Rocky road for direct-seeded rice: understanding the adoption barriers of this climate resilient technology

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Direct-seeded rice (DSR) offers several advantages over puddled transplanted rice (PTR), yet inconsistent adoption persists due to systemic gaps in farmer knowledge, skills and institutional support. Key challenges include imprecise land levelling, high seed rates, inefficient herbicide application and improper irrigation practices. Manual broadcasting and delayed weed control result in uneven crop geometry, increased production costs, yield penalty and reduced farmer confidence. Irrigation methods like sprinklers or alternate wetting and drying are recommended for DSR, yet farmers often replicate PTR's continuous flooding, negating water-saving benefits. DSR feasibility is region-specific, contingent on soil texture, water availability and agroclimatic suitability. Scaling DSR requires targeting ecologically suitable regions and integrating technical, educational and policy interventions. Farmer-centric strategies (on-farm training, field demonstrations and peer learning) can address knowledge gaps. Policy measures, such as subsidies for seed drills, laser levellers, and weeders, alongside custom hiring centres, can enhance access to critical equipment. Financial incentives linked to water savings or emission reductions (carbon/water credits) may further motivate adoption.

Rice cultivation originated with direct seeding, a labour, water and energy-efficient method suited to rainfed ecosystems. As societies mastered irrigation, puddled transplanted rice (PTR) emerged as the golden standard. By flooding fields, farmers suppressed weeds, retained moisture, and boosted yields. Transplanting seedlings post-monsoon shielded crops from floods, while mechanisation entrenched PTR adoption. However, water scarcity, labour shortages, and climate pressures have reignited interest in direct-seeded rice (DSR). DSR reduces water use by 30%, labour and energy costs by 50% and 30% respectively, and methane emissions by 40% (1.5–4.0 tons of CO_2 equivalent per hectare). Innovations like precision seeders, broad-spectrum herbicides, and their flexible application windows bolster its feasibility. Governments now champion DSR as a climate-smart alternative, offering subsidies to accelerate adoption. In India, COVID-19 labour crises in Punjab and Haryana states, and water shortages in Chhattisgarh, accelerated the adoption. Yet, post-pandemic, Punjab's DSR acreage sharply declined, and Odisha's traditional direct-seeding areas contracted. This volatility exposes systemic barriers, viz. flawed practices, fragmented policies and entrenched mindsets.

Many farmers lack awareness of optimal DSR practices such as sowing timing, seed rates, land preparation, and nutrient/water management. Broadcast sowing, poor seeding depth, uneven moisture, and bird/pest damage lead to patchy germination, sub-optimal plant density, and irregular crop geometry. Farmers are less aware of the importance of line seeding and the seed drills available for DSR. Even when known, their high cost and limited availability, especially for smallholders, hinder adoption. High upfront investments in equipment and herbicides, coupled with insufficient training on calibration and usage, further deter farmers.

The most glaring hurdle in DSR is weed control. Unlike PTR, where continuous flooding suppresses weeds, DSR's aerobic soil allows multiple weed flushes (3–4 vs. 1–2 in PTR), overwhelming young rice plants. Farmers often fail to apply the correct herbicide at the right time, leading to higher weed pressure in DSR. In some cases, farmers apply it at an excessive rate, leading to herbicide toxicity, increased production costs, environmental harm, and escalated risk of the development of herbicide-resistant crops. To combat weeds, farmers often use excessive seed rates ($\sim$100 kg/ha vs. the recommended 25–30 kg/ha). However, it intensifies competition among rice plants and reduces yield attributes like tillers/m^2, panicle length, and filled grains.

Farmers fail to understand the importance of laser land levelling, minimum disturbance to the topography while sowing and spraying herbicides. In wet DSR systems, even seed drills displace soft mud, creating small ridges on both sides of a drill (aerated zones favouring weeds) and depressions while turning (waterlogged areas drowning rice seeds). Farmers unknowingly disturb the topography while broadcasting seeds and spraying herbicides. DSR demands precision land levelling and minimal disturbance to the field topography during sowing and herbicide application to achieve optimal and uniform rice stand establishment. While laser land levelling remains unaffordable for many, basic tools and techniques can be used to ensure

Figure 1. Major challenges faced by farmers in the direct-seeded rice (DSR) system. (***a***) Inconsistent seedling growth despite being sown on the same date, which is a result of intense competition. (***b***) Suboptimal plant density and weed infestation are critical factors largely responsible for low productivity in DSR. (***c***) Nitrogen and Iron chlorosis, a common nutrient deficiency, especially at the seedling stage in DSR. (***d***) Sprinkler irrigation in DSR to ensure a uniform and optimal crop stand. (***e***) Rice seedling infested with root-knot nematodes grown under the DSR method in light-textured soil. (***f***) The overcrowding of rice seedlings due to high seed rate in DSR. (***g***) Uneven field topography, which leads to poor germination in waterlogged areas, and weed proliferation on shallow ridges. The image also shows flood irrigation in DSR, which leads to the displacement of rice seeds and disturbed crop geometry. (***h***) Volunteer rice, a persistent issue in subsequent seasons under rice–rice system.

uniform topography and minimal disruption.

Farmers often delay rice crop sowing until the monsoon arrival and choose medium-duration varieties (130–135 days), despite the increased risk of early-stage waterlogging and poor germination (Figure 1). For post-monsoon sowing, it is recommended to grow short-duration varieties (110–120 days) to minimise climate risks. In Punjab, for example, the PR126 variety has performed better and gained popularity due to its short duration. If a farmer wishes to grow a medium-duration variety, it is advisable to sow 2–3 weeks before the monsoon. This allows for crop establishment before heavy rains, preventing early waterlogging, but requires supplemental irrigation, laser land levelling, and seed priming to ensure good germination and establishment.

Flood irrigation in DSR elevates the risk of seed and seedling mortality in uneven fields. In contrast, sprinkler irrigation mitigates the problem of waterlogging, even in fields with poor topography. Therefore, employing sprinkler irrigation, especially during the early stages of crop establishment, is paramount for water conservation and ensuring a uniform and optimum crop stand. Farmers often equate DSR with lower yields, despite research showing parity with PTR under optimal management. DSR outperforms traditional rainfed upland practices but falters in flood-prone wetland conditions. Farmers hesitate if neighbours report failures or lack confidence. Misleading comparisons worsen perceptions, and peer influence amplifies scepticism.

DSR is not a one-size-fits-all solution. Soil suitability is critical – medium/heavy soils (e.g. alluvial loams) perform best, while light-textured soils (e.g. Punjab's sandy loams) risk nematode infestations and increase irrigation water use. Similarly, heavy clay soils are prone to surface sealing and make it difficult for seeders to operate, potentially clogging or not planting seeds at the desired depth. Also, clay soil causes waterlogging as it has good water retention capacity and negatively impacts seedling establishment if heavy rain occurs after sowing. DSR is highly sensitive to the timing of rainfall. Heavy rains immediately after sowing negatively impact germination and early crop establishment. Therefore, a national DSR suitability map, factoring in soil type, water access and rainfall patterns, is urgently needed.

DSR showed increased vulnerability to certain pests and diseases, although this varies depending on the specific conditions and management practices. For example, root nematode infestation is exacerbated in light-texture soil of Punjab, combined with practices like Sesbania green manuring (Figure 1). Again, this risk was poorly communicated to farmers.

Farmers have inherited generations of expertise in PTR, mastering practices like water management and manual transplanting through decades of tradition. In stark contrast, DSR demands an entirely new skill set, one requiring precision in sowing, herbicide application, and irrigation scheduling. This abrupt shift leaves most farmers unprepared, necessitating urgent, large-scale training through on-farm demonstrations, field days, and video-based extensions. Critically, these programmes must prioritise ecologically suitable regions, such as water-stressed areas or non-floodplain zones where DSR's water-saving benefits align with local needs, rather than scattering resources indiscriminately.

Similarly, policy interventions must adopt a laser focus. Financial incentives (e.g. subsidies for seed drills, herbicide discounts) should target farmers in high-potential DSR zones, while carbon and water credit systems must recognise and reward ecological gains. For instance, paying farmers ₹ 1,500–2,000 per acre for verified reductions in methane emissions or water savings would directly link adoption to economic benefit. By streamlining credit transfers through platforms like India's National Carbon Registry, governments can transform DSR from a risky experiment into a financially viable choice. This two-pronged approach (geographically tailored training and precision policy incentives) ensures resources align with regional agroecology, accelerating adoption while avoiding the pitfalls of one-size-fits-all strategies.

Emerging technologies offer promising solutions to DSR's persistent challenges. Unmanned aerial vehicles (UAVs), for instance, enable seed sowing, herbicide spraying and fertiliser broadcasting without damaging field topography or seedlings. By automating these tasks, UAVs slash labour demands, reduce energy costs, and minimise farmers' exposure to hazardous pesticides. Complementing these advancements, non-GM herbicide-resistant rice cultivars, such as Pusa Basmati 1979, Pusa Basmati 1985, Sava 127 FP, Sava 134 FP, and CR Dhan 807, simplify weed control in DSR systems. These varieties, engineered for resistance to imazethapyr herbicides, allow targeted weed management without harming crops. However, their success hinges on integrating this trait into locally preferred DSR cultivars and enforcing strict stewardship protocols.

Farmers must adhere to guidelines, such as herbicide rotation, integrated weed management, manual removal of escaped weeds, rotating with non-imazethapyr-resistant rice varieties every two years, and buffer zones, to delay resistance development in weeds. Together, UAVs and herbicide-resistant rice could address DSR's twin bottlenecks – topographic precision and weed management. Yet, their adoption requires parallel investments in farmer training and policy frameworks to ensure equitable access and sustainable use.

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