-significant. *** is for 1%, and ** is for 5% level of significance respectively

We also find minimal difference between the yield under DSR and TPR methods across all the varieties, but this difference is not significant. Even across same paddy varieties, there is no significant difference in yield between DSR and TPR except in Pusa Basmati 1692, where DSR exhibits a slightly lower yield, likely due to its higher susceptibility to weather fluctuations. The district wise yield comparisons between DSR and TPR plots revealed varying results as shown in Figure 10. In Fatehabad, Karnal, and Yamunanagar, TPR slightly outperformed DSR, with yields ranging from 2.4 to 2.6 tonnes/acre. Conversely, Sirsa saw higher yields with DSR (2.3 tonnes/acre) compared to TPR (2.1 tonnes/acre).

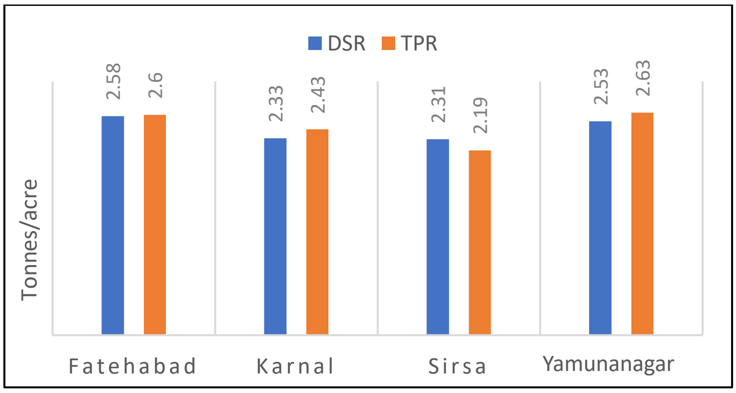

Figure 10: Comparison of yield under DSR and TPR across different districts

Despite similar costs and yields, revenue is generally higher for DSR (except for Pusa Basmati 1692) due to higher market price linked to better grain quality factors, lower breakage rates during milling, and reduced chalkiness[6]. In terms of overall returns, PB-1401, Pusa-1509, and PR-14 show higher profitability under DSR, whereas PR-126 and Pusa Basmati 1692 yield lower returns compared to TPR (Table 10). On average, net returns are INR 52409/acre in DSR compared to INR 42983/acre in TPR[7]. A notable 22% increase in net returns has been reported by DSR adopters over TPR farmers. The enhanced profitability makes DSR an attractive option for farmers, particularly in regions where water efficiency and labour shortages are key concerns.

Table 10: Comparison of cost and returns for different paddy varieties amongst DSR and TPR farmers

Seed variety	Yield (tonnes/acre)			Total revenue (INR/acre)			Cost of cultivation (INR/acre)			Net returns (INR/acre)		
	DSR	TPR	Sig	DSR	TPR	Sig	DSR	TPR	Sig	DSR	TPR	Sig
Pusa basmati 1401 (N=174/36)	2.41	2.35	NS	91182	82671	**	23383	24823	NS	67800	57848	***
Pusa-1509 (N=49/79)	2.23	2.26	NS	69494	68321	NS	20530	21185	NS	48964	47136	NS
PR-14 (N=19/35)	2.64	2.63	NS	61181	59129	NS	21540	22157	NS	39641	36971	NS
PR-126 (N=28/22)	2.54	2.71	NS	55294	59871	NS	20727	19976	NS	39641	39895	NS
Pusa basmati 1692 (N=28/20)	2.08	2.33	*	61609	73600	**	22813	24294	NS	39641	49307	*

NS means non-significant. Sig means significance level. *** is for 1%, ** is for 5%, and * is for 10% level of significance respectively

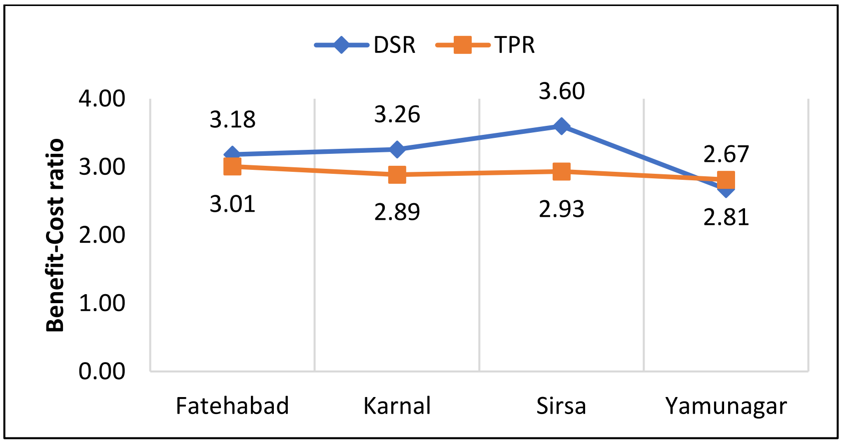

Figure 11: Comparison of benefit-cost ratio between DSR and TPR across different districts

DSR resulted in a higher Benefit-Cost Ratio in Fatehabad, Karnal, and Sirsa, suggesting its greater profitability. Only in Yamunanagar TPR exhibited marginally better returns (Figure 11).

Besides analysing costs and returns, DSR impact on labour use, including total labour involvement, family labour and hired labour was also examined. DSR requires 18% less total labour compared to TPR (Table 11). Reduced involvement of family labour at 7% looks small but is statistically significant.

[6] Chalkiness refers to a physical characteristic of milled rice affecting appearance quality - if part of the milled rice kernel is opaque rather than translucent it is characterised as chalky. Consumers prefer non-chalky rice. (Fan et al.,2022)

[7] 1 USD = about INR 83 (2024)

Female participation in agriculture in Haryana is limited primarily in sowing and weeding (15-20%). We find an overall decrease in involvement of female labour in DSR, but increased involvement in weeding offsets to some extent the reduced requirement in the sowing operation (Table 11).

Table 11: Comparison of total and gender-disaggregated labour use in DSR and TPR

Average labour-use (person days/acre)	DSR	TPR	Significance level
Total labour	24.6	30.0	***
Family labour	13.9	15.0	***
Hired labour	10.6	15.0	***
Female labour (sowing)	0.0	3.8	***
Female labour (weeding)	3.5	2.1	***
Female labour (total)	3.9	6.3	***

*** is for 1%level of significance

4.3. AET comparison and DSR/TPR classification in Haryana

Comparative analysis of AET trend during Kharif season

Figure 12 presents a comparative analysis of the Average Actual Evapotranspiration (AET) values for DSR and TPR systems during the Kharif season of 2024. The AET for DSR and TPR show an identical seasonal trend starting at low levels in May and experiencing a significant increase in June. Peaks are observed between July and August, reaching approximately 4.5-5.0 mm/day, followed by a gradual decline post-August as the harvest period approaches. TPR system exhibits slightly higher AET than DSR from July to September which indicates higher water consumption in transplanted rice during its peak growth stages compared to direct-seeded rice. This trend is interpreted in the percentage difference between TPR and DSR. AET values which starts high in May (~4%), decrease sharply, and stabilizes around 0% from June to August. It increases again in September before showing a strong negative trend towards November (-7% to -15%), indicating that DSR has lower AET than TPR during late-season stages.

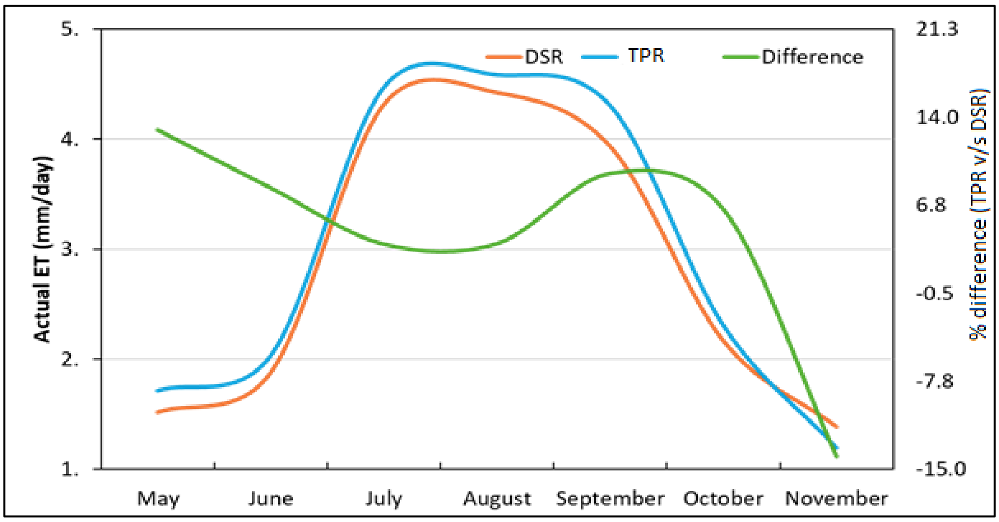

Figure 12: Seasonal trend and percentage difference in average actual evapotranspiration between DSR and TPR during Kharif - 2024.

This slight lower AET in case of DSR is likely due to the different establishment process, i.e., direct seeding vs. transplanting with puddling. Mid-season (July-September) higher AET in TPR in comparison to DSR can be attributed to the well-established denser canopies in the TPR. The difference between systems is most pronounced in May (around 14%) and remains positive through the season, meaning TPR consistently has higher evapotranspiration rates than DSR. During the season, an average percentage difference of 5-7% is observed in AET values of the TPR to DSR system. This overall positive average difference suggests that TPR systems utilise more water than DSR systems for most of the growing season, though the relationship reverses near the end of the season. The shift in this difference indicates that DSR's water-saving effects are most evident in the early establishment phase and then again in the late vegetative/reproductive phase.

This pattern has significant implications for water management and sustainability in rice production. The lower AET in DSR during the late season indicates enhanced water-use efficiency, placing it as an attractive option for regions witnessing water scarcity. Higher AET in TPR might indicate increased transpiration associated with denser canopies, while DSR's lowered water usage in later stages could lead to overall water conservation.

Year wise AET trends for selected districts

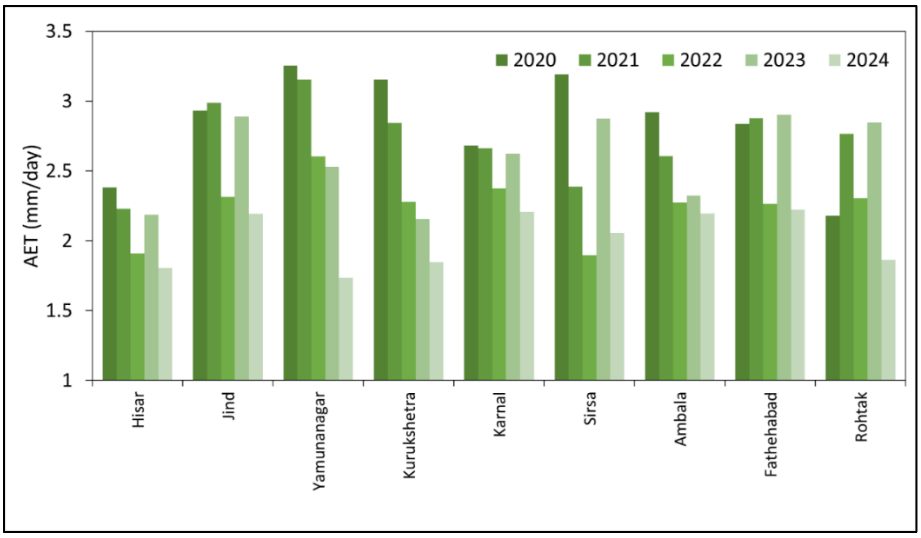

Figure 13: District wise mean Actual Evapotranspiration (AET) for year 2020-2024 showing inter-annual variations

Figure 13 shows the annual trends of AET during the Kharif season across various districts in Haryana, India, from 2020 to 2023. This figure reveals a general decline over the years in AET, a key indicator for assessing crop water demand, as it includes both crop transpiration and soil evaporation. This decline indicates a shift towards more water-efficient agricultural practices, for example implementation of DSR, improvements in irrigation management, and/or fluctuations in monsoon rainfall. District level comparisons revealed that Yamunanagar and Kurukshetra experienced consistent declines in AET, whereas Sirsa exhibited a significant decrease following particularly higher levels in 2020. Jind and Fatehabad showed stable AET values with slight decreases, while Rohtak demonstrated a less significant decline, with 2023 values comparable to those prior to 2021.

This suggests that Rohtak may exhibit reduced adoption of DSR or a persistent reliance on conventional transplanting techniques. The observed decline in AET corresponds with initiatives aimed at sustainable water conservation in rice cultivation regions, suggesting that districts experiencing more significant reductions in AET may be at the forefront of adopting new water-efficient practices. Overall, the decline in AET across most districts suggests progress in reducing water use in agriculture. However, variations between districts highlight the need for targeted interventions to further optimise water use, especially in regions where traditional practices persist.

Piloting UAV survey for DSR study

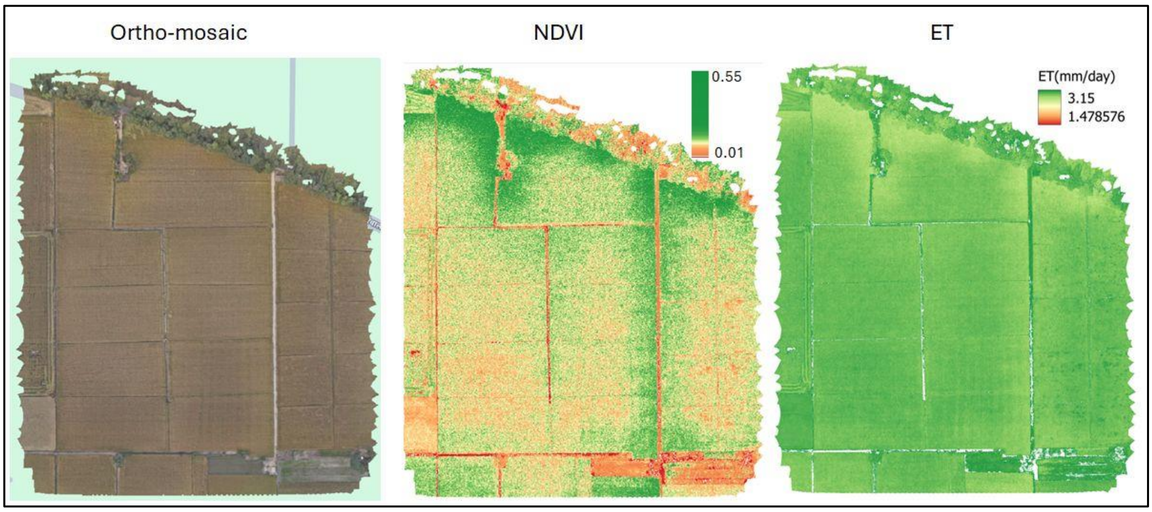

Figure 14: UAV-based remote sensing outputs for the surveyed agricultural field (Site C). Here left is Ortho-mosaic image, middle is Normalized Difference Vegetation Index (NDVI), right is Evapotranspiration (ET)

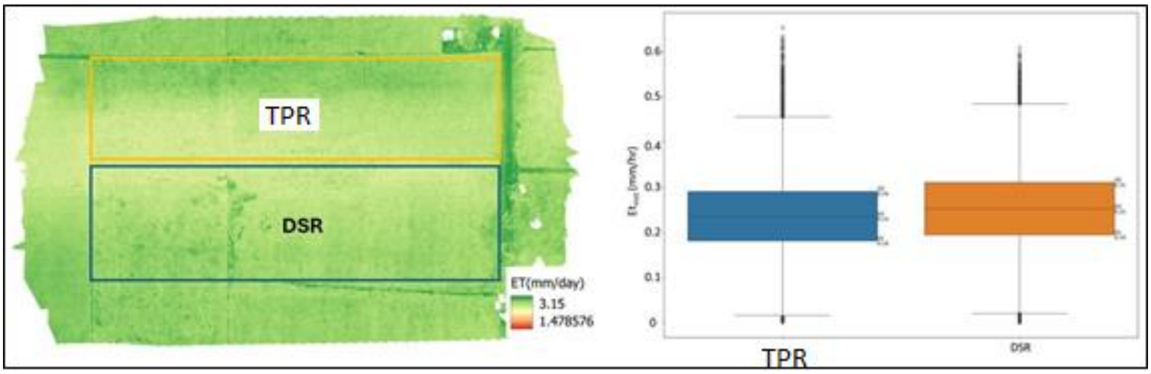

Figure 15: Comparison of evapotranspiration (ET) between DSR and TPR systems at Site A. (Left) Spatial distribution of ET (mm/day) over the field, with DSR and TPR areas highlighted. (Right) Box plot of instantaneous ET (mm/hr) for both systems

UAV-based remote sensing could provide a thorough way to evaluate evapotranspiration (ET), and the effectiveness of water use in different farming methods. Images captured by multispectral and thermal cameras were processed through a surface energy balance model to estimate ET. Integration of thermal imagery with multispectral indices (NDVI, SAVI, LAI, etc.) enhances the accuracy of ET estimation. Figure 14 shows orthomosaic, NDVI, and ET for survey site C, revealing a heterogeneity in water use across the field, where spatial variability in ET values suggests that areas with higher ET correspond to regions with denser vegetation and better crop vigour. Lower ET regions indicate potential water stress or lower soil moisture conditions that require targeted irrigation interventions. Figure 15 shows farm plots with two different rice systems (DSR and TPR), wherein they have a distinct ET pattern, with DSR farm plots exhibiting higher ET rates compared to TPR. TPR fields are showing lower ET values, suggesting lower evaporative loss. These inferences are based on the survey images captured during the late season and align well with the ET trends observed from Landsat ET products for the season.

While we were able to conduct only one survey of these sites due to time limitations, this study demonstrates the effectiveness of using UAV survey data for the analysis of ET variations over TPR and DSR systems. Multiple surveys during the season at the same sites might reveal more distinct trends in the ET, which would enhance model accuracy and decision support capabilities.

Classification of DSR and TPR systems

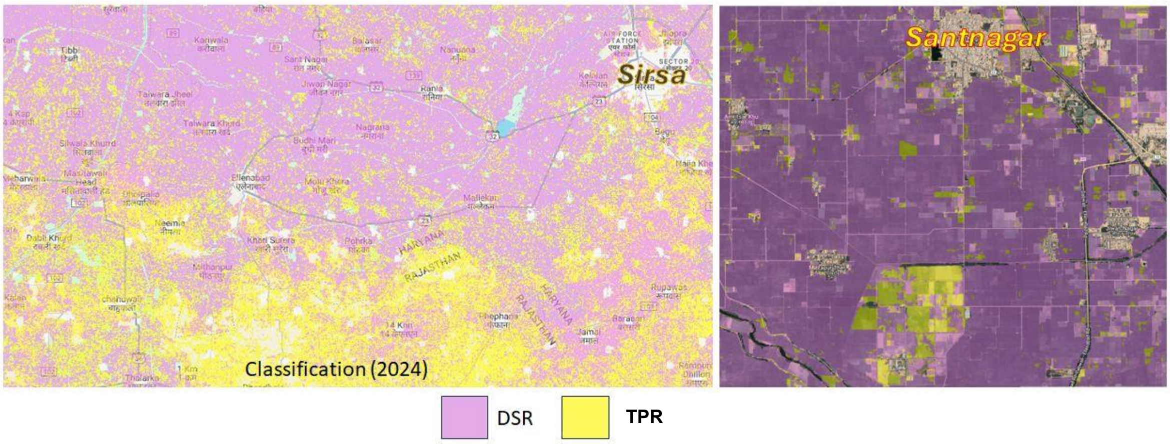

Figure 16: Classification of DSR and TPR areas in 2024. (Left) Large-scale spatial distribution of DSR and TPR across the Sirsa region (Right) Zoomed-in view of Santnagar village of Sirsa, highlighting the dominance of DSR

Figure 16 shows classification outputs of DSR and TPR systems from other land classes in Haryana, India, using a Machine Learning (ML)-based approach (Random Forest) applied in Google Earth Engine. This classification is applied on the multi-year optical and Synthetic Aperture Radar (SAR) data (ESA Sentinel-1 and Sentinel-2) from 2022 to 2024. The left map provides a broader regional classification (Sirsa district and its surrounding region), while the right map offers a zoomed-in view of a specific area (Santnagar and surrounding agricultural fields). From the classification, it can be interpreted that there is a higher DSR in Sirsa as compared to the adjacent districts and state, showcasing spatial variations in rice cultivation methods. This classification highlights the feasibility of using remote sensing and ML techniques for large-scale agricultural monitoring, which can support water management and policymaking. However, the reported accuracy of 75% suggests that further refinement, additional training data, and validation are necessary to enhance the classification's reliability.

4.4. Understanding agronomic practices in DSR

Soil type

According to the survey, most farmers (around 98%) were practicing DSR in non-sandy soil (52% loamy soil, 29% sandy-loam soil, and 17% clayey soil, Table 12). It aligns well with the package of Practices for Kharif crops released by CCSHAU, Hisar, PAU, Ludhiana, and other organizations recommending avoiding DSR on sandy soils. While DSR in clay soil was less prevalent compared to loam and sandy loam, but yield on clayey soil significantly outperformed that of other soil types. Our data indicated that the differences in irrigation frequency between the soil types are non-significant, with an average irrigation frequency of 18. However, total irrigation hours differed significantly, with the highest in sandy soil and at par among other soil types. This suggests that clay soil may require frequent irrigation, but each event of fewer operational hours. Since rice thrives in moist conditions, soils that retain moisture for longer periods are ideal.

Table 12: Total number and hours of irrigation, and crop yield as influenced by soil types in DSR

Soil type	**Yield (tonnes/acre)**	**Total irrigation frequency (Numbers)**	**Total hours of irrigation operation (Avg)**	**Correlation coefficient between yield and total Irrigation frequency**
Sandy-loam (29%)	2.34±0.44	17±5	46.16	0.158**
Sandy (2%)	2.3 ± 0.58	17±5	48.23	0.167
Loam (52%)	2.36± 0.44	17±5	46.25	0.038
Clay (17%)	2.43±0.44	18±6	46.17	0.025
Correlation coefficient between soil type and respective column	0.811*	0.817*	0.699*	

Note: The correlation is for soil type with parameters in the respective column; ** is for 5% level of significance & * is for 10% level of significance

Crop Varieties

Another key area to explore is the impact of rice varieties on various production activities and overall income, as this directly influences adoption rates. The state department recommends varieties such as Pusa 1509, Pusa 1401, Pusa 1121, PR 126, and the newer varieties Pusa 1885 and Pusa 1979, based on their crop growth characteristics. Farmers during the interaction were found to be favouring varieties Pusa 1401 (44%), Pusa 1509 (9.7%), PR 126/127 (7.3%), Pusa 44 (3%), Pusa 1692/1847 (11.81%), 7301 (3.6%), other PR varieties (1.8%), other Pusa varieties (6.5%), and other hybrid varieties (13%). Commonly used varieties by the farmers have been categorized in 6 groups (Table 13). It may be mentioned that the observed crop duration based on reported sowing and harvesting dates often exceeds the recommended duration by the breeders for the respective crop varieties reported in Table 13. Most varieties across farmers' fields were observed to surpass the 125-day growing period.

The study showed that the non-aromatic Pusa variety (Parmal) yielded the highest, followed by the short-duration Parmal variety (Figure 17 a. The long-duration aromatic Pusa variety yielded the least, but farmers still prefer it due to its stable and high selling price. In recent years, the adoption rate of short-duration aromatic rice under DSR had been increasing, driven by its high selling price (Figure17b), superior grain quality, and MSP. Additionally, these short-duration varieties have more time between cropping seasons, and water savings have been reported to be higher with these varieties.

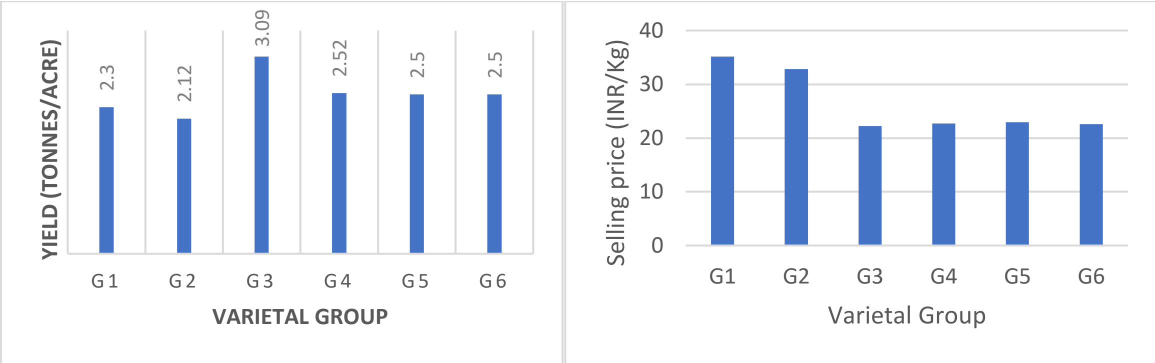

Figure 17 a: Varietal classification and its relationship with crop yield and b: selling price in DSR

Table 13: Grouping of commonly used varieties by the DSR adopters

Code for graph	Classification of variety	Varieties used
G1	Aromatic Pusa rice (110-125 days maturity)	PB 1509, PB 1692, PB 1775, PB 1847, PB 1849, PB 1401
G2	Aromatic Pusa rice (>125 days maturity)	Pb 1718, PB 1, PB 1885, PB 1121
G3	Non-aromatic Pusa variety	Pusa 44
G4	Parmal, 100-125 days of maturity	PR 127, PR 26, PR126
G5	Parmal, >125 days of maturity	PR 121, PR 14
G6	Hybrids and other varieties	Delta, Sava 127, Sava 134, Kaveri 468, Suprim 52, Suprim 110, Sift Gold etc

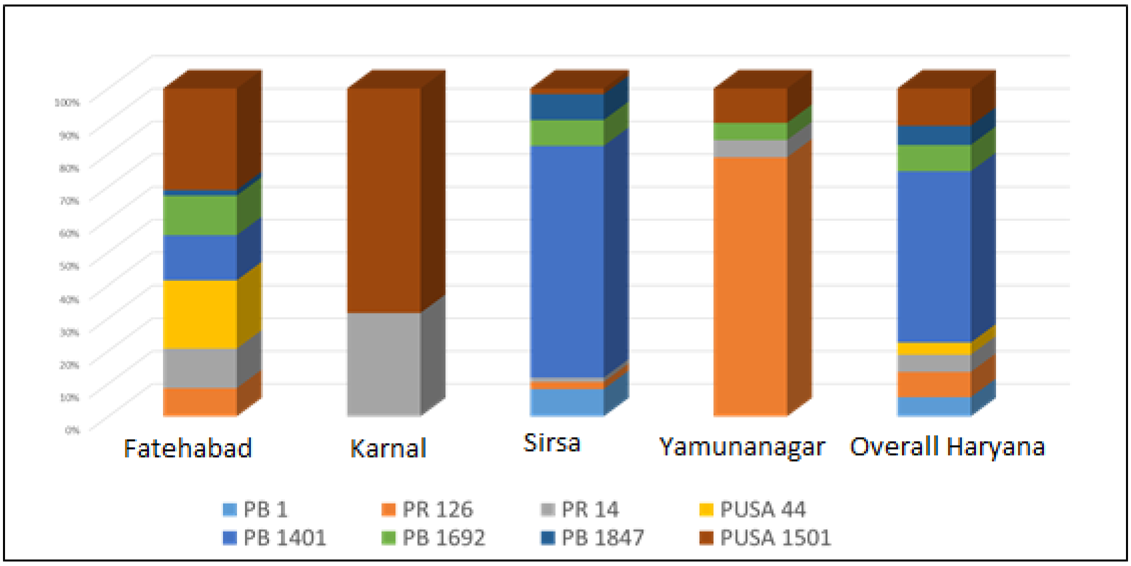

Figure 18: Varietal distribution amongst DSR farmers in different districts of Haryana

The average selling price varied across the districts, which can be attributed to differences in varietal distribution (Table 14). Fatehabad grows a wide range of varieties, with short-duration

Basmati/aromatic varieties being the most widely cultivated. In contrast, farmers in Karnal have less diversity in the varieties (Figure 18). While PR14 has a lower selling price, the dominance of Pusa 1501, which commands a higher selling price, boosts the district's overall average. Sirsa, where short-duration Basmati/aromatic rice was predominantly grown, recorded the highest average selling price. Yamunanagar, on the other hand, had the lowest selling price, with farmers mainly growing PR 126, a short-duration Parmal variety. Despite growing similar varieties, the seed rates differ across districts, with Sirsa having the highest average seed rate and Yamunanagar the lowest. Sirsa had a higher presence of private companies and direct selling, while Karnal and Fatehabad rely more on middlemen. Government procurement in Yamunanagar was significantly higher compared to other districts in the study. In the following table correlation of major varieties found in each district with crop duration of the varieties, yield, seed rate, selling price and selling agency is given in Column 7 (C7).

Table 14: Varietal impact on seed rate (Kg/acre), yield (Tonnes/acre), and selling price (INR/Kg) across districts

Item	Fatehabad	Karnal	Sirsa	Yamunanagar	Correlation between varieties and respective row (C7)
Crop duration of the varieties	138.98±16.15	133.1±16.7	151.07±21.4	137.77±18.2	0.28***
Yield	2.504±0.507	2.055±0.441	2.312±0.363	2.506±0.557	0.09**
Seed rate	7.46 ±1.21	7.45±2.03	8.36±1.62	6.64±1.59	0.28***
Selling price	27.782±06.64	28.114±5.44	35.605±6.928	21.969±6.23	0.553***
Selling agency*	D:1.38 %, G:4.1% M:80.5% PC: 1.38% W: 12.5%	D:0% G:10% M:85% PC: 0% W:5%	D:4.7% G:2.2% M:65.6% PC: 6.5% W:20.8%	D:0% G:29.3% M:68.9% PC: 0% W:1.7%	0.19***

Note: Direct sell=D; Government=G; Middlemen=M; Private Company=PC; Wholesaler=W. * is for 1% level of significance & ** is for 5% level of significance*

Sowing time

The guidelines recommend a sowing window between May 25 and June 15. Due to the Preservation of Sub-soil Water Act, 2009, farmers normally adhere to this timeframe. According to household survey data, sowing time has no significant impact on irrigation numbers and yield (Table 15).

Table 15: Relationship between sowing time on crop yield and irrigation frequency (number) for DSR farmers

Sowing time	Yield (tonnes/acre)	Straw yield (tonnes/acre)	Total irrigation frequency (number)
Early sowing (before 25th May)	2.38±0.52	2.61±0.09	17.23±5.8
Optimum (25 May to 15 June)	2.38±0.38	2.94±0.13	18.17±5.9
Late sowing (15-30 June)	2.32±0.46	2.80±0.12	17.43±5.7
Very late sowing (July)	2.32±0.41	2.53±0.07	17.26±5.5
Level of significance	NS	NS	NS

Land preparation on water requirement and yield

Some farmers believe that more tillage leads to better and uniform germination, and finer soil provides greater surface contact for seeds. However, this is not the case for most crops. In the case of paddy, which has relatively large seeds, fine land preparation is unnecessary. Survey data show that less land disturbance, with minimal tillage, results in lower water requirements and fewer irrigation events. Laser land levelling improves water application efficiency. One primary tillage followed by ~~a~~ laser land levelling reduced the number of irrigations to 15, while giving a high average yield of 2.5 tonnes/acre, compared to two or more tillage passes, which required 22 irrigations and yielded an average of 2.3 tonnes/acre (Table 16).

Table 16: Relationship between different tillage methods on numbers of irrigation, hours of irrigation operation and crop yield for DSR farmers

Tillage	Total Irrigation frequency (numbers)	Before sowing irrigation (numbers)	Total time of irrigation before sowing (hours)	Yield (tonnes/acre)
1 tillage	16±5.08	2	1.55	2.19±0.48
1 tillage + laser levelling	15±5.12	1	1.66	2.52±0.37
2 tillage operations	17±4.85	1	1.98	2.36±0.39
More than 2 tillage operations	22±5.27	2	2.42	2.33±0.59
More than 2 tillage operations + laser levelling	18±5.28	1	2.37	2.43±0.43
Correlation coefficient between tillage and respective column variables	0.118**	NS	0.116**	NS

*** is for 5% level of significance*

Inputs Requirements in DSR and TPR

Input requirements in DSR are higher than TPR except irrigation water mainly due to the fear of poor germination, which necessitates a higher seed rate, and the increased inputs like fertilizers (Table 17). One potential area to reduce cost and consequently net benefits in DSR could be to reduce these inputs making DSR cost-competitive or even more economical than traditional TPR. It may encourage wider adoption of the practice from a cost-effectiveness standpoint.

Table 17: Comparison of input application amongst DSR and TPR farmers

Input	TPR	DSR
Yield (tonnes/acre)	2.431±0.444	2.365±0.535
Seed rate (kg/acre)	4.54±1.78	7.88±1.59
Urea (kg/acre)	132.77±26.2	135.95±25
MOP (kg/acre)	19.98	23.51
Zinc (kg/acre)	5.1	5.84
Iron (kg/acre)	1.64	4.51
Total irrigation (hours)	61.54	46.11

Weed management

Type of herbicide to be used for weed management depends upon the kind of weeds infestation. Therefore, understanding and identifying the weed flora or at least identifying the category of the weed like broad leaf weeds, narrow leaf (grassy) weeds or sedges becomes important.

Table 18: DSR Farmers' response to weed flora (most abundant) in different districts

District	*Echinochloa colona*			*Echinochloa crusgalli*			*Leptochloa sinensis*			*Cyperus difformis*			*Eleusine indica*		
	Y	N	B	Y	N	B	Y	N	B	Y	N	B	Y	N	B
Sirsa	56	18	26	57	16	26	47	27	26	52	22	26	33	41	26
Fatehabad	23	11	66	28	7	66	14	20	66	27	8	66	12	22	66
Karnal	21	12	67	26	7	67	9	25	67	23	10	67	16	17	67
Yamunanagar	27	15	58	28	14	58	25	18	58	33	9	58	17	26	58

Note: Y=Yes, N= No, B= No response from respondents

The weed flora distribution shown in Table 18 reveal that *Echinochloa colona*, *Echinochloa crusgalli*, *Cyperus difformis* are major weed types in district Sirsa. Weed infestation is much less in Fatehabad, the most problematic weed being *Echinochloa crusgalli* reported by 28% only. Most problematic weeds are *Echinochloa crusgalli* and *Cyperus difformis* in District Karnal (in less than 25% cases). Majorly found weeds in Yamunanagar are *Cyperus difformis, Echinochloa crusgalli, Echinochloa colona, Leptochloa sinensis* and *Eleusine indica.*

Most farmers applied herbicides during pre-emergence and post-emergence phases (Table 19). Among the pre-emergent herbicides, 68% of farmers used Pendimethalin, with a few mixings it with Pyrazosulfuron or Oreian/Parago, regardless of the weed types observed in their fields. For post-emergence applications, farmers primarily used Bispyribac, either singly or as a mixture. Bispyribac is favoured due to its affordability and availability in various formulations under different brand names, and it is often recommended by agrochemical dealers for use in DSR.

Table 19: Farmers' response to commonly used herbicides in DSR

Pre-emergence herbicide		Post-emergence herbicide	
Herbicide name	**Percent adoption**	**Herbicide name**	**Percent adoption**
Pendimethalin (Stomp/Panida)	68	Bispyribac (Nominee gold/Tarak/Adora)	84
Pyrazosulfuron (Saathi)	3	Multiple chemical use: Bispyribac +Azimsulfuron/Cyhalofop/Kalincher	16
Pendimethalin+Pyrazosulfuron	14	Others	0
Pendimethalin+Pyrazosulfuron +Oreian/Parago	0.5		
Other herbicides	14.5		

Only 44% of adopters applied the correct dose (1-1.5 liters) of pre-emergence herbicide (Pendimethalin), while just 27% applied the correct dose (100-150g) of post-emergence herbicide (Bispyribac). Despite the significant variation in herbicide doses, it emerged that higher doses did not lead to notable differences in yield. Numerical differences, if any were not statistically significant (Table 20).

Table 20: Average dose of herbicide application and crop yield (tonnes/acre) for DSR farmers

Stage of application	Most used herbicide	Doses (per acre) in 150-200 l water	Yield (tonnes/acre)
Pre-emergence	Pendimethalin	Less than 1 litre	2.35±0.364
		1 litre and above	2.43±0.511
Post-emergence	Bispyribac	Less than 100g	2.28±0.434
		100-150g	2.38±0.518
		150g and above	2.32±0.477
Both Pre- and post-emergence	Pendimethalin+Bispyribac	less than 1 litre + >100 g	2.37±0.39
		1 litre and above +100-150 g	2.37±0.433
		1 litre and above +150g<	2.37±0.403

Herbicide application timing, specifically the gap between application and harvest, is crucial to minimize chemical residue in the grains. The recommended safe gap between herbicide application and harvesting is at least 50 days, ideally before the grain filling stage. On an average, most farmers in all the four districts were aware and applied the last dose of herbicide within the recommended time limit (Figure 19) although few farmers applied the last dose shortening the gap to about 40 days.

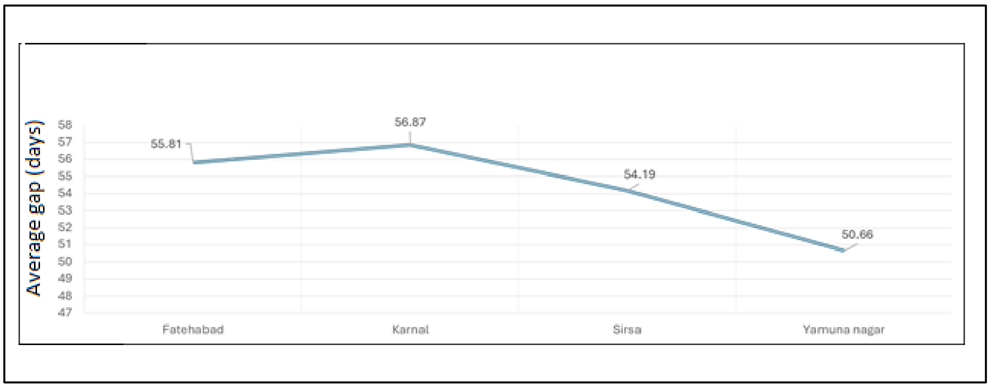

Figure 19: Average gap in days from last herbicide application to harvesting in DSR

Irrigation impact on weed management and yield

To understand the impact of numbers of irrigation at various growth stages on weeding and crop yield, the data based on numbers of irrigation were grouped into 3 classes namely average (O), below average (B) and above average (A). Numbers of irrigations and times of weed management practiced were found to be significantly correlated at most growth stages except tillering and ripening stages. Although numbers of irrigation impacted weed infestation but had no significant effect on yield (Table 21). Based on this information, optimal irrigation numbers without compromising yield can be summarized as: 1 irrigation before sowing, 4-7 irrigations each during the tillering, panicle initiation, and flowering stages, and either no or just 1 irrigation at the ripening stage.

Table 21: Correlation between irrigation application with weed management at different developmental stages and yield corresponding to low, optimum and high irrigation numbers

**** is for 1% level of significance; ** is for 5% level of significance & * is for 1% level of significance*

Developmental stages	**No. of weed management** (correlation coefficient)	**Irrigations numbers and corresponding yield (tonnes/acre)**
Irrigation before sowing	0.203***	**B= <**2 irrigation= 2.312 **0**= 2-3 irrigation =2.405 **A**= 3> irrigation =2.369
Tillering stage	NS	**B**= <4 irrigation=2.31 **O**= 4 -7 irrigation= 2.391 **A** = 8 > irrigation=2.371
Panicle initiation stage	0.11*	**B**= <4 irrigation=2.321 **O**= 4 -7 irrigation=2.389 **A**= 8 > irrigation=2.362
Flowering stage	0.179**	**B**= <4 irrigation=2.353 **O**= 4 -7 irrigation= 2.385 **A**= 8 > irrigation=2.375
Ripening stage	NS	**B**= No irrigation=2.309 **O**= 1- 3 irrigation=2.38 **A**= 4 and above =2.300

Nutrient management

The recommended fertilizer amounts are 130 kg of urea per acre, 50-55 kg of DAP per acre, 30-35 kg of MOP per acre, and 8-10 kg of zinc and iron per acre. Varying the amount of fertilizer use does not notably affect the yield (Table 22), meaning that increasing fertilizer doses does not lead to higher production. However, it's too early to say that higher fertilizer doses won't increase yields, as the relationship is likely more complex (We also did not consider the nutrients left in the soil from the previous crop or the soil's biochemical activity). There is no specific recommendation on FYM application amount, though a generic dose is taken as 5-10 tons per acre. Based on the survey data, there is no difference in yield with (2.306±0.402) or without FYM (2.39±0.45).

Table 22: Crop yield across different doses of fertilizer use amongst DSR farmers

	Crop yield (tonnes/acre)					
	Urea	**DAP**	**MOP**	**Zinc**	**Iron**	**Overall**
Low dose	2.38±0.46	2.39±0.43	2.39±0.43	2.38±0.44	2.38±0.44	2.43±0.47
Optimum	2.38±0.44	2.36±0.43	2.18±0.55	2.34±0.435	2.36±0.42	2.29±0.38
High	2.32±0.39	2.33±0.46	2.31±0.42	2.4±0.36	2.22±0.38	2.33±0.4

Note: Optimum= recommended doses, Low= below optimum dose, High= above optimum doses

4.5. Factors affecting DSR adoption in Haryana

Through focus group discussions, we interviewed different groups of farmers in Haryana including both adopters, and non-adopters respectively. We had 5 types of farmers in our interviews - i) DSR adopters who have reduced their cultivated area; ii) former DSR adopters who have discontinued DSR; iii) DSR adopters who have expanded their area or maintained consistency; iv) late adopters of DSR; and v) DSR non-adopters (traditional TPR practitioners). The responses from different farmer groups help us understand the different issues faced by farmers in the region in adopting DSR.

Type 1: DSR adopters who have reduced their cultivated area

Many adopters of Direct Seeded Rice (DSR) have opted out of the practice or reduced the area under cultivation, suggesting that they perceive DSR as less profitable compared to TPR due to the more labour required for weeding. Overall, the reason cited for reducing the area under DSR is the change in the location of leased land, coupled with the weed infestation especially *Eleusine indica* at the new location, which has made cultivation more difficult. Additionally, the scarcity of labour for hand weeding is considered a major concern, with estimated costs for weeding alone ranging from Rs 4000-5000 per acre. Farmers also point out that DSR requires more careful monitoring and timely interventions to avoid yield penalty, which they view as an added burden. Yet, they note that there is no difference in irrigation costs between DSR and TPR farmers, because of the government's flat subsidy on electricity charges, which remains unchanged, Rs 300 per month regardless of usage. The overall result has been a decrease in yield of 5-6 quintals per acre, leading to reduced income for those practicing DSR.

Type 2: Former DSR adopters who have discontinued

The farmers who have discontinued practicing Direct Seeded Rice (DSR) primarily did so because they found it to be less profitable than the conventional Transplanted Rice (TPR). Like the former category, these farmers mentioned weed infestation and the need for frequent irrigation, particularly during the summer months, added to the overall difficulty of managing DSR. Additionally, they viewed DSR as more labour-intensive, especially due to the challenges of weeding in harder and drier soils, which made the process even more demanding. These factors collectively contributed to their decision to move away from DSR.

Type 3: DSR adopters who have expanded their area or maintained consistency

The farmers who practice Direct Seeded Rice (DSR) perceive it as marginally profitable and choose to plant early through DSR to make room for crops like potatoes before wheat sowing. Potatoes grow well in sandy soils and this early planting strategy makes it beneficial. However, they face significant challenges with weed infestation, particularly with major weed species such as *Echinochloa crusgalli*, *Cyperus iria*, *Cyperus difformis*, and *Eleusine indica* being common in their DSR plots. To manage these weeds, they use herbicides like Sempra, Cyno, and Nominee Gold, applying 3 to 4 sprays per growing season, typically within 45 days (about one and a half months) after emergence. This integrated approach to weed management is helping them in maintaining the viability of DSR.

Type 4: Late adopters of DSR

The late adopters in our study groups were large-scale farmers who decided to experiment with DSR in 2024, following an awareness program at the district level. These farmers practiced DSR using the PR-1509 and PR-1401 rice varieties. Like other groups of farmers, late adopters also encountered significant weed pressure, with predominant species including *Echinochloa crusgalli*, *Cyperus difformis*, *Amaranthus viridis*, and *Echinochloa colona*, along with minor weeds like *Ischaemum rogosum*. To manage these weeds, they applied herbicides such as Craze, Nominee Gold, and Rice Star, with three applications costing around Rs 2500, including labour charges. These farmers irrigate their fields once every 10 days and believe that DSR requires less water compared to traditional methods, reflecting their acceptance of the water-saving potential of this cultivation practice.

Type 5: DSR non-adopters (traditional TPR practitioners)

Non-adopters of DSR continue to favor the conventional method of TPR, as they believe DSR is not productive and see no need to change their cultivation practices. Water availability is not a concern in their village, which further reinforces their decision to stick with TPR. They also emphasized that weed management in TPR is relatively minimal, as the standing water helps decay the initial weed flush. The major weed species they encounter include *Fimbriostylis miliacea*, *Echinochloa crusgalli*, and *Leptochloa chinensis*. For weed control, they use cost-effective herbicides such as Sathi for pre-emergence and Calidan for post-emergence, applying them around 40 days after emergence to manage the weed pressure effectively.

The key takeaways highlight diverse farmer experiences with DSR adoption. The problem of weed infestation remains constant among all adopters making it the most cited challenge of DSR practice. Abundant water availability with good accessibility is another reason most farmers take DSR less desired alternative as they do not feel the need to save water. Despite facing the same challenges as other adopters and having good irrigation facilities, Type 3 adopters continue with DSR, seeing it marginally profitable. Overall, discussions with several adopters revealed that while DSR has the potential for water savings, an effective weed management solution must be shared and/or developed to encourage farmers to adopt it.

Table 23: Perception of all sample farmers across different years of adoption regarding the advantages and challenges of DSR adoption

Year	No. of adopters	Benefits	Limitations/Challenges
2000	1	Decrease in water usage, reduced cost of cultivation, reduced lodging, saving in energy	Weed
2010	2	Reduced labour requirement, decrease in water usage, reduced lodging	Weed
2013	1	decrease in water usage, decrease of major diseases and pest infestation, saving in energy	Weed
2016	2	Reduced labour requirement, shortened cultivation time, reduced cost of cultivation, more tillering	Weed
2017	1	Decrease of major diseases and pest infestation	Weed and non-availability of herbicide
2019	4	Decrease of major diseases and pest infestation	
2020	18	Decrease diseases and pest infestation (major diseases and pest), rabi crop yield is improved	Weed, yield penalty, diseases and pests (minor), non-availability of suitable varieties
2021	30	Decrease of major diseases and pest infestation, rabi crop yield is improved	Weed, lack of awareness, yield penalty, diseases and pests, non-availability of suitable varieties
2022	109	Decrease of major diseases and pest infestation, rabi crop yield is improved, early harvest of crop, survive longer dry spells	Weed, lack of awareness, yield penalty, diseases and pests, non-availability of suitable varieties, lack of machinery, slower growth rate

As we can see in Table 23, like any other technological advancement, the adoption process has been gradual. However, it gained significant traction in 2023, with widespread adoption. Out of 800 respondents, the number of adopters has remained minimal since 2000 till 2022. Based on the interviews, we were able to identify a range of benefits as perceived by them over the years, as well as the challenges they've encountered. Some of the key benefits of DSR (Direct Seeded Rice) include reduced water usage, lower cultivation costs, less lodging, energy savings, reduced labour requirement, fewer diseases and pest infestations (major diseases like Bakane have been reduced), shorter cultivation periods, increased tillering, improved rabi crop yields, earlier harvests of rabi crops, and greater resilience during dry spells, among others. Main issues that have been identified by the adopters since 2000 can be summarised as weed infestation, minor yield penalties, diseases and pests (minor diseases have become more noticeable), non-availability of suitable varieties, lack of awareness, insufficient access to machinery, and slower growth rates.

Table 24: Perception of current DSR adopters regarding the advantages and challenges of DSR adoption

Even for the subsample of current adopters, weed infestation continued to be a primary concern (Table 24). To encourage broader adoption, efforts need to focus on addressing this issue while expanding the benefits. Among these benefits decrease in water usage was identified as a major benefit by adopters, since these were mostly adopted in regions with limited water access with very low rainfall. This is particularly important because with climate change, the erratic nature of precipitation is going to increase besides the rising temperature. DSR can create resilience in the long run in its capability to survive longer dry spells. TPR produces robust root system but because of abundant water, there is lateral branches however due to the puddled layer, the rooting is more horizontal. While in DSR, the rooting is more vertical, as it reaches to deeper soil layer and derive the moisture required for extended survival despite water stress condition. Hence, DSR's ability to establish deeper roots and its reduced reliance on standing water make it more drought-resistant during dry spells compared to TPR, which is more vulnerable due to its dependence on consistent water flooding. Thus, reduction in water usage could be a major driver for adoption in areas facing water shortages.

We also ran a simple logit regression with our farmer survey data to correlate how different farmer characteristics predicted DSR adoption probability. In the table below (Table 25), we find that certain variables show statistically significant impacts on DSR adoption probability. Water-logged areas have a significant negative effect (-0.17*), indicating an adverse impact. Canal irrigation shows a significant

Benefits	**Challenges**
Decrease in water usage (41%)	Weed (56%)
Reduced labour requirement (34%)	Yield penalty (12%)
Reduced lodging (15%)	Diseases and pests-minor diseases (9%)
Decreased diseases & pest infestation - major diseases (14%)	Others (3%)
More tillering (3.7%)	Risk during unusual summer spells (2%)
Shortened cultivation time (3.2%)	Slower growth rate (2%)
Reduced cost of cultivation (3.2%)	lack of availability of machinery (2%)
Saving in energy (1.6%)	lack of awareness (1%)
Rabi crop yield is improved (1.4%)	Rat infestation (1%)
Can survive longer dry spells (1%)	Non-availability of seed variety suitable for DSR (1%)
Early harvest of crop (0.7%)	soil type (0.6%)
Convenient intercultural operations (0.5%)	Lack of govt. official's visit for support/advise (0.6%)
	Non-availability of herbicide (0.6%)

positive effect (0.12*), underscoring the benefits of reliable water sources. Other variables, such as household head education (-0.12), female household head (0.08), and the proportion of own land (0.11), show marginal or insignificant effects, while regional variations reveal better outcomes in Sirsa (0.27) and moderate positive effects in Yamunanagar (0.12). However, Karnal shows a slight negative association (-0.09). Soil types, such as saline soil, exhibit positive effects, though not statistically significant. Similarly, clayey soil, paddy duration and total cultivated land, show negligible or insignificant overall impacts.

Table 25: Factors affecting adoption of DSR in sample villages in Haryana

Variables	Margin (dy/dx)	Sig.
Paddy duration	0.01	***
HH head education (dummy=1 if at least some education)	-0.12	
HH head age	0.00	
Female HH head	0.08	
HH head belongs to general category	-0.04	
Total cultivated land	0.01	***
Proportion of own land	0.11	
Proportion of clayey soil in cultivated area	0.01	
Proportion of saline soil in cultivated area	0.21	
Proportion of canal irrigated in cultivated area	0.12	*
Proportion of water-logged in cultivated area	-0.17	*
Karnal	-0.09	
Sirsa	0.27	
Yamunanagar	0.12	

**** is for 1% level of significance; ** is for 5% level of significance & * is for 1% level of significance*

4.6. Impediments and policy issues in scaling DSR

DSR has been practiced for some time with many research studies and field trials suggesting multi-fold benefits over the conventional TPR. The findings from different data sources in this study also find many of these benefits for DSR adopters in Haryana. Despite that DSR uptake is slower than expected. Three important aspects that need to be understood for effective upscaling of the technology are:

- Impediments for the slow pace of DSR adoption
- Researchable topics to resolve technological and agronomic challenges
- Policy initiatives to resolve socio-economic issues

Impediments

Initial Investment: DSR besides the normal tractor and tillage equipment requires specific machinery such as laser land leveller and tractor operated seed drills and seed drills-cum-sprayers, which are all expensive. While the long-term benefits of reduced labour costs and water use are clear, yet the upfront cost of acquiring such machines deters the farmers in adopting the technology.

Large versus Small Farmer Syndrome: As per Haryana Agricultural Statistics, 2024 Small and marginal farmers (constituting 80%) need to be targeted, as they often lack in economic ability, behavioural characteristics (ability to take risks), access to resources, agricultural technologies, and extension services to adopt new technology (Chikkalaki et al., 2024). These disparities enable large farmers to adopt advanced agricultural practices such as DSR more readily than their counterpart small farmers, who may struggle with limited resources. This underscores the importance of targeting small farmers to make a positive headway in the spread of DSR technology in the state. Gearing the extension services alone can help to bridge the gap between small and large farmers enabling them to adopt DSR and contribute to the overall sustainability and profitability of the Rice wheat cropping system (RWCS).

Weed Management: Weed control is a major challenge in DSR. Not only the weed pressure is higher compared to transplanted rice, mixed flora of hard-to-kill weeds, infestation of fields with new weeds and the dynamic nature of the weeds over the years are few issues of concerns to the farmers. Recommendation to adopt integrated weed management comprising manual, mechanical, chemical and biological methods are new to the farmers and involve additional costs and learning.

Unfavourable Weather Conditions: Direct seeding is more sensitive to weather conditions than TPR. Since, the monsoon season rainfall in Haryana can be quite erratic, an untimely rainfall especially after the sowing can negatively impact seed germination resulting in poor crop establishment. Insufficient rainfall during the cropping season may impact crop growth. The yield penalty under such adverse conditions makes it less reliable than the traditional transplanting method.

Cultural Resistance: Changing farmers' entrenched practices requires significant time, effort, and motivation, which might not be immediately forthcoming for many farmers. It can only be achieved through well planned awareness and training programmes geared to impart the knowledge about DSR as well as to break the taboo of change. This requires transfer of knowledge by extension functionaries, for which they are not well equipped, being mainly accustomed to extending the input based or subsidy-based technologies.

Water Management and Irrigation Issues: DSR can help save water but effective water management in this system is still a significant challenge. Farmer mind-set of seeing the fields wet all the time forces them to frequently irrigate their fields than required. Moreover, to harness full potential benefits of DSR, it must be tagged with other micro-irrigation or water management schemes. Although investments may be slightly high, yet full potential of water saving in DSR can only be achieved through a switchover from surface to sprinkler irrigation.

Soil Health and Fertilizer Management: So far, the farmers have been following fertilizer recommendations made for transplanted rice cultivation. Soil physical conditions under DSR being entirely different, macro and micro fertilizer requirements as well as their application strategies are entirely different. Recommendations from soil testing laboratories and soil health cards have to be geared to this requirement to ensure improved nutrient use efficiencies, good soil health and higher yields.

Government Policies and Support: No doubt government incentives such as one time grant every year for adopting DSR and subsidies on farm machinery are available yet the allocations under these heads are quite inadequate considering the extent of the area that has to be brought under DSR. This coupled with inadequate extension support and limited support for training and awareness programs are proving to be major impediments in the spread of DSR. Besides, the government policy of almost free supply of canal water and almost free electricity for groundwater extraction do not provide enough incentive to the farmers to save water.

Market Dynamics and Yield Uncertainty: There is limited localized research on the long-term performance of DSR in Haryana's various agro-climatic conditions. Farmers are often hesitant to adopt new methods without seeing or having access to data on their economic and agronomic benefits in their region. It seems that even after voluminous data generated, the performance of DSR in terms of yield stability compared to conventional methods is still uncertain. Moreover, uncertainty about the market price for the produce (Basmati rice) makes it a riskier option for many farmers.

Rodent Control: Although not a very serious problem, yet damage to direct seeded rice crop at germination stage by rodents has been reported. This requires additional care and attention in rebuilding bunds to destroy rat burrows and burrow baiting during lean period.

A multi-faceted approach involving financial incentives, policy advocacy, research inputs, institutional support, stakeholder engagement and capacity building at village level is the way forward to break these barriers for the smooth transition from conventional to DSR system.

Researchable topics

Despite the benefits in terms of increased profitability, lower irrigation and labour requirement, the pace of DSR uptake is slow because of many technological, agronomic and socio-economic challenges as discussed above. Few key research initiatives aimed at making direct-seeded rice a viable technology is listed as under.

Improved Seed Varieties: Traditional rice varieties that have withstood the test of time under TPR may not be suitable for direct seeding due to poor establishment, weed competition, or sensitivity to water stress. Successful transition from TPR to DSR system of rice cultivation demands breeding of conducive rice varieties tailored for DSR. These varieties should be amenable to mechanical planting, able to withstand early weed competition, and tolerant to water stress at various growth stages. Shorter duration varieties having modified panicle architecture giving more primary branches per panicle to avoid the adverse effects of dry spells, modified root system to draw moisture and nutrients from deeper depths, and resistant to lodging are likely to be more suited to DSR. The varietal traits having high seedling vigour, faster leaf area development during early vegetative stage and resistant to commonly applied herbicides in DSR may prove quite beneficial. Moreover, multi-stress tolerant varieties that can handle drought, heat, or saline conditions are essential for DSR, especially in regions facing climate change-related challenges. A two-pronged strategy of selection and breeding may be needed to meet the short and long-term goals.

Soil Management Practices: Several alternative tillage practices such as dry tillage, reduced tillage, and minimal soil disturbance are being advocated to reduce the cost. Besides many seeding practices such as dry sowing followed by irrigation, vattar (field capacity) sowing and wet sowing (standing water) have emerged to improve seed establishment and reduce weed competition. Among these many different options available to farmers, there is need for identifying and popularizing the best options considering specific soil and agro-climatic conditions.

Weed/Pest Management: One of the major challenges for the success of DSR is to control weeds compared to flooded field environment. Research efforts are needed to develop effective, eco-friendly herbicide molecules for broad spectrum weeds, mechanical weed control technologies such as precision weeding, and cost-effective and easy to adopt integrated weed management strategies. Investigating the use of allelopathic plants or cover crops that suppress weed growth without affecting the yield of rice can offer a natural way to control weeds in DSR systems. Cost-benefit of the stale seedbed technique for weed control needs investigations. Integrated pest management (IPM), conservation tillage, and crop rotations to minimize pest attacks may be studied to make DSR more environmentally sustainable while improving yields.

Nutrient management: Yield penalty in DSR can be minimized through effective fertilizer applications for maintaining soil health critical to promote optimal rice growth. Research on nutrient dynamics in DSR, nutrient management strategies such as split fertilization and precision placement, need for applying soil specific micro-nutrients, and developing strategies to improve nutrient use efficiency should begin in right earnest.

Water Management: DSR potential to save water has been well documented but careful water management, especially in dry land conditions or in low rainfall years still remains an issue. Research into alternate wetting and drying (AWD) techniques with identifiable markers, application of micro-irrigation systems (e.g., sprinkler and drip irrigation), and moisture retention techniques in light-textured soils is crucial for improving water use efficiency in DSR. Studies at ICAR-Central Soil Salinity Research Institute have shown that sprinkler systems have potential to improve on-farm irrigation efficiency under DSR rice and following wheat crop (Singh *et al*., 2023). It should be possible to apply a desired depth of water during pre- and post-sowing irrigations using pressurized irrigation systems. The integration of rainwater harvesting and reuse to complement DSR needs investigation, especially in water-scarce regions.

Collaboration with International Organizations: DSR is practiced widely in many Asian countries few of them having long experience with this technology. Global partnerships and collaboration with international research organizations (like IWMI, IRRI, CIMMYT, and FAO) can help transfer knowledge, technologies, and resources for region-specific research where direct seeding can prove to be a game-changer.

Economic and Policy Research: Researching the economic viability of DSR system, especially in terms of labour savings, input costs, and yield outcomes, can provide insights into the profitability of DSR system. Economic studies should also explore how DSR can be integrated into smallholder farming systems. Policy research that may lead the government in formulating favourable policies in terms of adequate subsidies, financial incentives, and institutional support vital for scaling the technology may be undertaken.

Precision Farming and Technology Integration: Precision agriculture tools, such as drones, remote sensing, and satellite imagery, can be used to monitor the growth of rice fields and detect issues like pest outbreaks, nutrient deficiencies, or water stress. Technology development including design of new sensors for identifying, and dissemination of information to DSR farmers may help them to make more informed decisions regarding input application and management.

Mechanization and Automation: Developing low-cost machinery for direct seeding (seed drills, precision seeders), fertilization, irrigation, and sprayers for weed and pest management should receive priority.

Climate Resilience and Sustainability: Research activities should address the question how DSR can be adapted to changing climatic conditions, such as increased temperatures, erratic rainfall, and increasing prevalence of pests and diseases. This may also include investigating the benefits of DSR in mitigating greenhouse gas emissions compared to traditional rice farming. Some reports indicate that reduced CH_4 emissions in DSR may be counterbalanced by increased emissions of N_2O. Given the dynamics, it is important that all three GHGs (CH_4, N_2O, and CO_2) are measured at a system level to assess the overall global warming potential of the production system. Improved tillage and agronomic practices related to water and nutrient management and residue management need to be developed to minimize GHGs emissions from DSR fields. These studies may further be extended to develop strategies to reduce N losses vis-à-vis N_2O emissions under aerobic conditions.

Farmer-led Research and Participatory Approaches: This approach having wide connotations is based on action research theory. It emphasizes collaboration between farmers and the research community and comprises involvement of the farmers in carrying out experiments in their own fields to identify technologies suited to their local conditions. It involves an iterative process of identifying problems, testing potential solutions, discussing results and promotes learning, and knowledge sharing. Such innovative research approach may increase the chances of successful DSR adoption in specific agro-ecological zones.

Policy issues

Besides technological issues socio-economic barriers also constitute a major hurdle in the adoption of technology. State government and relevant stakeholders need to devise few enabling policy initiatives to address the socio-economic barriers to facilitate the widespread adoption of DSR.

Financial Incentive: Even though net profit for DSR adopters is higher than TPR farmers, as a new technology DSR can appear riskier for farmers. Consequently, attractive financial support is required to compensate the farmers who might be risk averse and otherwise unwilling to adopt. Government of Haryana already provides an incentive of Rs. 4000 per acre for switching over from traditional TPR to DSR, but it may be worthwhile to constitute a working group for analysing and suggesting any potential change that might be required in the quantum of this incentive for more quicker uptake of the technology. Besides, it may be worthwhile to incorporate DSR as a key component in the state's water management policy to ensure its systematic promotion.

Subsidies on Farm Equipment for DSR: Access to high-cost machinery such as seed drills, seeders, and other tractor-mounted equipment such as sprayers is proving to be a major hurdle in the popularization of this technology. Currently state government provides subsidy to individual farmers at 50% of the cost of the machines and at 85% to custom hiring centres (CHCs). It looks reasonable but the adequacy of funds available under this head is not enough to meet even the existing demand. The likely projected demand for covering large areas under the technology may far exceed the funds available for this purpose. It may be worthwhile to provide low-interest loans to farmers for purchasing machinery to resolve this bottleneck. Pro-active actions by the state Department of Agriculture and Farmers welfare in establishing custom hiring centres in rural areas may make the technology more accessible to small and medium farmers.

Promote Research on DSR: State government should provide special funds to state agricultural university, ICAR research organizations and other relevant institutions for developing varieties with traits suited for DSR. Besides, these organizations may be suitably supported for research on soil management practices specific to DSR, such as optimizing water usage and soil preparation methods.

Public-Private Partnerships (PPP): Necessary support may be extended to foster collaboration and partnerships between the government and private sector companies to develop cost-effective and region-specific machinery, tools, and services for DSR. Some companies have come out with Full-Page Rice Cropping Solution catering to DSR. Such kinds of capsules with local touch needs to be developed by public sector institutions and made available during the farmer's fair. This may be achieved either through their own mechanisms or by roping in the private enterprises in PPP mode.

Awareness, Training and Demonstration Programs: Lack of awareness especially amongst the small and marginal farmers appears to be the major stumbling block in the popularization of this technology. Regular workshops and training programs focusing on the technical aspects of DSR such as varietal selection, use of new machinery and soil management should be organized in KVKs, Extension Education Institutes, and ICAR Institutes. There is a need to conduct awareness campaigns for dissemination of knowledge by employing specially trained field functionaries and successful farmers. Community meetings and exposure visits to fields may prove to be quite educative. Full potential of mass media (radio, TV, newspapers) and mobile technology may be harnessed in spreading the message. It may be quite useful to set-up demonstration plots in different regions of the state where farmers are able to see the effectiveness of DSR.

Collaborations with NGOs and Farmer Groups: NGOs working in the field of rural development may be suitably engaged to support grassroots-level adoption of DSR through community-based training, workshops, and on-field support. Besides, farmers' groups comprising early adopters may be constituted to support and guide farmers to adopt this practice within and outside their villages. Formation of farmer producer organizations (FPOs) may be encouraged to pool resources for purchasing equipment, accessing markets, and spreading knowledge about DSR.

Monitoring and Evaluation: A data monitoring cell may be set up in the department to monitor the adoption rates and outcomes of DSR in the state. The cell may also undertake impact assessment studies to evaluate the success/failure of DSR in terms of water conservation, yield improvement, and economic benefits to the farmer. Such an inventory may help in learning and refining the technology. The data so generated may be analyzed to understand the barriers and challenges faced by farmers, and suitable adjustments in the policies and plans.

In summary, popularization of Direct Seeded Rice hinges on a multi-faceted approach that combines incentives, subsidies, training, infrastructure development, and market support. Framing policies that align DSR with environmental and economic goals may further boost the expansion of the technology. It may be stressed that such a gigantic task cannot be accomplished alone by one entity. It needs convergence of actions across multiple institutions and stakeholders such as government departments, public institutions, research organizations, the private sector, NGOs, and self-help groups. Strengthening these institutions and creating an enabling environment can bring about a revolutionary change in the way rice cultivation is practiced in Haryana.

5. Conclusion

The study highlights the significant water-saving potential of DSR, requiring 15-20% less irrigation on average compared to TPR, with consistent results across farmer survey data, water flow meter data and satellite data. This reduction in water usage can help control the declining water table in Haryana but also decrease government electricity subsidies and reduced methane and greenhouse gas emissions from decreased pumping.

At the farmer level, DSR reduces costs associated with land preparation, sowing, and irrigation but increases costs for fertilizers, pest control, weed management, and harvesting. Overall, in this study we did not observe significant difference in the total cost of cultivation between DSR and TPR, contrary to some previous reported studies. It looks that recent change in the technology making laser land levelling an essential part may have flattened the cost differential. However, DSR results in higher net returns due to better grain quality, lower breakage rates during milling, and reduced chalkiness, leading to higher market prices. On average, net returns for DSR are almost 22% higher. It is crucial to make farmers aware of this advantage to refrain them from mixing DSR with TPR, which could negate the price benefit.

DSR adoption also reduces total labour use by 18%, with a significant decline in female labour participation. Although women are more involved in weeding, the reduction in labour required for sowing offsets this increase. Moreover, the peak demand during transplanting is flattened over a longer period as weeding is undertaken at different time intervals.

Despite these benefits, DSR adoption faces several challenges. Weed management is the most significant barrier, with 56% of farmers reporting it as a major issue. Other concerns include yield penalties (12%) and diseases/pests (9%). Interestingly, many farmers tend to overdose on herbicides, especially post-emergence, which does not lead to significant yield differences, indicating room for optimization. Additionally, DSR plots recorded higher fertilizer use and almost double the seed rate compared to TPR with no observed difference in yield. Hence there are several opportunities to bring down the cost of cultivation in DSR. Some cost-cutting strategies can include optimum seed rates, infrequent irrigations, minimal tillage, and reduced fertilizer and herbicide use. Stakeholders need to be made aware of these issues through training and awareness campaigns.

To scale up DSR adoption effectively, other challenges such as high initial machinery costs, weed management, and farmers' concerns about market yield and risks need to be addressed. Public-private partnerships, increased R&D investment, and training in optimal practices are crucial. Additionally, attractive incentives and collaborations with NGOs and farmer groups can support grassroots adoption. Establishing a data monitoring cell to track DSR's impact will help inform necessary policy adjustments.

In summary, DSR presents a promising alternative to traditional rice cultivation methods, especially in water-stressed areas. Its successful scaling requires a multi-faceted approach with concerted efforts from all stakeholders, including farmers, researchers, policymakers, and the private sector. By addressing the identified challenges and leveraging the observed benefits, DSR can significantly contribute to mitigating groundwater depletion issues, supporting the broader mission of sustainable groundwater management, and addressing the issues of groundwater-energy nexus.

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7. Appendices:

Appendix A: Depth of irrigation in inches (the actual status)

	Water Depth at Nursery stage	Water depth at sowing	Water Depth at tillering	Water depth at panicle initiation	Water depth at flowering	Water depth at ripening stage
TPR	1.65 ± .60*	2.21 ± .95	2.13 ± .82	2.06 ± .78	2.06 ± .79	2.03 ± .77
DSR		2.25± .820	2.19± .872	2.13± .83	2.02 ± .785	2.02± .73

*Mean ± Standard deviation

Appendix B: No. of Irrigation, Kharif 2023

	Irrigation number at Nursery stage	Irrigation number at sowing stage	Irrigation number at tillering stage	Irrigation number at panicle initiation stage	Irrigation number at flowering stage	Irrigation number at ripening stage
TPR	8.03 ± 3.07	2.22 ± 1.46	6.27 ± 2.93	5.06 ± 2.21	3.55 ± 1.89	1.81± 1.37
DSR		1.28 ± .89	5.13 ± 2.26	5.14 ± 2.25	3.90 ± 2.00	1.98 ± 1.29

*Mean ± Standard deviation

Appendix C: No. of Irrigation, Kharif 2024

	Irrigation number at Nursery stage	Irrigation number at sowing stage	Irrigation number at tillering stage	Irrigation number at panicle initiation stage	Irrigation number at flowering stage	Irrigation number at ripening stage
TPR	7.93 ± 3.17	2.31 ± 1.45	6.24 ± 2.97	4.98 ± 2.24	3.56± 1.96	1.71 ± 1.30
DSR		1.23 ± .85	5.23 ± 2.22	5.31 ± 2.24	3.95 ± 1.99	2.02 ± 1.31

*Mean ±Standard deviation

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