

OPTIMIZING AND SCALING WATER PRODUCTIVITY IN IRRIGATED RICE FOR CLIMATE RESILIENT AGRICULTURE IN SOUTH ASIA

OPTIMISATION ET MISE À L'ÉCHELLE DE LA PRODUCTIVITÉ DE L'EAU DANS LA RIZICULTURE IRRIGUÉE POUR UNE AGRICULTURE RÉSILIENTE AU CLIMAT EN ASIE DU SUD

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ABSTRACT

Rice is a major staple food for about half of the global population, and South and Southeast Asia are the major rice producers in the world. Globally, irrigated rice consumes about 34–43% of global irrigation water and 24–30% of developed freshwater resources. Climate change is widening the water supply–demand gap. In South Asia, heavy dependence on groundwater irrigation—particularly in northwestern India, Pakistan's Punjab, and Bangladesh's Barind tract—has led to severe groundwater depletion and high energy use, increasing the water and carbon footprint of rice systems.

With increasing water demand, low water use efficiency, and climate change, optimizing water use is critical for sustaining rice productivity in water-scarce, climate-vulnerable regions of South Asia. Puddled transplanted rice and continuous flooding are the traditional practices of this region. *Boro* rice cultivation is also commonly practiced in the eastern Indo-Gangetic Plains in parts of eastern India and Bangladesh, which are largely irrigated with groundwater. Context-specific agricultural water management (AWM) is central to adaptation.

Direct seeded rice (DSR) and Alternate Wetting and Drying (AWD) have emerged as a cornerstone of "climate-smart" agriculture in South Asia. DSR saves water by avoiding puddling, transplanting, and standing water. AWD can reduce irrigation water inputs and reduce global warming potential (GWP) by 30–40% as compared to continuously flooded rice. AWD and DSR offer a promising proposition to traditional transplanted rice cultivation in South Asia, especially in water-stressed areas, to save water, increase water productivity, and reduce emissions.

Governments, NGOs and donors in India, Bangladesh and Pakistan have taken initiatives to scale these interventions and while they offer significant benefits, widespread adoption faces challenges. In this paper, we present use cases from India and Bangladesh, discuss barriers to adoption and offer recommendations for scaling up. Successful scaling of DSR and AWD will require a multi-faceted approach with concerted efforts from all stakeholders, including farmers, researchers, officials of irrigation systems, policymakers, and the private sector.

Keywords: Water productivity; Groundwater depletion; Rice systems; Climate-smart agriculture; Water-stressed areas.

RÉSUMÉ

Le riz constitue un aliment de base majeur pour environ la moitié de la population mondiale, et l'Asie du Sud et du Sud-Est regroupe les principaux producteurs mondiaux de riz. À l'échelle mondiale, le riz

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irrigué consomme environ 34 à 43 % de l'eau d'irrigation et 24 à 30 % des ressources en eau douce aménagées. Le changement climatique creuse l'écart entre l'offre et la demande en eau. En Asie du Sud, la forte dépendance à l'irrigation par les eaux souterraines — notamment dans le nord-ouest de l'Inde, le Pendjab pakistanais et la région de Barind au Bangladesh — a entraîné un grave épuisement des nappes et une forte consommation d'énergie, augmentant ainsi les empreintes hydrique et carbone des systèmes rizicoles.

Face à l'augmentation de la demande en eau, à la faible efficacité d'utilisation de l'eau et au changement climatique, l'optimisation de l'utilisation de l'eau est essentielle pour maintenir la productivité du riz dans les régions d'Asie du Sud exposées à la pénurie d'eau et vulnérables au climat. Le repiquage du riz en sol mis en boue et l'inondation continue constituent les pratiques traditionnelles de cette région. La culture du riz *Boro* est également courante dans l'est de la plaine indo-gangétique, notamment dans certaines parties de l'est de l'Inde et du Bangladesh, où elle est principalement irriguée à partir des eaux souterraines. Une gestion de l'eau agricole (AWM) adaptée au contexte est au cœur de l'adaptation.

Le semis direct du riz (DSR) et l'alternance d'humidification et d'assèchement (AWD) sont devenus des piliers de l'agriculture « intelligente face au climat » en Asie du Sud. Le DSR permet d'économiser l'eau en évitant la mise en boue, le repiquage et la présence permanente d'une lame d'eau. Par rapport à une culture de riz continuellement inondée, l'AWD peut réduire les apports d'eau d'irrigation et le potentiel de réchauffement planétaire (GWP) de 30 à 40 %. L'AWD et le DSR constituent une solution prometteuse en remplacement de la riziculture traditionnelle par repiquage en Asie du Sud, notamment dans les zones soumises au stress hydrique, afin d'économiser l'eau, d'accroître sa productivité et de réduire les émissions.

Les gouvernements, les ONG et les bailleurs de fonds de l'Inde, du Bangladesh et du Pakistan ont pris des initiatives pour déployer ces interventions à grande échelle. Malgré leurs avantages importants, leur adoption généralisée se heurte à des difficultés. Dans cet article, nous présentons des cas d'utilisation en Inde et au Bangladesh, examinons les obstacles à l'adoption et formulons des recommandations pour leur mise à l'échelle. Le déploiement réussi du DSR et de l'AWD exigera une approche multidimensionnelle et des efforts concertés de l'ensemble des parties prenantes, notamment les agriculteurs, les chercheurs, les responsables des systèmes d'irrigation, les décideurs publics et le secteur privé.

Mots clés : Productivité de l'eau; Epuisement des nappes; Systèmes rizicoles; Agriculture intelligente face au climat; Zones soumises au stress hydrique.

BACKGROUND AND CONTEXT

Rice is a major staple food crop for about half of the global population, with South and Southeast Asia as the major rice producers in the world (Kumar and Katagami, 2016). Irrigated rice cultivation consumes a large share of global irrigation water, accounting for approximately 34–43% of total irrigation water, and 24–30% of the world's developed freshwater resources. Rice underpins food security and rural livelihoods across South Asia. Rice is cultivated under diverse soil and agro-climatic conditions in about 60 million ha in South Asia, accounting for 37.5% of the global area in 2013 (Rice Today, 2014). Within South Asia, India cultivates rice in about 43.8 million ha (maximum globally), followed by Bangladesh (about 11 M ha), Pakistan (3.9 M ha), Nepal and Sri Lanka (Agriculture situation in India, 2021; [Pakistan Credit Rating Agency Limited, 2025](#)).

The rice cultivation in the region is water and energy-intensive, relying on puddling, transplanting and continuous flooding. The traditional practice of continuously flooding rice paddies not only uses more irrigation water, but it also creates low-oxygen environment in soil, leading to substantial methane emissions. These prevalent practices drive inefficient water use, accelerate groundwater depletion, and increase greenhouse gas (GHG) emissions. Intensive pumping of groundwater for irrigating rice entails high energy, leading to a high carbon footprint compared to other crops, as in South Asia over 60% of irrigation is from groundwater. Inefficient water management in rice cultivation is a major

contributor to GHG emissions from rice fields. Rice fields account for approximately 20% and 10% of methane (CH₄) and nitrous oxide (N₂O) emissions, respectively.

Climate change further compounds these challenges through altered hydrology, increased evaporative demands, erratic monsoon and increased frequency of droughts and floods and these are expected to further exacerbate the water supply and demand gap in South Asia. A large portion of irrigated rice cultivation, especially in northwestern India, Pakistan's Punjab, and the Barind area of Bangladesh depends on intensive groundwater irrigation, which are already water stressed and facing groundwater depletion. With increasing water demand, low water use efficiency, and climate change, optimizing water and energy use is critical for sustaining rice productivity in water-scarce, climate-vulnerable regions of South Asia. *Boro* rice cultivation (winter rice) is also commonly practiced in the eastern Indo-Gangetic Plains in parts of eastern India and Bangladesh, which are largely irrigated with groundwater. Groundwater resources are heavily affected by *boro* rice cultivation, raising concerns about the long-term viability of *boro* farming in the parts of eastern Indo-Gangetic plains, Barind area of Bangladesh for instance.

Water is the principal pathway through which climate impacts manifest in agriculture; thus, improving water productivity—output per unit of water consumed or applied—is central to adaptation and mitigation. As water is the medium through which climate change impacts are expressed, agricultural water management for enhanced water productivity is at the centre of adaptation and climate resilient agriculture (Sikka, et al, 2022). The water productivity of rice is low in South Asia compared to other countries in Asia like China, Philippines (Bouman and Tuong, 2001).

This paper presents pathways to optimize water productivity in irrigated rice systems through climate-smart practices, with a focus on Direct Seeded Rice (DSR) and Alternate Wetting and Drying (AWD) methods, amongst other practices. Using synthesis of peer-reviewed literature, secondary datasets, and use case evidence from India, Bangladesh and Pakistan, we quantify water savings, yield impacts, and greenhouse gas mitigation potential. We analyze barriers to adoption and propose recommendations for enabling conditions to shape large-scale adoption of DSR and AWD for water resilience and resilient agriculture.

WATER PRODUCTIVITY ASSESSMENT AND PRIORITIZATION: A POTENTIAL PATHWAY

Assessing water productivity, water, and carbon footprints across spatial scales is critical for identifying and prioritizing hot spots to optimize water productivity. With increasing water scarcity in South Asia, metrics such as water productivity (WP) and water footprint (WFP) are becoming important tools to guide practical and policy decisions for their scaling.

A Water Productivity Atlas of India has been developed by the International Water Management Institute (IWMI) (Amarasinghe et al. 2024) for assessing physical, economic, and nutritional water productivity and water footprints (blue and green WFP) of major crops. It is a one-stop shop that visualizes and presents spatial and temporal variations in water productivity and water footprints across districts, states, river basins/sub-basins, and national levels using large public datasets. In the recent update of the Water Productivity Atlas, energy productivity has also been included for groundwater-pumped rice irrigated areas.

Similarly, Water Productivity Atlas of Pakistan has been developed for Punjab, Pakistan⁴, intended to help in improving water, food, and climate planning through data-driven analysis. The atlas serves as a geospatial, data-driven platform to assess how efficiently water is converted into agricultural, economic, and nutritional outputs across different areas and cropping systems. It supports evidence-based planning by identifying where water use is productive, where inefficiencies exist, and how water-management choices in rice or alternative crops may improve outcomes across Punjab.

⁴ <https://www.iwmi.org/news/digital-tools-launched-to-improve-water-climate-planning/>

Physical water productivity (PWP) of rice shows a large variation across India (Figure 1a), varying from a low of 0.03 kg/m³ (Solapur in Maharashtra) to a high of 1.12 kg/m³ (Coimbatore in Tamil Nadu-non-traditional rice growing areas), with an average rice PWP of 0.49 kg/m³. In the predominant rice-growing regions of India, the PWP ranges from 0.11 kg/m³ (Lalitpur in Uttar Pradesh) to 0.84 kg/m³ (Ludhiana in Punjab). The total water footprints of rice vary from approximately 918 to 3552 m³/T.

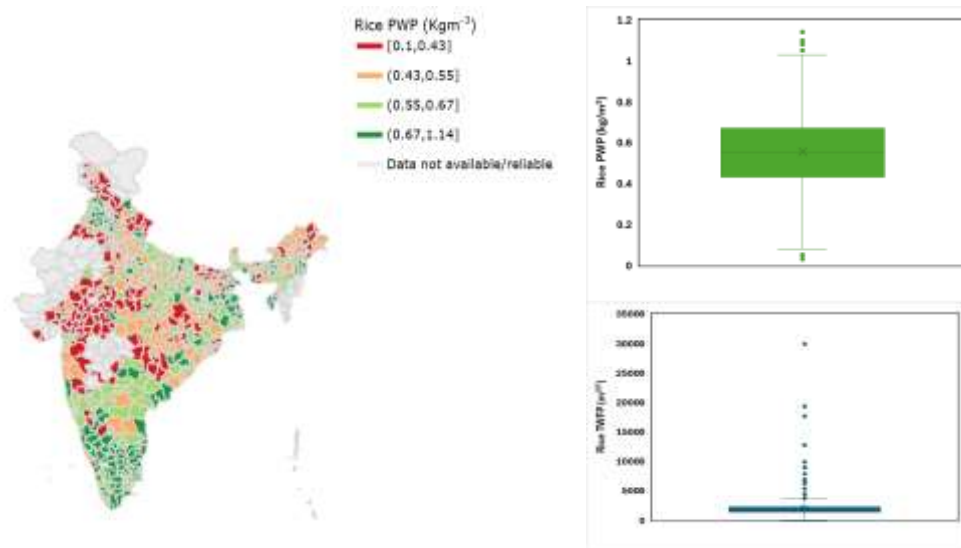


Figure 1a. Variation of physical water productivity of Rice in the Indian districts and the associated water footprint.

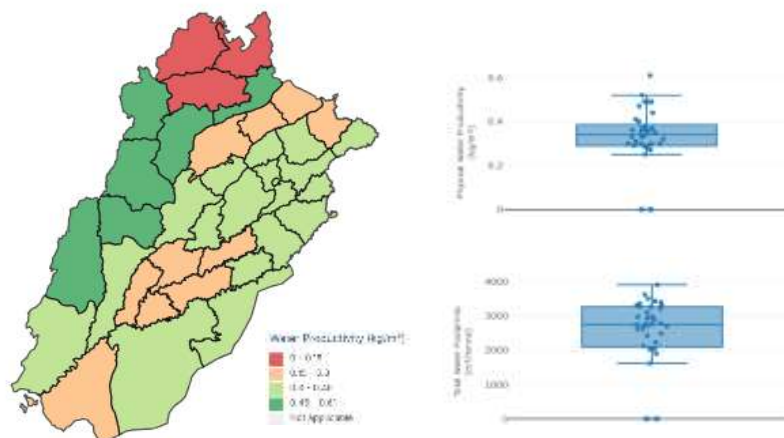


Figure 1b. Variation of physical water productivity of Rice in the districts of Punjab Pakistan and the associated water footprint.

Figure 1b shows the spatial distribution of physical water productivity of rice crop across the Punjab, Pakistan, classified into four ranges from low productivity (0–0.15 kg/m³) to high productivity (0.45–0.61 kg/m³). The accompanying boxplots showcase the variability in physical water productivity and total water footprint across administrative units. Overall, the map shows clear spatial variation, with higher productivity concentrated in selected western and central areas, while lower productivity appears mainly in the northern region.

A wide gap in PWP shows potential for prioritizing areas for optimizing rice WP and reducing water footprints by adopting context-specific AWM interventions/practices by scaling up best practices like direct seeded rice, alternate wetting and drying. The study also reveals that the major water-consuming crops, namely rice, wheat, and sugarcane, occupy 41% of the gross cropped area of India while constituting 72 % of the total water footprints. This clearly underscores the significance of agricultural water management in rice for enhancing resilience, with water productivity as its cornerstone in South Asia, prioritizing hot-spot areas and AWM practices. For instance, Figure 2a depicts large variations in PWP of rice across the eastern and northern states of Odisha and Haryana, respectively, which can help prioritize AWM interventions to optimize WP, reduce emissions, and arrest groundwater depletion.

Figure 2b compares district-level physical water productivity for rice across Pakistan's Punjab between 2001–2005 and 2022–2024. The recent period shows wider spatial coverage and generally higher productivity values, especially in western and south-western districts, while central and eastern districts mostly fall within moderate productivity classes.

In Odisha, Figure 2a clearly shows substantial spatial variation in the district-level PWP for the rice crop. While 9 districts are classified as high, 13 and 8 districts exhibit moderate and low PWP (Table 1). It is evident that high-water-productive districts are primarily located in southern Odisha and some in the northern region. On the other hand, districts such as Bargarh, Sundargarh, Debagarh, Balasore, Jagatsinghpur, Kendrapada, and Kandhamal, primarily located in the western, eastern, and coastal sides, exhibit low PWP. This variability is attributed to pronounced spatial heterogeneity in irrigation accessibility, efficiency, agronomic practices, and resource utilization across the state. Further, by overlaying the moderate-to-severe climate-vulnerable districts with water productivity performance categories, priority districts for targeted interventions were identified in each category as listed in Table 1. In these prioritized districts, more focus can be given to water-saving irrigation practices such as 'Alternate Wetting and Drying (AWD)', 'Direct Seeded Rice (DSR)', and climate-resilient crop varieties, and precision irrigation scheduling.

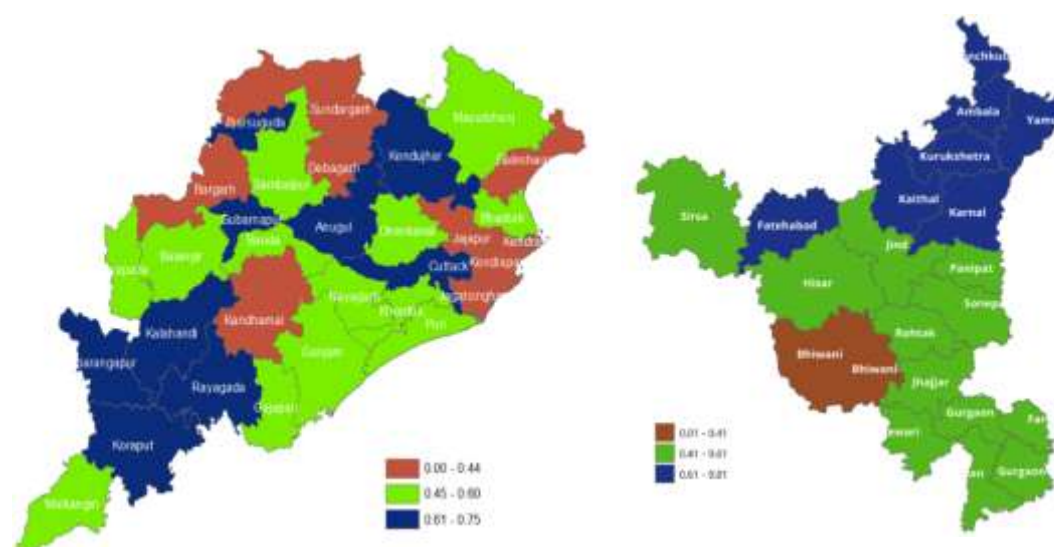


Figure 2a. Comparison of the Rice PWP in the districts of Haryana and Odisha.

This demonstrates the utility of WP Atlas as a spatial decision support tool for prioritizing targeted water management interventions in the districts. These decision support tools are designed to help inform decisions to optimize water productivity, help farmers and policymakers plan best AWM practices, crop diversification, and high-value crops for resilient agriculture.

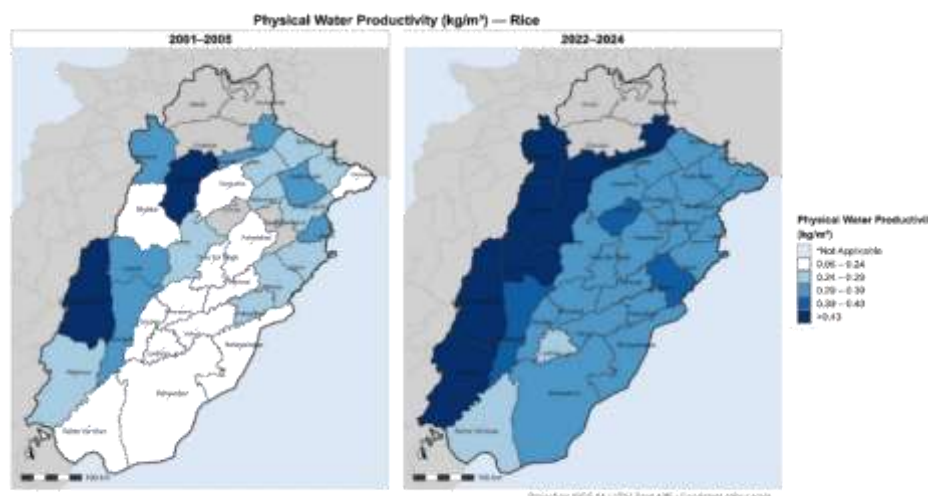


Figure 2b. Spatial comparison of physical water productivity for rice across Punjab during 2001–2005 and 2022–2024.

A pilot intervention study by Mahapatra et al. (2025), conducted in Cuttack and Ganjam districts of Odisha, demonstrated that water management interventions, such as AWD and DSR, can significantly reduce water application by 10-35% and ~ 17%, respectively, while enhancing irrigation water productivity by 25-50% and ~40%. Such interventions can help reduce groundwater abstraction and achieve climate resilience under changing climatic conditions.

The Punjab Pakistan WP Atlas provides insights into the water productivity and water use for rice crop that varies substantially across districts, with irrigation water productivity ranging from 0.09 to 0.19 kg/m³ (Akbar et al., 2025). This variation stems from excessive irrigation practices, with farmers applying 95-123% more water than actual crop requirements (Akbar et al., 2025). Spatial analysis across Punjab districts shows variability in water productivity for rice (Ahmad et al., 2004), with Gujranwala identified as the highest-yielding district and Narowal as the lowest (Gaydon et al., 2021). Priority interventions include optimized irrigation scheduling, alternate wetting-and-drying technology, laser land levelling, and adoption of drought-tolerant varieties (Nizami et al., 2020).

AGRICULTURAL WATER MANAGEMENT IN RICE

Intensive cultivation of rice especially in the semi-arid northwestern states of India, Barind area of Bangladesh and Punjab province of Pakistan with increasing dependence on groundwater irrigation has led to large scale groundwater depletion and increased energy usage in pumping groundwater. Context-specific agricultural water management (AWM) practices have therefore become critical to optimize rice water productivity, reduce water footprints and mitigate emissions for resilient agriculture in South Asia. There are many AWM interventions and our focus in this section is on the two potential AWM practices in the context of irrigated rice-direct seeded rice (DSR) and alternate wetting and drying (AWD), for enhanced water productivity, reduced blue water footprints, and reduced GHG emissions.

Direct seeded rice (DSR)

Direct seeded rice (DSR), with no or reduced tillage, eliminates nursery raising, puddling and transplanting by sowing seeds directly. It reduces water requirements and shortens crop duration. It is a feasible alternative to conventional puddled transplanted rice with the potential to save water, energy, labour and reduce GHG emissions (Pathak et al, 2011). The amount of irrigation water that goes into nursery raising, puddling, and transplanting rice is saved directly in the DSR method. DSR is reported to have irrigation water saving of about 12-33% compared to the traditional puddling method

(Kumar and Ladha, 2011; Gupta et al., 2016). Research station trials conducted in four districts of Haryana under the CGIAR Nexus Gains Initiative have reported reduced water use by 30-40% (Deb et al, 2025). However, field trials in farmers' fields found that farmers tend to over-irrigate due to fear of rainfall uncertainty and unreliable water supply as a measure against potential yield loss (Deb et al., 2025).

Table 1. List of districts under each water productivity performance category in Odisha and Haryana in India and Punjab in Pakistan

State	PWP Status	Number of Districts	District Names
Odisha, India	Low	8	Bargarh, Sundargarh*, Debagarh*, Baleswar, Jajpur, Kendrapada, Jagatsinghpur, Kandhamal*
	Moderate	13	Malkangiri*, Nuapada*, Balangir, Bouda, Sambalpur, Mayurbhanj*, Bhadrak, Dhenkanal, Nayagarh, Khorda, Puri, Ganjam, Gajapati*
	High	9	Koraput*, Nabarangpur*, Kalahandi*, Rayagada*, Sonepur (Subarnapur), Anugul, Jharsuguda, Kendujhar*, Cuttack
Haryana, India	Low	1	Bhiwani*
	Moderate	9	Rohtak, Rewari*, Faridabad, Jhajjar, Sirsa, Sonapat, Gurgaon, Jind, Panipat
	High	7	Kaithal, Fatehabad, Karnal, Panchkula, Ambala, Yamuna Nagar, Kurukhetra
Punjab Pakistan	Low	12	Rahim Yar Khan, Sargodha, Multan, Khanewal, Lodhran, Mandi Bahauddin, Vehari, Bahawalpur, Muzaffargarh, Sahiwal, Gujrat, Sialkot
	Moderate	10	Faisalabad, Gujranwala, Jhang, Sheikhupura, Pakpattan, Hafizabad, Narowal, Chiniot, Nankana Sahib, Kasur
	High	6	Bahawalnagar, Okara, Toba Tek Singh, Rajanpur, Layyah, Dera Ghazi Khan

N.B.: * indicates prioritized districts in each category

In another study conducted under the Science Policy Program of CGIAR, a multi-faceted approach including qualitative surveys with stakeholders, focus group discussions, field visits, and a large-scale quantitative survey of DSR and TPR farmers across selected districts in Haryana was employed to assess the impact of DSR. These farmer-level sources were complemented by water flow meter data analysis and remote sensing analysis (Mutum et al, 2025). The data analysis found that water application was 20% lower for DSR fields. The analysis of remote sensing data also indicated that DSR's water-saving effects are most evident in the early establishment phase and in the late vegetative/reproductive phase. 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.

DSR is recommended especially for the northwestern states of Punjab and Haryana, the rice bowl of India with significant area under rice grown with the ground water (Shah *et al.*, 2018). Continuous flooding, nitrogen fertilizers and machinery are responsible for the higher GHG emissions from conventional method of planting. Puddling and continuous submergence of rice fields facilitates the activity of methanogenesis by methanogenic bacteria, thereby increasing methane emissions (Pathak et al., 2013). There are mixed results in terms of rice yield, some findings of DSR report similar yield levels while few suggest minor yield penalty due to issues of weed management.

One of the major driving forces for the adoption of direct seeding is the scarcity of labour since direct seeding does not require labour for transplanting and can be easily mechanized. It is worth noting that during the COVID-19 pandemic, large numbers of farmers in Indian Punjab, for instance, switched to DSR during *kharif* 2020 because of labour scarcity as a result of labour migration. The area under DSR increased to 34% higher than the total area of the last decade (Chaba, 2020).

There is field-based evidence to support DSR's potential not only as an important climate resilient intervention but also to help farmers grow rice with less labour and/or during labour shortages. Overall, the findings indicate that DSR significantly reduces irrigation water use and cost of rice cultivation while improving profitability (Mutum et al. 2025). Despite the above demonstrated benefits, large-scale adoption of DSR remain low due to socio-institutional and socio-technical barriers and limited farmer awareness.

Alternate wetting and drying (AWD) method of irrigation

Alternate Wetting and Drying (AWD) is a proven agricultural water management practice for irrigated rice systems, in which rice fields are periodically dried for a few days between flooding events, unlike the predominant practice of continuous flooding. This practice of allowing soil to dry out for one to several days after the disappearance of ponded water before it is flooded again was developed in India many years ago, then known as "intermittent irrigation" (Sandhu et al., 1980; Lampayan, 2015). Its early implementation in Asia has been very site-specific.

In India, under the All India Coordinated Programme on Integrated Water Management (AICRP-IWM) of Indian Council of Agricultural Research (ICAR), multilocal field studies were undertaken to optimize the Days after Disappearance (DAD) of water for scheduling irrigation in rice across the country. Rice water productivity and water savings under continuous flooding and irrigation after 1, 3 and 5 days of drainage periods at multiple location, demonstrated irrigation water saving of 23 – 55% with 3 days de-saturation period (Upadhyaya, 2018). Rice water productivity was also found to be higher under intermittent irrigation (1-5 days) compared to submergence. This demonstrates that intermittent irrigation (with drainage periods 1-5 days) saves water and increases water productivity. Based on AICRP-IWM studies, irrigation scheduling for rice was recommended by applying 5 cm of water 3-5 days after the disappearance of ponded water (DAD). In some regions of China, irrigation was done after every 6–8 days for heavy soils and 4–5 days for lighter soils, with each irrigation of 50-60 mm (Lampayan, 2015).

Typically, under AWD, rice fields are subjected to alternate cycles of saturated and unsaturated conditions where irrigation is interrupted, and water is allowed to subside until the ponded water disappears and the soil reaches a certain moisture level (Carrijo *et al.*, 2017; Adhya *et al.*, 2014). Many researchers in Asia, including South Asia have demonstrated the potential for water saving, higher irrigation water productivity, and reduced greenhouse gas (GHG) emission from AWD irrigation practices in paddy fields (Mondal and Islam 1991, Sattar et al. 2009, Adhya *et al.*, 2014; Lampayan et al. 2015; Pathak, 2015; Sander et al. 2014, Romasanta et al. 2017, Shakoor et al. 2021, Win et al. 2021, Sikka et al, 2022). Considering the challenges of prescriptive implementation guidelines and farmers concerns, the International Rice Research Institute (IRRI) developed the field water tube (an easy-to-use and practical tool) (also called in parts of South Asia *Paani* pipe) to allow farmers to reduce irrigation water input while maintaining yield, in the form of "safe" AWD which is being used in many Asian and South Asian countries including Bangladesh, India and Pakistan.

The studies in Bangladesh observed that AWD maintained yields comparable to conventional methods (6.3–10.6 t/ha) while significantly reducing environmental impact (IRRI, 2025). Adoption of AWD in paddy fields reduced methane emissions by 34–39% and Global Warming Potential (GWP) by 33–37%, emerging as an effective strategy for mitigating climate change without compromising food security. Their findings from the 2024-25 season show that farmers saved approximately 19% of irrigation water using AWD in the Barind region of Bangladesh (IRRI, 2025). Asian Development Bank (ADB) in collaboration with IRRI and other partners, implemented a project on scaling AWD in Bangladesh (Rice Today, 2025). ADB has initiated a project with Pakistan Government in 2024 with field pilots at the Rice Research Institute, Sheikhpura, and at the On-Farm Water Management Research Farm, Okara investigating the water productivity, emissions, and adoption barriers and opportunities for adoption of AWD. In India, many on-farm/field studies have been conducted on AWD in irrigated rice areas. AWD is reported to have reduced irrigation water inputs by 23–43% and reduced global warming potential (GWP) by 45–90% compared to continuously flooded rice (Adhya *et al.*, 2014). Pathak (2015) reported a reduction in global warming potential (GWP) by 25–30% using

intermittent flooding in rice over continuous flooding. Deelstra *et al.* (2018) reported an increase in water productivity of 0.59 kg/m³ under AWD over conventional paddy rice (0.22 kg/m³) due to water saving and better yields in two districts of Telangana in the Krishna River basin. These results clearly demonstrate the effectiveness of AWD in climate-resilient agriculture under water-deficit conditions.

ICAR-Indian Institute of Water Management developed and demonstrated a sensor based automatic AWD instrument with a farmer-friendly water depth sensing system for irrigation scheduling for the implementation of AWD.

The device consists of a sensing unit and a pump control unit, and an Android mobile application which are connected to the cloud server. The depth measured by the ultrasonic sensor inside the pipe was calibrated against the actual water depth, ensuring the highest measurement accuracy. Irrigation gets started by a switch-on command from the mobile application when water level goes 10 cm below ground level, and irrigation stops when the water level reaches 5 cm above ground level. The results of the field demonstration at Darpanarayanpur and Derash canal command areas in Odisha state, India revealed that sensor-based AWD irrigation, significantly outperformed puddled transplanted rice, with irrigation water use reduced up to 24%.

Although AWD has benefits and potential, its adoption has been limited in South Asia despite its promotion, perhaps largely due to farmers' apprehensions about yield reductions, lack of awareness, lack of attractive incentives, reliability of irrigation water, amongst many reasons (Carrijo *et al.*, 2017; Alauddin *et al.* 2020; Sikka *et al.*, 2021). One of the reasons could also be the realization that water scarcity is neither physically nor economically imposed in most cases due to various policies and programmes in the interconnected water, agriculture and energy sectors. These policies and programs when working in silos may lead to unintended consequences and deserve to be investigated from the Water-Energy-Food nexus lens.

BARRIERS TO ADOPTION AND SCALING AND RECOMMENDATIONS

The results of various field and farm studies across the region clearly demonstrate the promising proposition of AWD and DSR it offers to the traditional puddled transplanted rice cultivation in South Asia, especially in water-stressed areas, to save water, increase water productivity, and reduce emissions. Governments, NGOs, and donors in India, Bangladesh, and Pakistan have taken initiatives to scale these smart interventions. However, despite the significant benefits DSR and AWD offer, widespread adoption faces challenges. In this section, based on field experiences and available studies, we discuss barriers to adoption and offer recommendations for scaling and integrating policy, technology, markets, and institutions.

Key challenges/barriers to scaling and recommendations

- **Weed Management Challenges:** Weed management is reported as one of the major challenges in DSR and AWD by farmers. DSR as well as AWD fields face higher weed pressure than traditional puddled transplanted rice (TPR). Manual weeding is labor-intensive and costly, and the scarcity of labor for weeding is a major concern.
- **Economic and Machinery Constraints:** High initial investment in DSR-specific machinery deters especially small and marginal farmers (who make up lion share). While some governments, like Haryana state, have a policy to subsidize DSR, funding is insufficient to meet demand, and access to custom hiring centers is limited.
- **Agronomic and Water Management Issues:** DSR requires careful monitoring and timely interventions to avoid yield penalties, which some farmers find burdensome. DSR and AWD are more sensitive to erratic rainfall and the reliability of timely irrigation water availability, leading to risks of poor crop establishment and/or crop growth. Limited control structures for flexible delivery of irrigation to deliver the right volume of water at the right time for the farmers.

- **Cultural and Behavioral Barriers:** Many farmers are reluctant to shift to DSR and AWD from familiar puddled transplanted rice, especially where water is abundant, and weed management is easier. Lack of awareness, capacity building, and insufficient extension support also hinder adoption, particularly among smallholders.
- **Policy and Market Issues:** Lack of economic incentives to save water. Government policies of free/cheap canal water and electricity for pumping groundwater reduce incentives to save water. Uncertainty about market prices and the lack of procurement increase perceived risk.

Recommendations for scaling DSR adoption

- **Strengthen Weed Management Support:** Develop and disseminate integrated weed management protocols (manual, mechanical, chemical, biological) tailored for DSR. Increase training for farmers on correct herbicide use and timing to reduce costs and environmental impact. Invest in R&D for herbicide-resistant rice varieties and eco-friendly weed control solutions.
- **Improve Access to Machinery and Financial Support:** Attractive incentivization for conserving water and energy, and low-interest loans for DSR machinery, especially targeting small and marginal farmers. Establish more custom hiring centers and promote Farmer Producer Organizations (FPOs) to pool resources for equipment access. Encourage public-private partnerships to develop affordable, region-specific DSR machinery and services.
- **Optimize Agronomic Practices:** Promote optimum seed rates, minimal tillage, and rational fertilizer/herbicide use through training and demonstration plots. Support research on DSR-conducive rice varieties, soil management, and water-saving irrigation techniques (e.g., micro irrigation).
- **Enhance Extension, Training, and Awareness:** Organize regular workshops, field demonstrations, and exposure visits for farmers, especially smallholders. Engage NGOs and early adopter farmer groups to support grassroots training and peer learning. In Bangladesh context, scaling AWD adoption requires shifting from Farmer Field Schools (FFS) to a Cluster FFS (CFFS) approach like DAE's synchronized block-wise irrigation to address the disconnect between pump owners and farmers while correcting misconceptions about yield loss and production costs.
- **Policy and Institutional Measures:** Review and support attractive financial incentives for DSR and AWD adoption, linking them to water and energy savings. Integrate DSR and AWD into state water management policies and align incentives with development schemes. Set up a data monitoring cell to track adoption, water savings, and economic outcomes, enabling timely policy adjustments. Link DSR and AWD adoption incentives to measure reductions in groundwater and electricity use. Facilitate carbon trading support and pass on the benefits to farmers. Prioritize transitioning from diesel pumps to solar and electric irrigation pumps.

Understanding water saving across the scales-fields, irrigation system, sub-basin/basin, and national levels is important, as the interest and purpose of water saving varies across different actors for each aggregation level. Therefore, interest in water productivity gains or water saving would vary across actors and scales and how they view these gains. Understanding incentives, the tradeoffs of different management options, and the proper alignment of incentives across various actors are key to adoption. Many incentives may even come from outside the water sector's policies, such as energy and agriculture, due to close interconnectedness.

High water productivity may not be a suitable target, where the concurrent opportunity costs or forgone values, like the alternative potentials of the saved or lost water, are not taken into account (Zoebl 2006). It is important in groundwater irrigated areas, where water is either scarce due to faster depletion of aquifers, as in the western Indo-Gangetic (IG) basin, or it is costlier to pump water, as in the eastern part of the IG basin, owing to the use of diesel-operated pumps (Sikka, 2009).

CONCLUSIONS AND WAY FORWARD

Optimizing water productivity in irrigated rice is critical for climate resilience in South Asia. The field evidence from South Asia and elsewhere indicates significant potential for DSR and AWD to improve rice water productivity, substantial irrigation water savings, and emission reductions. However, outcomes are context-specific and depend on soil type, irrigation control, and farmer capacity. Trade-offs (e.g., weed management in DSR, N₂O risks in AWD) require integrated management. Scaling success depends on aligning incentives, strengthening institutions, and ensuring access to knowledge and technology. Cross-country learning and regional knowledge exchange within South Asia can accelerate adoption.

Despite these visible benefits and ongoing efforts, the adoption of DSR and AWD is rather limited. Successful scaling of DSR and AWD will require a multi-faceted approach with concerted efforts from all stakeholders, including farmers, researchers, officials of irrigation systems, policymakers, and the private sector. By addressing these challenges and leveraging the observed benefits, scaling water productivity measures in irrigated rice can significantly contribute to a resilient agricultural production system in South Asia. Scaling adoption of DSR and AWD at scale should stress on developing scalable business models involving rural youth and women, local entrepreneurs, attractive incentives, creating effective custom hiring centres for scale-appropriate mechanization, building partnerships, and enhanced capacity development of all stakeholders.

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