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REVIEW ARTICLE

Direct seeding in rice: Current innovations, agronomic perspectives and future opportunities for global adoption

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Abstract

Traditional puddle-transplanted rice cultivation faces increasing constraints due to climate change, declining water availability and acute labour shortages. Additionally, the management of nurseries for transplanting is labour intensive and requires intensive care and supervision, further complicating its adoption under modern agricultural conditions. In response to these challenges, alternative rice establishment techniques are being explored to sustain productivity while using reduced resource inputs. Among these, directseeded rice (DSR), including wet and dry seeding methods, offers a viable and sustainable alternative. Specifically, dry direct seeded rice has emerged as a promising technique that conserves water, reduces labour requirements, minimizes greenhouse gas emissions and enhances adaptability to climatic variability. With appropriate agronomic management, DSR can achieve yields comparable to conventional transplanting methods. Despite being farmer-friendly and cost-effective, its widespread adoption is constrained by challenges in weed control and crop establishment. Recent advancements in precision technologies, mechanization and integrated crop management have shown strong potential to overcome these barriers, leading to improved productivity, profitability and resource-use efficiency. This review consolidates research evidence and technological interventions on DSR, emphasizing its agronomic practices, advantages, challenges and future prospects. The findings not only demonstrate the eco-efficient and resource-conserving nature of the DSR package but also underline its practical relevance for farmers and its policy significance in promoting sustainable rice intensification. The article aims to provide comprehensive insights into DSR while offering directions for innovations that can accelerate its large-scale adoption across diverse agro-ecological regions.

Keywords: dry seeding; greenhouse gas emissions; labour intensive; precision technologies; resource-use efficiency; sustainable rice intensification

Introduction

Rice (*Oryza sativa L.*) is the staple food of India with more than 2/3 of the population depends on rice and rice derivatives for food. It has a cultivated area of 47.82 million hectares and a production of 2800 kg/ha (1). Traditionally, rice is grown in the wetlands, which significantly alter ecosystems and this requires intensive nursery management, soaking pits and planting operations. However, in rain-fed ecosystems, direct seeded rice provides an alternative to conventional rice during the *Kharif* season. Direct seeding of rice has the advantages of 34 % energy saving (2), fast and easy reduction of energy during planting, early ripening of crops 7-10 days and reduced the amount of water required by 12-35 % (3), high tolerance to water scarcity, generally leads to higher yields, production costs can be saved 29 % (4). Plants not only compete with crops for space, light, water and nutrients but also affect crop quality. At the beginning of plant development, the emergence of crop plants causes a lot of damage due to the high competitiveness of the plants, while at the time of emergence, when it reaches the next stage, damage will be minimal. Therefore, timely management of weeds is important for DSR (5).

Due to the inefficient use of inputs like fertilizer, water and labour, the increasing scarcity of resources, particularly labour and water, the unforeseen climate change, the sudden energy crisis and the rising cost of fuel, as well as the emergence of socioeconomic changes like urbanization, labour migration, preference for non-agricultural work and worries about pollution related to farms, the efficiency and long-term viability of rice-based systems are increasingly threatened (6). Puddling offers some benefits for rice, because it reduces weed infestation, promotes seedling growth, minimizes water percolation losses and creates anaerobic conditions that boost nutrient availability. However, frequent puddling damages soil aggregates, lowers subsurface layers and creates hard pans at shallow depths, all of which have a negative impact on the physical characteristics of the soil (7). Additionally, rice farming is less economical due to the high labour and water requirements of transplanting and puddling, both of which are becoming more expensive and scarcer. Water-intensive agriculture, growing labour expenses and growing water shortages have prompted a quest for new farming practices that can improve water efficiency (8). The only practical solution to these issues is direct seeded rice (DSR). DSR is the process of cultivating seeds in the field instead of transplanting them from a nursery. Direct sowing can be done by planting the seeds in soil (irrigated sowing) or in standing water (irrigated sowing), or in a prepared seedbed (dry sowing) before planting. Short-term productive varieties, nutrients and weed control have encouraged farmers to switch to DSR farming from conventional farming. Benefits of broadcasting include lowering carbon emissions, assuring the growth of the following crop and conserving time, labour, energy and water (9).

Globally, DSR is implemented in diverse ways, with each region adapting practices to local conditions such as water management, weed control, fertilizer application, seed rates, establishment techniques and tillage methods (10). Over the last decade, research has increasingly focused on reducing tillage intensity, optimizing inputs and developing locally adapted DSR technologies (11). This review synthesizes recent advances in DSR agronomy, compares wet-DSR, dry-DSR and water seeding systems with conventional puddled transplanting and highlights key research gaps and innovations in weed management, mechanization and climate-resilient practices to support large-scale, sustainable adoption across diverse agro-ecological zones.

Methods of DSR system

Direct seeding of rice system is broadly categorized into wet-DSR and dry-DSR, depending on soil conditions and the method of seed establishment. Wet-DSR involves sowing pre-germinated rice seeds on moist soil, either by broadcasting or line-sowing. When these seeds are placed on the surface of puddled soil, they experience an aerobic germination environment, commonly referred to as aerobic wet-DSR (12). In contrast, anaerobic wet-DSR occurs when pre-germinated seeds are drilled or sown into puddled soil, leading to a predominantly anaerobic seed environment. Various equipment, such as drum seeders or anaerobic seeders with furrow openers and closers, facilitates seed placement in both aerobic and anaerobic wet-DSR systems (13).

On the other hand, dry-DSR involves sowing dry rice seeds onto unpuddled soil, typically after dry tillage or zero tillage. This can be done either by broadcasting seeds on raised beds, drilling them in rows using power tiller-operated seeders, or employing the dibbling method in well-prepared fields. Dry-DSR is increasingly preferred in areas facing water scarcity as it eliminates the need for puddling (14). Another distinct DSR approach is water seeding, where rice seeds are allowed to sprout before being broadcast into standing water. This method is particularly useful in regions where early flooding is common and water cannot be drained from the fields. Water seeding is widely adopted in the United States, primarily to aid weed management, as it helps suppress weeds that are otherwise difficult to control (15). The rice varieties used for this method are highly adaptable to stress conditions such as low light and reduced oxygen levels.

The adoption of wet-DSR has gained momentum in several countries, including Sri Lanka, Malaysia, Vietnam, Thailand and Philippines, as it helps mitigate labour shortages (16). Dry-DSR is rising due to increasing water constraints. While dry-DSR is predominantly used in rainfed upland regions of Asia, its application in irrigated areas remains limited. Both wet-DSR and dry-DSR methods offer significant advantages over conventional puddled-transplanted rice cultivation, particularly in terms of water and labour savings. Research conducted in the Philippines found that wet-DSR reduced water consumption by 67-104 mm (11-18 %) compared to puddled-transplanted rice, under similar irrigation conditions (17). In Malaysia's Muda region, irrigation water usage in dry-DSR was approximately 200 mm (40 %) lower than that of puddled-transplanted rice (18). Additionally, studies in India suggest that DSR can lead to water savings ranging from 10 - 50 %. Besides conserving water, DSR significantly reduces labour requirements. It has been observed that direct seeding minimizes total labour demand by 11 - 66 % compared to puddled-transplanted rice. Specifically, the labour requirement for rice crop establishment drops by more than 75 % when switching from transplanting to direct seeding (19). Table 1 presents a comparative summary of the different DSR types highlighting their key features, advantages and limitations.

Production technology for DSR

In DSR, the basal fertilizer combination should be added at the time of puddling. Intermittent field wetting is recommended to prevent seedling desiccation caused by water stress following germination. Water is pumped when seedlings reach a height of around 5 cm (about 1 week after sowing), to stop weeds from germinating and seedlings from drying out (20). When adopting this approach, stand establishment is influenced by field

Table 1. Comparative summary of DSR types

DSR type	Key features	Advantages	Limitations/challenges
Wet-DSR	Pre-germinated seeds sown on moist or puddled soil; aerobic or anaerobic conditions	•Faster crop establishment •Less labour requirement •Moderate water savings (11-18 %) •Suitable for mechanization	•Weed pressure is higher than transplanting method •Requires good land levelling •Seed damage risk if soil dries early
Dry-DSR	Dry seeds sown on unpuddled soil via drilling, broadcasting or dibbling	•Eliminates puddling •Conserving 10-50 % water •Labour saving >75 % •Suitable for water-scarce areas	•High weed infestation risk •Uneven germination if the soil moisture is low •Nutrient deficiencies are more
Water seeding	Pre-sprouted seeds broadcast into standing water	•Effective suppression of weeds •No need for field drainage before sowing •Suitable for flood-prone areas	•Limited to stress-tolerant varieties •Less common outside specific ecologies

preparation quality, weed competition, water management and rainfall over the first several days after sowing. The following elements have a major role in maximizing DSR productivity when it is irrigated.

Land preparation

Preparation of land is a prerequisite for effective crop husbandry. DSR begins with proper field preparation. Effective land preparation promotes uniform crop establishment, helps with drainage and water control, lowers irrigation water requirements, expands cultivable area by reducing bunds, improves input efficiency (fertilizers, agrochemicals, water, etc.), boosts crop yield and inhibits weed growth (21). The introduction of laser-assisted precision field levelling in 2001 marked a significant advancement for alternative tillage and crop establishment techniques in the area. Enabling planters and drills to put seed at a regular depth and distance guarantees improved crop establishment and leads to accurate water control, consistent crop stand and increased pesticide use efficiency (22). During the summer, ploughing the fields helps to control weed infestation. Precision land levelling has shown benefits in DSR technology, including improved germination, weed control, uniform irrigation, significant water savings and increased water use efficiency, all of which led to an improvement in grain output (23).

Time of sowing

The timing of sowing is a critical factor for success in DSR crops during the primary rice growing season (*Kharif*). Crops should be sown 10-15 days before the start of the monsoon season. The crop should have two to three leaves before it starts to rain. This would allow the crop to readily compete with growing weeds by facilitating the early root establishment. It would also allow for the timely seeding of the next wheat crop (24). Since the monsoon arrives at different times in many regions, it is best to adjust the sowing schedule and complete the seeding between the end of May and the third week of June.

Selection of varieties

Cultivar selection is crucial to achieving the intended yield. The types of soil and irrigation water determine the choice of cultivars. Early to medium duration types (100-135 days) may be preferred in light textured sandy loam soils with irrigation; medium to late maturing varieties (135-165 days) should be grown on heavy textured clay soils (25). Table 2 lists the varieties appropriate for various DSR ecosystems.

Seed priming

Seed priming is a practical and effective short-term approach to mitigating the impact of drought stress (27). In direct seeded rice, where seeds are sown at shallow depths (typically less than 2 cm) before the onset of monsoon rains, inadequate soil moisture often poses a challenge to uniform germination and crop establishment (28). Seed priming, a pre-sowing hydration method, involves partially hydrating seeds to enhance metabolic activity and promote germination without allowing radical emergence, thus maintaining seed viability (29). Primed seeds generally exhibit improved germination rates, faster and more uniform seedling emergence, enhanced growth, increased dry matter accumulation and better overall crop performance, including higher yield and harvest index (30). In some cases, seed priming also leads to a higher total germination percentage (31). Several seed priming techniques, such as hydro-priming, on-farm priming, osmo-hardening, hardening and priming with growth regulators and vitamins, have been successfully implemented in DSR to improve seed emergence, yield and crop quality (32).

In the early stages of vegetative growth, the application of *Azospirillum* treatment produced the largest shoot to root ratio and the largest number of tillers. To some extent, seed priming helps lower the seeding rates in DSR. Furthermore, higher levels of soluble sugars and enhanced alpha-amylase activity were linked to faster and more consistent seedling emergence from primed seeds (33). The physiological alterations brought about by osmo-hardening (KCl or $CaCl_2$) enhance starch hydrolysis, boosting the quantity of sugars accessible for kernel synthesis, embryo growth and quality characteristics at maturity. Osmo-hardening with potassium chloride (KCl) significantly enhanced the yield and overall performance of direct seeded medium-grain rice (34). The treatment resulted in higher kernel yield (3.23 tons/ha), straw yield (9.03 tons/ha) and harvest index (26.34 %) compared to untreated control plants, which produced a kernel yield of 2.71 tons/ha, straw yield of 8.12 tons/ha and a harvest index of 24.02 %. Furthermore, osmo-hardening with calcium chloride ($CaCl_2$) was found to improve the uptake of essential nutrients such as calcium, potassium and phosphorus, with KCl treatment following closely in effectiveness. These findings suggest that osmo-hardening with either $CaCl_2$ or KCl can enhance crop establishment, growth, productivity and quality in direct seeded rice systems, making it a beneficial practice for farmers (35).

Seed treatment with fungicides and insecticides

Seed treatment with appropriate fungicides is a crucial step in managing seed-borne diseases such as loose smut, false smut, root rot, collar rot and stem rot. To achieve effective disease control, seeds should be soaked in a fungicidal solution before sowing. The seeds are immersed in a solution containing carbendazim (Bavistin) at a rate of 2 g per kg of seed, with the volume of water used for soaking being equal to the volume of the seeds (36). The seeds should remain in the solution for 24 hrs, after which they are removed and left to dry in the shade for one to 2 hrs before being sown in the field. In addition to disease management, it is equally important to monitor insect pest infestations in the field.

In areas where termites and other soil-borne pests pose a significant threat, treating seeds with insecticides can be highly beneficial. A recommended approach is to use imidacloprid (Gaucho 350 FS) at a dosage of 3 mL per kg of seed, either alone or in combination with tebuconazole (Razil Easy) at 0.3 mL per kg of

Table 2. Varieties suitable for direct seeding of rice in different rice ecosystems

DSR ecosystem	Varieties
Upland	CR Dhan 100 (Satyabhama), Ankit, CR Dhan 103 (Pramod), Unnat Vandana, Phalguni, CR Dhan 807, CR Dhan 808, Kalinga III, Anjali, PMK 3, Lalat, Khandagiri, Heera
Medium land	Pyari, CR Dhan 201, CR Dhan 202, CR Dhan 203 (Sachala), CR Dhan 204, CR Dhan 205, Gopinath, CR Dhan 211, Naveen, IR64, ADT 45, CO 52
Low land	CR Dhan 802 (Subhas), CR Dhan 317 (Roshan), Pooja, CR Dhan 414 and CR Dhan 702, Swarna Sub1, MTU 1010, ADT 47, IR64-Sub1, CO 51, Jalkunwari, Savitri

Source: (26)

seed. The combined treatment is particularly effective in providing protection against both insect pests and soil-borne fungal pathogens, ensuring better crop establishment and health (37). By implementing proper seed treatment strategies, farmers can significantly reduce the incidence of seed-borne diseases and soil-borne insect infestations, ultimately leading to improved crop productivity and sustainability.

Seed rate, row spacing and seeding depth

The ideal seed rates for coarse grains, 20-25 kg/ha, hybrids and fine grains, 15-20 kg/ha, are all achieved using zero till ferti-drill sowing. It is highly helpful to utilize planters with slanted plate devices or a cupped metering system to reduce seed rate and maintain optimum spacing of 20 cm (38). A greater seed rate (25-30 kg/ha) is needed for broadcasting. The depth of the seed is crucial for successful germination. The depth needed to achieve the required crop stand level should not be greater than 3 cm. The dynamics of seed emergence are negatively impacted when seeds are planted lower than 3 cm because the soil moisture in the upper layer dries out quickly (39).

Drone seeding in direct seeded rice (DSR)

DSR is an emerging precision agriculture innovation aimed at improving the efficiency and sustainability of rice cultivation. Traditional transplanting methods require significant labour, large volumes of water and longer operational time, whereas drone seeding directly delivers rice seeds into the soil with speed and precision. This approach offers multiple benefits, including reduced labour costs, more efficient seed distribution and improved resource management (40).

Drone seeding utilizes unmanned aerial vehicles (UAVs) equipped with seed dispensers to distribute rice seeds across a field evenly. Unlike conventional transplanting, which involves raising nurseries and manually transplanting seedlings, drone-based DSR eliminates nursery costs and reduces establishment time. Uniform seed placement enhances crop stand density and establishment, leading to potential yield increases of 5-15 % over poorly sown fields (41). In addition, drone seeding can cover 6-8 hectares per hour, compared to 0.4-0.5 hectares per day for manual transplanting, significantly addressing labour shortages and reducing operational bottlenecks (42). Cost- benefit insights of drone seeding in DSR are:

- In regions with high labour costs, drone seeding has reduced establishment costs by 20-30 % compared to manual or mechanical sowing.
- In a trial in Punjab, India, drone seeding reduced crop establishment time from 5 days to less than 1 day for a 25 ha farm, enabling timely sowing and better weed control.
- Studies from China and Vietnam report yield increases of 4-12 % due to improved stand uniformity and optimal plant spacing achieved through precision seeding.
- Precise placement of seeds in dry or moist soil eliminates the need for continuous flooding, leading to water savings of 15-25 % while reducing methane emissions (43).

Despite its advantages, drone seeding presents challenges such as high initial investment costs and the need for technical training. Small-scale farmers may face financial barriers in adopting this technology. Furthermore, regulatory policies on drone usage may limit widespread implementation. However, with government support, subsidies and training initiatives, drone seeding can become more accessible and revolutionize rice farming worldwide (44).

Water management

Water management is important for the growth of crops at every step, including active tillering, panicle initiation, blooming and seedling emergence. In dry drill-seeded rice, proper water management is very important during the crop establishment phase (first 7-15 days after sowing). From seeding to emergence, the soil needs to be kept damp but not soggy to prevent seed rotting (45). If it is unlikely to rain after sowing in dry soil, it is imperative to use flush irrigation to moisten the soil before flooding the field at the three-leaf stage. This procedure will guarantee strong roots, promote the establishment of seedlings and improve weed germination (46). To prevent weed emergence and growth, early weed management using a potent pre-emergence herbicide will be feasible.

In many regions across India, pre-monsoon rains typically occur between mid-May and mid-June, providing a favourable window for implementing stale seedbed techniques in direct seeded rice. This method involves preparing the seedbed in advance and using non-selective herbicides, such as glyphosate and paraquat, to eliminate the initial flush of weeds before seeding. By doing so, rice crops can be directly sown using a zero-till machine, reducing the need for extensive soil preparation and conserving moisture (47). However, if rainfall is insufficient during this period, surface irrigation may be required before seeding to ensure optimal soil moisture levels. Ideally, the soil should remain moist but not waterlogged from sowing until seedling emergence (48). Once the crop has emerged, irrigation is generally unnecessary, except for one or two supplemental irrigations between the onset of the monsoon and the early growth stage, ensuring proper crop establishment (49). This approach not only facilitates effective weed management but also enhances water-use efficiency, making it a sustainable alternative to conventional transplanting methods in rice cultivation.

When it comes to the dry DSR crop establishment phase, precise field levelling is crucial for simple drainage and equal water distribution. Poor drainage and water management increase the risk of early crop failure (50). In addition to preventing leaks and seepage, bund management is crucial for preserving a constant water depth. After sowing, the bunds need to be prepared as soon as possible. This includes plastering up any cracks or holes (51). Indiscriminate usage of groundwater and surface water for diverse agricultural, domestic and industrial uses is declining the amount of water that is available worldwide. By 2025, approximately 50-55 % of the water that was accessible for agriculture in 1993 is expected to remain so. Precise water management in the first 7-15 days following seeding in the field is crucial for crop establishment. Seed rotting can be prevented by making sure the field doesn't become too wet.

Nutrient management

The main elements controlling the nutrient dynamics in transplanted puddled rice and DSR systems are water management and land preparation. DSR land has different nutritional dynamics than transplanted puddled rice since it is frequently prepared in dry soil and stays aerobic over the crop season. Significant research efforts have been directed toward improving fertilizer use efficiency in transplanted puddled rice systems. However, relatively limited work has focused on optimizing nutrient management practices for direct seeded rice (52). While the total nitrogen (N), phosphorus (P) and potassium (K) requirements remain similar for both systems, DSR typically demands a slightly higher nitrogen application, ranging from 22.5 to 30 kg/ha. This additional N compensates for the extended crop duration in DSR fields and mitigates early-stage nitrogen losses caused by volatilization and mineralization, which reduce nitrogen availability (53).

During seed sowing in DSR, a basal application of one-third of the total nitrogen, along with the full dose of phosphorus and potassium, is recommended. The use of a seed-cum-fertilizer drill or planter enables precise fertilizer placement beneath the seeds, enhancing fertilizer use efficiency while improving crop germination and establishment rates. However, dry-DSR systems experience greater nitrogen losses and lower nitrogen availability, necessitating higher nitrogen application (54). To address this, efficient nitrogen management strategies should be developed and integrated into farmers' practices. One potential solution is the use of slow-release fertilizers (SRF) or controlled-release fertilizers (CRF), which gradually release nitrogen, minimizing losses and ensuring nutrient availability throughout critical crop growth stages. These fertilizers provide a "one-shot dose" of nitrogen, aligning with the crop's nutrient uptake pattern more effectively (55). Additionally, potassium application through split doses is beneficial, particularly in medium-textured soils. Research suggests that applying 50 % of the total potassium as a basal dose and the remaining 50 % at the panicle initiation stage improves nutrient uptake and crop performance (56).

Iron deficiency is another common issue in DSR, particularly in light textured and sandy loam soils. This deficiency manifests as iron chlorosis in leaves, which can be alleviated through ferrous sulfate ($FeSO_4$) application. Basal application of fertilizers such as NPK (12:32:16) and diammonium phosphate (DAP) (18:46:0) is typically done using a fertilizer-drill machine. However, the hygroscopic nature of urea often results in improper drilling, necessitating its use as a top-dressed nitrogen source (57). In some cases, symptoms of iron deficiency observed at later crop growth stages may be attributed to cereal cyst nematodes. If root examination reveals gall formation, it is advisable to avoid growing DSR in affected fields in the future (58). Additionally, addressing sulfur deficiency requires the application of 2 kg/ac of sulfur to the soil to ensure optimal crop growth and nutrient balance. Efficient fertilizer management in DSR systems is essential for optimizing nutrient use, minimizing losses and improving overall crop productivity. By implementing advanced nutrient management techniques, such as controlled-release fertilizers, split potassium applications and targeted micronutrient supplementation, farmers can enhance fertilizer efficiency and achieve sustainable rice production (59).

Weed management

In DSR, weeds pose a serious threat during the rainy season and poor weed control has resulted in a significant reduction in grain productivity. Standing water in puddled transplanted rice prevents weeds from growing. Conditions in DSR are more conducive to weed germination, which causes significant yield losses in rice by competing with it for nutrients, moisture and sunlight (60). Table 3 enumerates the significant weeds connected to irrigated direct seed rice crops.

Keeping DSR crop-weed free for the duration of the crop cycle is exceedingly tough and rather uneconomical. Glyphosate (at 0.5 % two days before planting) or one or two extremely shallow ploughings (stale seed bed method) can be used to suppress pre-germinated weeds. The second flush of weeds can be physically eradicated (64). It is proven that the best grain production of DSR was obtained in weed-free conditions that were provided between two and six weeks after sowing.

Mechanical weed management: Mechanical weeding can be performed using sophisticated tools, like as mechanized cono-weeders, or it can be done by hand. The process of manual weeding entails removing the weeds from the ground. This requires weeds to grow to a size that makes them easy to pull, which takes 25-40 DAS and reduces yields. Due to the inefficiency of weed control, the declining trend in labour availability and the rise in wages, this is practically and economically not practicable on a commercial scale (65). Farmers were forced to consider mechanical weed management methods due to the growing need for labour, rising pesticide costs and phytotoxicity impacts. The benefits of mechanical weeding included low cost, little pollution, no aftereffects and a reasonably safe working environment for the operator. Compared to hand weeding, rotary weeding resulted in a 9.9 % increase in crop yield/ha. Using a mechanical weeder increased yield by 22-24 % (66). Under mechanical hoeing, rice output increased by 25 % over an unweeded check and the greatest weed suppression was achieved; statistically, this result was comparable to hand weeding.

Cultural weed management:

Stale seedbed technique: This weed-management method encourages weeds to come up by lightly irrigating the area one month before the rice is sown. Once the weeds sprout, they can be eradicated using tillage or non-selective herbicides like glyphosate or paraquat. It is believed that this technique can control weeds by up to 53 %. This technique not only reduces weed emergence but also decreases the number of weed seeds

Table 3. Important weeds associated with direct seeding rice crop

Weed group	Weed species
Grassy	*Echinochloa crus-galli* (Barnyard grass), *Echinochloa colona* (Jungle rice), *Leptochloa chinensis* (Chinese sprangle top), *Ischaemum rugosum* (Wrinkled duck-beak), *Dactyloctenium aegyptium* (Crowfoot grass), *Setaria glauca* (Yellow foxtail), *Paspalum distichum* (Knot grass), *Eleusine indica* (Goosegrass)
Broad-leaved	*Ammania baccifera* (Tooth cup), *Eclipta alba (syn. Eclipta prostrata)* (False daisy), *Monochoria vaginalis* (Pickerel weed), *Alternanthera philoxeroides* (Alligator weed), *Aeschynomene indica* (Indian joint vetch), *Commelina benghalensis* (Benghal dayflower), *Marsilea quadrifolia* (Water clover), *Enhydra fluctuans* (Water cress), *Sagittaria trifolia* (Arrowhead)
Sedges	*Cyperus rotundus (Purple nutsedge), Fimbristylis miliacea* (Grass like fimbry/ Hoorah Grass), *Cyperus iria* (Rice flat sedge), *Cyperus difformis* (Small flower umbrella sedge), *Scirpus articulatus* (Jointed bulrush)

Source: (61-63)

in the soil seedbank (67).

Residue mulch and cover crops: Crop residue on the soil's surface suppresses weed populations by decreasing seedling recruitment and early growth. The underlying theory behind this method is that the mulch residues serve as a physical barrier to weeds that are just starting to sprout and secrete allelochemicals that have a suppressive effect on weeds' early growth and development. According to an Indian study, using wheat waste as mulch at a rate of 4 tons/ha decreased the emergence of broadleaf weeds by 56-72 % and grass weeds by 44-47 % in dry direct seeded rice (68).

Sesbania co-culture (Brown manuring): In this technique, rice is seeded with *Sesbania* seeds. Sesbania is destroyed with 2, 4-D ester at 0.50 kg/ha after 25-30 days. Through mulching and competition with weeds during emergence, sesbania lowers the number of weeds. It is anticipated that using sesbania co-culture will result in a 50 % decrease in weed population while maintaining output (69).

Chemical weed management: The fastest and most efficient way to reduce weeds is through chemical weed treatment. Herbicides are not always the greatest weed management solutions; nevertheless, when combined with other weed management strategies, they produce the best results in terms of yield and quality. Herbicides are thought to be the most effective way to manage weeds in DSR, even though they pose a severe environmental risk (70). When weed control is simpler, chemical control methods are typically more focused on the early stages of weed emergence and growth. Weeds are hard to eradicate once they get large. The "critical period" of weed competition in dry direct drill seeded rice has been estimated to be 15-45 days following sowing (71).

Selecting the appropriate herbicide is essential for effective weed management, as different weed species require targeted control strategies. Equally important are the application method, rate and timing to ensure optimal efficacy (72). Research has demonstrated the effectiveness of various herbicides for controlling weeds at different growth stages (preplant/burndown, preemergence and postemergence) even in dry direct drill seeded rice systems where tillage is not involved (73). The main pre and post-emergence herbicides used in South Asian direct seeded rice are included in Table 4, together with information on treatment schedule, dosage and advantages and disadvantages.

Biological weed management: Traditional chemical herbicides, while effective, pose environmental risks and contribute to herbicide-resistant weed populations. As a sustainable alternative, biological weed control methods are gaining attention for their ability to suppress weeds while maintaining soil health. One promising strategy involves allelopathic crops, such as *Sesbania* and *Brassica* species, which release natural herbicidal compounds that inhibit weed germination and growth (92). Studies indicate that incorporating *Sesbania* as a green manure in DSR fields significantly reduces weed biomass while enhancing soil fertility.

Additionally, microbial bioherbicides are emerging as effective weed management tools. *Colletotrichum gloeosporioides*, a phytopathogenic fungus, has been explored for its ability to selectively infect and suppress major weed species like *Echinochloa crus-galli* (93). These fungi offer a natural alternative to chemical herbicides, reducing environmental impact while maintaining crop productivity. Furthermore, plant growth promoting rhizobacteria (PGPR), including strains of *Pseudomonas fluorescens*, have demonstrated weed suppression by altering root exudates and inhibiting weed seed germination (94). Such microbial interventions provide an eco-friendly weed management strategy that enhances soil biodiversity and sustainability. By leveraging natural weed suppression mechanisms, farmers can reduce herbicide dependency while improving crop resilience and environmental sustainability (95).

Drawbacks of DSR method

Direct seeding in rice is increasingly being adopted due to its potential to reduce water and labour requirements. However, several agronomic and environmental challenges limit its widespread use. Fig. 1 gives some of the important constraints in the DSR method.

One of the most critical constraints is herbicide resistance in weeds, often resulting from the continuous and indiscriminate use of the same chemical weed control strategies. Studies indicate that herbicide-resistant weed populations can

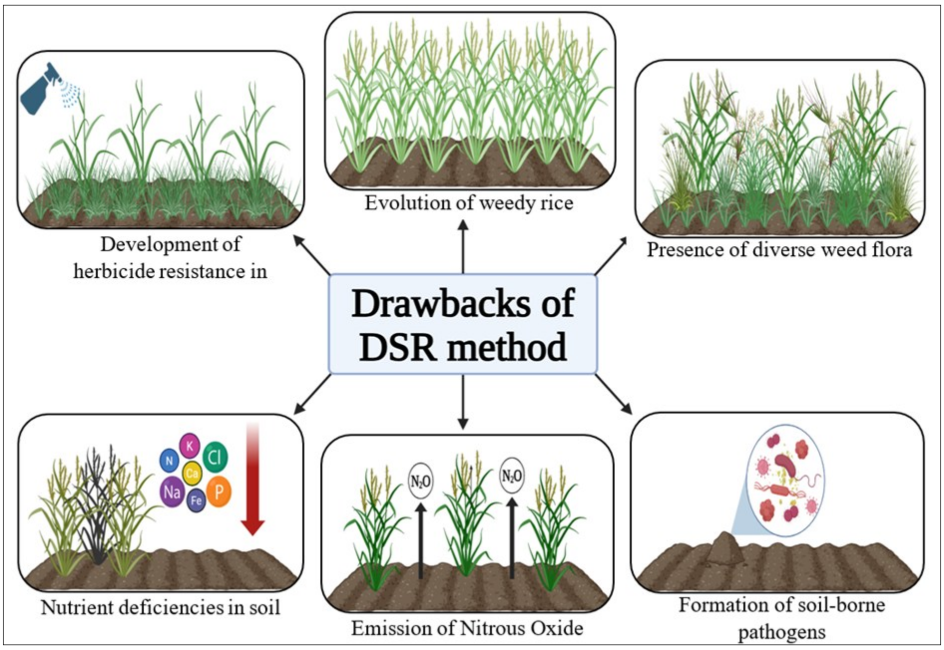

Fig. 1. Drawbacks of DSR method.

Table 4. Major pre-emergence and post-emergence herbicides used in direct seeded rice in South Asia

Herbicide	Dose (ai/ha)	Application time	Mode of action	Strengths	Weaknesses
Pendimethalin	1-1.5 kg	1-3 DAS	Mitosis disruption; inhibits microtubule formation	Controls annual grasses and some broadleaves, long residual effect, safe when used properly	Not effective on emerged weeds or sedges; needs moist soil; risk of crop injury if overdosed
Oxadiargyl	90-100 g	1-3 DAS	Protoporphyrinogen Oxidase (PPO) inhibitor; cell membrane disruption	Controls broadleaves and sedges well; good tank mix option	Not for emerged weeds; needs moist soil; short residual effect
Pyrazosulfuron	20-25 g	0-5 DAS or 15-20 DAS	Inhibits ALS enzyme and blocks amino acid synthesis	Controls broadleaved weeds, sedges, some grasses; low dose	Poor on large/emerged grasses; resistance risk; needs moist soil
Bispyribac-sodium	25-30 g	15-25 DAS	Inhibits ALS enzyme and stops amino acid synthesis	Controls grasses, sedges, broadleaves; very effective in DSR	Slow action; crop injury if overdosed or tank-mixed improperly
Penoxsulam	22.5-25 g	10-15 DAS	ALS inhibitor	Controls sedges, grasses and broadleaves; low dose	Less effective on mature weeds; risk of resistance on repeated use
Triclopyr	0.4-0.6 kg	20-30 DAS	Mimics auxin (synthetic hormone)	Excellent on broadleaved weeds, especially woody plants; Systemic	Poor on grasses and sedges; may cause drift damage; needs careful handling
Cyhalofop-butyl	80-100 g	15-25 DAS	Inhibits ACCase enzyme and stops fatty acid synthesis in grasses	Controls grassy weeds (esp. *Echinochloa spp.*), crop-safe, quick action	No effect on broadleaves or sedges
2,4-D ethyl ester	0.5-1.0 kg	20-30 DAS	Synthetic auxin causes abnormal growth, which leads to plant death	Controls some sedges and broadleaved weeds; cost-effective, easy to apply	Ineffective on grasses, risk of crop injury
Azimsulfuron	35 g	10-20 DAS	Inhibits ALS enzyme and blocks amino acid synthesis	Controls broadleaved weeds and sedges	Less effective on grasses; may cause resistance with repeated use
Ethoxysulfuron	15-18	10-20 DAS	Inhibits ALS enzyme and disrupts amino acid synthesis	Very effective on sedges and broadleaves; Low dose, high selectivity	Weak on grasses, late application reduces efficacy
Carfentrazone	20-25 g	15-25 DAS	PPO inhibitor and causes membrane disruption, rapid cell death	Fast-acting, effective on broadleaved weeds	Weak on grasses and sedges, may cause crop injury if overdosed, no residual control
Fenoxaprop-ethyl + safner	60-75 g	15-25 DAS	ACCase inhibition and blocks fatty acid synthesis in grassy weeds	Effective on grassy weeds (*Echinochloa*, *Ischaemum*); Safener protects the rice crop; Quick action	Not effective on broadleaves and sedges
Chlorimuron + metsulfuron	4 g/acre (2+ 2)	20-25 DAS	ALS inhibitor and blocks amino acid synthesis	Effective on broadleaved weeds and sedges; low dose; good tank -mix option	Not effective on grasses; risk of resistance on repeated use
Bispyribac + azimsulfuron	20-25 g	15-25 DAS	ALS inhibition and inhibits amino acid synthesis	Controls grasses, sedges and broadleaves; effective in DSR; systemic	Risk of crop injury if overdosed; resistance buildup
Triafamone + Ethoxysulfuron	60 - 70 g	15-25 DAS	ALS inhibition and inhibition of amino acid synthesis	Controls grasses, sedges and broadleaves; systemic and selective; effective in DSR and transplanted rice	Not effective on mature weeds; needs adequate soil moisture
Propanil + pendimethalin	2.5-3.0 kg + 0.75-1 kg	7-15 DAS	Propanil: Inhibits photosynthesis (PS II) Pendimethalin: Inhibits cell division (microtubule)	Controls emerged grasses and broadleaves; better residual control and synergistic effect for mixed weed flora	Less effective on sedges; needs adequate soil moisture; risk of crop injury
Fenoxaprop + ethoxysulfuron	60-70 g	15-25 DAS	Fenoxaprop: ACCase inhibition and inhibition of fatty acid synthesis in grasses Ethoxysulfuron: ALS inhibition and inhibition of amino acid synthesis in sedges and broadleaves	Controls grasses, sedges and broadleaves; broad-spectrum; effective in DSR	Ineffective on large or weedy crops; needs moist soil;
Florpyrauxifen benzyl + Cyhalofop butyl	240-300 ml	15-25 DAS	Florpyrauxifen-benzyl: Synthetic auxin disrupts cell growth Cyhalofop-butyl: ACCase inhibition and blocks fatty acid synthesis	Controls broadleaves and sedges (Florpyrauxifen) and grasses (Cyhalofop); broad spectrum; systemic action; safe to transplanted and direct seeded rice	Expensive; Timing is critical, less effective on mature weeds; limited residual control

Source : (74-91)

cause yield losses of 30-60 % and in severe infestations, up to complete crop failure (96). Farmers, therefore, need targeted training on crop rotation, herbicide rotation and integrated weed management to prevent these externalities. A related issue is the evolution of weedy rice, a mimic of cultivated rice that thrives under similar conditions and competes directly with the crop. In heavily infested fields, weedy rice can reduce grain yield and quality by 20-80 % (97). Additionally, the presence of diverse weed flora such as *Cyperus iria*, *Paspalum spp.* and *Cynodon dactylon* often necessitates a combination of mechanical, cultural and chemical methods for effective control. Late-emerging weeds, particularly sedges like *Cyperus iria*, can reduce yields by 15-30 % if left unchecked (98).

Nutrient deficiencies are also more prevalent in DSR systems, as the absence of puddling alters nutrient dynamics and reduces nutrient-use efficiency. Nitrogen deficiency during early growth can cause 10-25 % yield loss, while iron chlorosis in sensitive varieties has been associated with reductions of up to 15 % in grain yield (99). Furthermore, the higher susceptibility of DSR to soil-borne pathogens favoured by aerobic soil conditions can exacerbate losses, particularly from root-rot diseases, by an additional 10-20 %.

From an environmental perspective, DSR can contribute to increased nitrous oxide (N_2O) emissions, with aerobic soil conditions potentially raising N_2O fluxes by 30-50 % compared to flooded systems (100). These challenges highlight the need for targeted research, precision agronomy and integrated management strategies to make DSR a viable and sustainable alternative to conventional rice cultivation.

Way forward

Given the current shortage of both labour and water, the DSR is a viable alternative. Due to its lower cost compared to transplanting, rice farmers are starting to use it more frequently. If the crop is handled correctly, the yields are likewise comparable to those of transplanted rice. Although the method is both affordable and farmer-friendly, more advancements in technology are needed to reap the full benefits. Some ideas are offered for policymakers, extension agents and scientists to think about. They are:

- Further investigation is required to create high-yielding rice cultivars that are appropriate for DSR in various agroclimatic circumstances. Varieties need to have the desired characteristics, such as fast growth, the capacity to suppress weeds, the ability to germinate in the presence of moisture stress and tolerance to nutritional deficiencies.
- The low productivity of DSR, which is brought about by insufficient nutrient inputs, ineffective water management and issues related to weed control, must be increased.
- Water availability must be guaranteed for timely DSR crop establishment during mid-May to mid-June.
- It is necessary to fortify a cooperative society comprising several villages to guarantee the cost-effective supply of agri inputs, laser land levellers, zero-till machines, LCCs, etc.
- The low-cost integrated weed management technology, which uses the stale seed bed technique, appropriate aerobic genotypes, cultural, physical and mechanical practices, as well as the application of low herbicide dosages for various ecosystems in various places, needs to be fine-tuned.
- When direct planting rice, particularly in places that receive canal irrigation, the issue of weedy rice arises. It is imperative to tackle this threat with a strategic approach.

Conclusion

DSR offers a sustainable, climate-resilient and resource-efficient alternative to conventional puddled transplanting systems. However, constraints such as inadequate mechanization, limited precision in field operations, weak extension support and poor weed management continue to limit its potential. To accelerate large-scale adoption, future research should focus on developing stress-tolerant, weed-competitive and nutrient-efficient varieties; optimizing integrated weed and nutrient management packages; refining precision water and land levelling technologies; and designing cost-effective mechanized seeders, drones and smart irrigation systems tailored for different agro-ecologies.

Strengthening public-private partnerships is crucial for scaling out DSR innovations. Collaborations between research institutions, agri-tech companies, input manufacturers and farmer -producer organizations (FPOs) can drive the co-development and dissemination of location-specific technologies, provide access to machinery through custom hiring centers and ensure timely delivery of quality seed, herbicides and fertilizers. Joint investment in digital advisory platforms, field demonstrations and farmer training programs will further enhance adoption rates. By integrating cutting-edge research with market-driven partnerships, DSR can transition from a promising alternative to a mainstream, high-impact solution that helps to safeguard rice productivity, conserve resources and strengthen climate resilience in global rice systems.

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Authors' contributions

RMS collected the articles and prepared the initial draft of the review paper. SE contributed through writing support, supervision, critical editing and manuscript corrections. KS, PR, PA, TSD, GS, RB and RA assisted in revising, refining and summarizing the content of the manuscript. All authors read and accepted the final manuscript.

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