PERSPECTIVE

Direct-Seeded Rice (DSR) in India: New opportunities for Rice Production and Weed management in post-COVID-19 pandemic period

N. T. Yaduraju[1], A. N. Rao [2], M. S. Bhullar[3], J. S. Gill[4] and R. K. Malik[5]

[1] Director (Retired), ICAR-Directorate of Weed Research (DWR), Mysore-570020, India

[2] Consultant Scientist (Weed Science), Hyderabad - 500033, India

[3, 4] Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab, India.

[5] International Maize & Wheat Improvement Centre (CIMMYT), NASC Complex, New Delhi 110012, India

Corresponding Author E-mail: **nyaduraju@gmail.com**

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Abstract

In India, rice is predominantly grown as puddled transplanted rice (PTR) under irrigated or assured rainfall conditions. The share of groundwater in net irrigated area, as compared to the area under surface irrigation, is more than 60% at present. The over-exploitation of groundwater through the explosion of tube wells has raised sustainability issues. India's Central Groundwater Board has warned of critically low groundwater availability by 2025.

Rice cultivation under PTR is labour and energy-intensive. The rising costs of labour and energy in India is making PTR less profitable. PTR is also not very environment-friendly due to its relatively higher methane emissions. Due to the above concerns, the shift of rice cultivation to direct-seeding (DSR) has been well researched and developed in India. The technology has also been actively promoted and disseminated for farmers to adopt across many Indian states.

The advantages of the DSR system can be obtained only by alleviating the significant constraints, including weed problems and issues related to crop nutrition. The research carried out at different agro-ecological conditions in India has amply proved that the adoption of improved DSR technologies results in several advantages over PTR. The benefits include savings in labour (40–45%), water (30–40%), fuel/energy (60–70%), and reductions in greenhouse gas emissions. In this paper, we briefly discuss the historical aspects of DSR in India, the advantages of DSR, the reasons for inadequate adoption of DSR during the pre-pandemic period, the farmers' adoption of DSR during the pandemic making the crisis an opportunity. We also discuss the potential and research/extension needs for further upscaling DSR in India during the post-pandemic period.

Keywords: Rice, Direct-seeded rice, Labor migration, COVID-19, Weed management

Introduction

Indian agriculture has made substantial progress in food grain production, increasing from 55 Mt in 1950-1951 to a new record of 308.65 Mt during 2020-2021. The robustness and resilience of Indian agriculture were amply reflected during the COVID-19 pandemic, with a positive growth of 3.4% in 2020-21, when growth in all the other sectors declined. The share of agriculture in the country's GDP, which showed a decreasing trend until 2019-20, increased from 17.8% in 2019-20 to 19.9% during 2020-21 (Government of India, 2021). This is a record in attainment in the past 17 years by agriculture within India's GDP.

. While India and the world were combating COVID-19, the Indian rice farmers in the north-west region saw an economic and resource use efficient opportunity during the crisis. They increased the area under direct-seeding of rice (DSR) as an appropriate rice establishment method. As the most popular staple food, rice provides food security to the majority of the Indian population.

India has the largest area under rice cultivation, 44.4 Mha, with a record production of 122 Mt during 2020-2021 (USDA, 2021). In India, rice is commonly grown by transplanting rice seedlings into the puddled soil (wet tillage) in lowlands (PTR).

Alternately, direct-seeding of rice (DSR) is done by (i) dry-seeding (dry-DSR), (ii) wet-seeding (wet-DSR), and (iii) water-seeding (water-DSR) (Rao et al., 2007; Kumar and Ladha 2011; Rao et al., 2017a). As the rice seeds are sown directly, the dry-, wet- and water-DSR methods are often collectively referred to as DSR. At present, 23% of the rice area is direct-seeded globally (Rao et al., 2007; 2017c).

Of these rice establishment methods, recently in several Asian countries, including India, dry-seeding (dry-DSR) has gained importance. The primary reasons are - it requires less irrigated water than other direct-seeding methods, and freshwater resources worldwide are declining year after year.

Dry-DSR (referred to in this paper as DSR from hereon) consists of sowing dry seeds on dry (unsaturated) soils. Seeds can be broadcasted, drilled, or dibbled. DSR production is practised traditionally in most Asian countries in rainfed upland ecosystems. In India, the upland rice is grown in 23 states, covering about 13% of the country's total rice area but contributing only 4% to the rice production (Singh et al., 2011).

Dry-DSR is also grown in irrigated areas with precise water control as aerobic rice. In certain states of India, farmers cultivate dry-DSR with the onset of monsoon and convert it to irrigated lowland rice after releasing the assured canal water in the system (Rao et al., 2015).

India's water resources

India has 18% of the world population, with only 4% of the world's freshwater. A whopping 80% is used in agriculture. India receives an average of 4,000 billion cubic meters of precipitation every year (Dhawan, 2017). Only 48% is used, and the rest flows into the oceans. Irrigation is the major contributor to increased food production in India, with more than 30% of global irrigated land (FAO, 2013).

The area under irrigation in India increased from 18.8% to 60.4% from 1951 to 2016 (Jain et al., 2019). The net irrigated area from different sources (canals, tanks, wells, and tube-wells and others) was around 68.38 Mha in 2015 (MOSPI, 2018). There has been a significant shift in the sources of irrigation (Jain et al., 2019). In 1950-51, the canal irrigated area was 8.3 Mha, and as of 2014-15, it stood at 16.18 Mha. The relative importance of canals has come down from 40% in 1951 to 24% in 2014-15.

On the other hand, the well and tube well accounted for 29% total irrigated area in 1950-51, and now they share 63% of the total irrigated area (Jain et al., 2019). This expansion reflects the reliability and higher irrigation efficiency of 70–80% in groundwater irrigation compared with 25–45% in canal irrigation. While proving to be a valuable source of irrigation expansion, injudicious utilization of groundwater through the explosion of tube wells has raised several sustainability issues.

The aquifers rapidly depleted across much of India because of high extraction rates. It is predicted to have critically low groundwater availability by 2025 (Central Groundwater Board, 2021; Rodell et al., 2009; Shah, 2009). India's total annual replenishable groundwater resource and net annual groundwater availability (AGWA) are around 433 billion m^3 and 398 billion m^3, respectively. Of the available groundwater, 230 billion m^3 is withdrawn annually (Dhawan, 2017).

A survey by the Central Groundwater Board (2021) indicated that around 39% of the wells show a decline in the groundwater level. Out of 6,607 assessment units in the country, in 15 States and two Union Territories,1,071 units have been categorized as "over-exploited" based on withdrawals and the long-term decline in the groundwater level. Aquifers in poor, densely populated regions, such as north-west India, are under maximum stress [1]

Rice, a low-water-use cereal, is the primary irrigated crop in India. The total area under irrigated rice in India is about 22 Mha, accounting for about 49.5% of the total area under rice crop in the country (RKMP.DRR, 2013). Thus, developing agronomic practices to reduce water use in rice is considered essential to minimize groundwater depletion in India.

In irrigated areas of India, rice is commonly established by transplanting seedlings in puddled soil. The method is resource-intensive (water, labour and energy), proving to be less economical as the needed resources become increasingly scarce and costly. In addition, the puddling and transplanting method of raising the rice crop deteriorates the physical properties of the soil. It adversely affects the establishment and performance of succeeding upland crops. More significant emission of greenhouse gasses (GHG) in PTR is another concern, considering its impact on climate change.

The years of research has shown that it is possible to get rice yields under DSR similar to PTR. The farmers in India have been exhorted for years to shift from puddled transplanting to dry-DSR in irrigated rice ecosystems because of the advantages mentioned above (Rao et al., 2015). However, despite efforts by various agencies, the shift has not happened at the desired pace.

This paper aims to discuss the historical aspects of DSR in India, the advantage of DSR, the reasons for lesser adoption of DSR during the pre-pandemic period, the farmers' adoption of DSR during the pandemic, which made the crisis an opportunity, and potential and research/extension needs for upscaling DSR in India during post-pandemic period.

Historical aspects of DSR in India

Dry direct-seeding is probably the oldest method of rice establishment. During the initial periods of rice domestication, rice was known to be dry sown as a mixed crop with other dryland crops under the shifting cultivation system, as per the historical accounts (Grigg, 1974). DSR continued to be the primary method of rice stand establishment for about six decades. It was replaced with PTR during the 1970s in most parts of the world (Pandey and Velasco, 2005).

[1] NASA GRACE Satellite data; **http://www.jpl.nasa.gov/news/news.php?feature=4626**)

With the expansion of area under irrigation, primarily through the construction of dams across rivers, farmers' first choice across the country has been to shift to PTR, as it offered higher productivity and profitability. DSR was practised during the early 1950s when rainfall was more uniform across crop seasons in the *Krishna* delta. However, this method lost its popularity due to new canal systems, which provided an assured water supply (Palanisami et al., 2014). With the abundant labour, water and land, farmers shifted to PTR under irrigated ecosystems.

The rapid shift to PTR was mainly due to the problem of weeds and the non-availability of cost-effective herbicides for controlling them in DSR. The introduction of high yielding, dwarf rice cultivars, tailored to respond to external inputs, also favoured the cultivation of PTR (Pandey and Velasco, 2005). However, in the 21st Century, the rapid decline in water resources and the scarcity of labour coupled with a sharp increase in wages are forcing farmers to shift towards DSR (Mortimer et al., 2005).

Employment data generated from National Sample Survey Office (NSSO) shows that the percentage of people employed in agriculture has been consistently declining in India, from around 60% in 1999-00 to 49% in 2011-12 (FICCI, 2015) and 41.49% in 2018-19 (data.worldbank.org). Between 2004-05 and 2011-12, there has been a net reduction of 30.57 million labour from the agricultural sector. This highlights the net migration of labourers from agriculture to other sectors.

DSR offers advantages, such as labour saving, faster and easier seeding, lower water requirements, greater drought tolerance, higher or similar yields, lower costs of production and increased profits. DSR also provides energy-saving opportunities and better soil physical conditions for the next crop (Balasubramanian and Hill, 2002), lower GHG emissions and resilience to climatic variations (Ladha et al., 2016; Chakraborty et al., 2017).

Flooded rice culture with puddling and transplanting is considered one of the significant sources of methane (CH_4) emissions. It accounts for 10-20% (50-100 Tg/year) of global annual methane (CH_4) emissions (Reiner and Aulakh, 2000). Methane emissions from the Indian rice fields were estimated to be 3.6 ± 1.4 Tgy^{-1} (Ramachandra et al., 2015). Joshi et al. (2013) reported a 30-58% reduction in CH_4 emissions under DSR compared to PTR.

These advantages notwithstanding, several production constraints are encountered in DSR in which heavy weed infestation is the major one (Rao and Nagamani, 2007; Rao et al., 2007; Rao and Ladha, 2011; Shekhawat et al., 2020).

Development of weed management technologies for DSR in India

The success of DSR lies in the effective management of weeds. DSR crop is exposed to a more diverse and competitive weed flora than PTR. It is reported that 136 weed species belonging to 82 genera are associated with DSR in India (Rao and Nagamani, 2007). Further, both the crop and the weeds emerge together. It is often difficult to differentiate between rice plants and the grass weeds (like *Echinochloa* spp.) in the initial stages (Rao, 2021). During the earlier years of DSR adoption in Punjab, typical rice weeds, such as

Echinochloa crus-galli (L.) Beauv*, E. colona* (L.) Link, *Cyperus iria* L*.,* and *C. difformis* L*.,* dominated the weed flora. But after more than two years of continuous adoption, Bhullar et al. (2018) recorded a shift towards aerobic grasses, such as *Dactyloctenium aegyptium* (L.) Willd*., Leptochloa chinensis* (L.) Nees and the perennial sedge *Cyperus rotundus* L*.*

In DSR, the competition by weeds for growth factors is very intense. Failure to control weeds in time results in low rice yields and may even lead to total crop failure (Rao et al., 2007). The extent of weed competition depends on the type of weed species, density, and cultural practices farmers follow. The critical weed-free period in DSR ranges from 11.8 to 83.2 days after sowing, which is longer than PTR (Singh et al., 2014); higher weed pressure increases the duration of the critical period.

Timely weed control is therefore crucial in improving the productivity of DSR. Both indirect (preventative) and direct techniques are employed for managing the weeds. Some of the indirect methods include tillage (Singh et al., 2015), cultivars (Mahajan et al., 2014), manipulating the seeding rate (Mahajan et al., 2010; Ramesh et al., 2017) and nutrient management (Hemalatha et al., 2020).

Other indirect methods include intercropping (Singh et al., 2007; Joshi et al., 2019), brown manuring (Singh et al., 2007), cover cropping (Singh et al., 2015), mulching (Yadav et al., 2018), live mulches (Singh and Kumar, 2020), weed control through solarisation (Khan et al., 2003), manipulating water regimes (Singh and Tewari, 2005) and establishing conservation agriculture cropping systems (Baghel et al., 2020).

The direct weed control techniques in DSR include manual and mechanical methods and herbicide use (Rao and Nagamani, 2007; Rao et al., 2014a; Rao and Chauhan, 2015; Chandra et al., 2020). However, it is widely acknowledged that in DSR, no single approach will address weed problems satisfactorily. An integrated approach involving two or more methods, preferably with an understanding of the biology and ecology of weeds, is likely to provide effective and sustainable solutions to weed problems (Singh, 2005; Rao and Nagamani, 2010; Rao et al., 2017a, c; Chandra et al., 2020).

Manual weeding is the predominant method of weed control practised by the majority of the farmers in India. In the case of rice, over 20% of the total labour requirement is required for weeding operations (FICCI, 2015). It involves hard labour and is gender-biased as weeding is mainly carried out by women. The efficiency of the work is often lowered by hot and humid weather during the rainy season. Multiple studies have shown that herbicides are an effective way to reduce the dependency on labour.

Herbicides are cost-effective in DSR and often increase crop yields. Hand weeding is about 4-5 times more expensive than herbicides, especially as labour is scarce and costly (Rao et al., 2007; Rao and Nagamani, 2007; Rao and Chauhan, 2015).

As DSR fields are characterized by floristically diverse weed communities (Rao et al., 2007), a single herbicide fails to provide effective and season-long weed control of all weeds (Khaliq and Matloob, 2011). The integration of pre-and post-emergence herbicide application decreased rice yield loss by 23-27% compared with pre-emergence herbicide only (Bhullar et al., 2016).

Singh et al. (2015) reported a 14-27% lower rice yield with pendimethalin followed by bispyribac-sodium than the weed-free check. They attributed this loss to the biomass build-up by weeds that escaped the herbicides. Sequential applications of pendimethalin and bispyribac-sodium effectively controlled *Echinochloa* sp. and *Digitaria sanguinalis*

(L.) Scop. while poorly managing *Eragrostis* sp. and *L. chinensis* (Brar and Bhullar, 2012).

Azimsulfuron and ethoxysulfuron controlled a wide range of broad-leaved weeds and sedges (Walia et al., 2008). Tank-mixture application of fenoxaprop-ethyl and ethoxysulfuron enhanced the efficacy of fenoxaprop-ethyl against *L. chinensis* and *Digitaria ciliaris* (Retz.) Koeler. In addition, Chauhan and Abugho (2012) reported that tank mixing of cyhalofop-butyl - with penoxsulam enhanced cyhalofop-butyl's efficacy against *L. chinensis*.

Tank mixing of fenoxaprop-ethyl with ethoxysulfuron improved the control of *E. crus-galli* and *E. colona* by 43-69%. Mixing it with azimsulfuron was antagonistic and reduced the control of *L. chinensis* by 86%. Tank mixing fenoxaprop-ethyl with bispyribac-sodium was also antagonistic. The mixture performed poorly against the grasses *D. aegyptium*, *Acrachne racemosa* (B. Heyne ex Roem. & Schult.) Ohwi and *L. chinensis,* compared to fenoxaprop-ethyl alone (Bhullar et al., 2016).

New herbicide molecules, such as florpyrauxifen-benzyl + cyhalofop-butyl at 25 + 125 g/ha (Mounisha and Menon, 2020; Wright et al., 2021), performed well in controlling the diverse weed flora in DSR. No antagonism was observed when florpyrauxifen-benzyl was tank-mixed with systemic herbicides like 2,4-D, bispyribac-sodium, cyhalofop-butyl, fenoxaprop-ethyl, halosulfuron, imazethapyr, penoxsulam, quinclorac, and triclopyr (Miller and Norsworthy, 2018). The herbicides used in DSR in India are summarised in Table 1.

The delay in weed emergence relative to the crop should be a fundamental principle in weed management strategies (Chauhan and Johnson, 2010). This may be achieved by management practices, such as herbicide application or mechanical cultivation that kill a cohort of weeds or reduce their growth. When the germination of *Echinochloa* spp. was delayed relative to that of rice, weed survival and rice yield losses were significantly decreased (Gibson et al., 2002).

Stale seedbed preparation is yet another effective way to control weeds in DSR. A light pre-sowing irrigation encourages weed seed germination. Such weeds are controlled either with shallow cultivation or application of a non-selective herbicide. The combination of stale seedbed with tillage, pendimethalin and bispyribac-sodium provided the highest DSR grain yield (7.3 t/ha) (Singh et al., 2018). The stale seedbed decreased the viable seed bank of *E. colona* and *D. aegyptium* by 25-30%. Singh et al. (2015) suggested that conservation practices, such as zero tillage and cover cropping, alongside herbicides, could form an essential component of integrated weed management in DSR.

An innovative approach popularly referred to as "Brown Manuring" could be used for weed management in DSR (Singh et al., 2007). Here, the rice and the popular green manuring crop *Sesbania* are planted together. The crop is sprayed with 2,4-D at 0.5 kg/ha to kill *Sesbania* 25-30 days after sowing. *Sesbania* acts like a live surface mulch conserving soil moisture and suppressing weeds.

On decomposition, following control with 2,4-D treatments, it supplements the crop with 10-15 kg N/ha. In areas where soil crusting is a problem, the germinating *Sesbania* helps in breaking the crust and facilitates the emergence of rice seedlings. Bhullar et al. (2020; 2021) provide details of different integrated weed management practices for the effective management of weeds in DSR.

Weed management with herbicide-tolerant crop technology

Weedy rice (*Oryza sativa* f. *spontanea*), also referred to as red rice and wild rice, is widespread in many rice-growing regions and countries, including India (Rao et al., 2007; Roma-Burgos et al., 2021). Weedy rice is reported to cause huge rice yield losses. It is challenging to control weedy rice due to its morphological similarities with the rice crop and similar plant growth requirements.

Several research reports suggest shifting from PTR to DSR would accentuate the weedy rice problem. This would be a considerable challenge as herbicides recommended for DSR do not control weedy rice. The GM technology employed globally in other crops to impart herbicide resistance traits has not been adopted in rice. However, using the non-GM approach, herbicide-tolerant rice varieties have been developed and cultivated commercially in many countries (Avila et al., 2021).

Referred to as Clearfield ™ rice, the technology uses herbicides to control weeds, including weedy rice. However, the technology used alone for long periods has led to herbicide-resistant weedy rice populations due to the gene flow effects.

In India, too, three herbicide-tolerant rice varieties, developed through the non-GM approach, have been released recently (Pandey, 2021). With these new varieties, farmers could use imidazoline herbicides (such as imazethapyr) to control weeds, including weedy rice. It is a new paradigm worth exploring with strict stewardship guidelines adoption.

Table 1 Herbicides used for managing weeds in dry direct-seeded rice in India (Rao et al., 2017c)

Herbicide(s)*	Dose (g/ha)	Time of application (DAS) *	Weeds controlled	
			Good control	Control not satisfactory
Azimsulfuron	17.5-35	15-20	Annual and perennial sedges, including *Cyperus rotundus* L. Some grasses, broad-leaved weeds are also controlled.	*Echinochloa* spp.
Bispyribac-sodium	25	15-25	*Echinochloa* spp. (Other grasses, broad-leaved weeds and annual sedges are also controlled).	*Dactyloctenium aegyptium, Eleusine indica, Leptochloa chinensis, Eragrostis* spp.
Carfentrazone	20	15-20	Broad-leaved weeds.	Grasses not controlled.
Cyhalofop-butyl	120	15-20	Annual grassy weeds.	Broad-leaved weeds and sedges not controlled.
Ethoxysulfuron	18	15-20	Broad-leaved weeds and annual sedges.	Grasses uncontrolled. Perennial sedges, such as *C. rotundus*, are poorly controlled.
2,4-D ethyl ester	500	15-25	Broad-leaved weeds and annual sedges.	Grasses are not well controlled
Fenoxaprop-ethyl	60	25	Annual grassy weeds.	Broad-leaved weeds and sedges not controlled. (Toxicity to rice if applied before 25 DAS)
Fenoxaprop-ethyl + safener	60-90	15-20	Annual grasses.	Broad-leaved weeds and sedges not controlled
Oxadiargyl	90	1-3 (adequate moisture essential)	Grasses, broad-leaved weeds and annual sedges.	-
Pendimethalin	1000	1-3	Most grasses, some broad-leaved weeds and annual sedges	-
Penoxsulam	22.5	15-25	Grass, broad-leaved weeds and annual sedges.	*L. chinensis, D. aegyptium, E. indica, Eragrostis* spp. are poorly controlled.
Triclopyr	500	15-20	Broad-leaved weeds.	Grasses not controlled.
Bispyribac-sodium + Azimsulfuron	25+17.5	15-25	Grass, broad-leaved weeds and sedges, including *C. rotundus.*	Grasses other than *Echinochloa* spp.
Chlorimuron + metsulfuron-methyl	4	15-25	Broad-leaved weeds and annual sedges.	Grasses not controlled.
Bispyribac-sodium + Pyrazosulfuron	25+25	15-20	Grasses, broad-leaved weeds and sedges, including *C. rotundus.*	Grasses other than *Echinochloa* spp.
Fenoxaprop-ethyl + Ethoxysulfuron	56+18	15-25	All major grasses, including *L. chinensis* and *D. aegyptium*. Broad-leaved weeds and sedges.	-

* Days after seeding

The advantage of DSR to farmers - resource use and economics

DSR is proved to have several advantages over PTR. DSR saves labour (40–45%), water (30–40%), fuel/energy (60–70%), and reduce greenhouse gas emissions (Kumar and Ladha, 2011; Ladha et al., 2016; Ali et al., 2018). In a farmer's field, a survey in Punjab found that DSR resulted in savings of 14 person-days/ha and 18 to 20% irrigation water compared to PTR (Bhullar et al., 2018).

The labour required in DSR was about one-third of the transplanted rice (Ho and Romli, 2002). Balasubramanian and Hill (2000) reported that DSR had higher resilience to water deficiencies and more profits in assured irrigation areas. DSR saved irrigation water by 11-18% (Tabbal et al. 2002) and reduced the labour required by 11-66% compared to PTR, depending upon location, season and type of DSR (Kumar et al., 2009; Rashid et al., 2009).

Easy planting, improved soil health, reduced methane emission and often higher net returns in assured irrigation areas were some of the other benefits of DSR (Kumar and Ladha, 2011; De, 1986; Pathak et al., 2009). In addition, rice matures 7-10 days earlier under DSR than PTR, allowing timely sowing and higher yields of succeeding wheat (Giri, 1998; Singh et al., 2006).

This has been found to compensate for any minor yield penalty in rice yield occasionally observed in direct seeding. With production costs being low (44-48%), the DSR is found to give significantly higher net returns (23%) compared to PTR. The benefit-cost ratio was substantially higher (69%) in DSR (Soriano et al., 2018). Higher yields and other advantages of DSR have been reviewed in detail by Rao et al. (2007), Kumar and Ladha (2011), Pathak et al. (2011) and Ladha et al. (2016).

Adoption of DSR in India: the potential

Rice in India is mainly grown by hand-transplanting rice seedlings in puddled (wet cultivation) fields. The transplanting method of rice establishment has been in practice for many years as farm labour was abundantly available with reasonable wages. Opening up the economy, increased urbanization and intensification of agriculture and allied activities have resulted in labour shortage with higher wages.

Simultaneously, the rural wages have been growing by 17% on average since 2006-07, outstripping the urban wages. There has been an increase in wages by 26-30% between 2015-16 and 2019-20 (Government of India, 2021). Further, many government schemes intending to improve the income and livelihood of under-privileged populations also added to the labour scarcity in the country. The shortage of labour and increasing wages have impacted agriculture adversely, particularly the PTR, which is more labour-intensive.

The increased cost of cultivation and over-exploitation of groundwater associated with PTR have influenced the scientific community to focus on developing rice production systems that are sustainable and efficient in utilizing resources with enhanced farmers profitability.

DSR adoption in Punjab

The agriculture in Punjab is heavily dependent on migrant labour. A large labour force coming from relatively economically poorer areas of Bihar and eastern Uttar Pradesh participate in agricultural operations, such as transplanting, seeding and harvesting of rice and wheat, the major crops in the State. However, following the implementation of the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) by the Indian government in 2005, the inflow of labour has decreased with a concomitant increase in wages (Deininger et al., 2016).

The cost of manual transplanting increased from INR 1500 in 2005 to more than INR 5000/ha in 2012 (Gill et al., 2013). DSR was introduced in Punjab in 2009-2010 as an alternative to PTR to save labour, water and energy. Labour scarcity, higher costs and declining groundwater table have forced farmers in Punjab to look for alternative methods of rice establishment (Bhullar et al., 2018).

In 2009, a few farmers in Punjab started experimenting with DSR on a small scale. The adoption was then rapid, and by 2014, the DSR area grew to 115,000 ha (Anonymous, 2014). The declining groundwater levels forced the state government to encourage DSR by extending subsidies to farmers to purchase seed drills, which played an essential role in adopting DSR on large acreages. The improvements in rice seeding machinery, high-yielding varieties, improved technologies, including weed management, and the enhancement of farmers' skills through training programs accelerated the adoption of DSR in Punjab (Singh et al., 2016; Bhullar et al., 2018).

To begin with, the DSR had a 2-5% yield penalty compared to PTR. However, the yield loss was compensated for by the higher productivity of the following wheat crop that could be planted 10-15 days earlier than PTR. The total net returns from the DSR-wheat system, therefore, exceeded the PTR-wheat system by INR 5050 to 8100/ha (Bhullar et al., 2018).

Adoption of DSR in other regions

The increased labour costs and reduced water availability made the farmers in the other States also adopt DSR. In 2012, the drought-hit *Krishna* River Basin of Andhra Pradesh saw a massive increase in the area under DSR from 200 ha to 35,000 ha (Palanisami et al., 2014). In Raichur district, Karnataka (Rao et al., 2015) and Krishna (Rao et al., 2008) and Guntur (Reddy et al., 2019) districts of Andhra Pradesh, the late release of water in irrigation canals, due to erratic rainfall, encouraged farmers to adopt DSR by sowing rice seed directly with the onset of monsoon and convert it as irrigated rice crop after the release of the canal irrigation.

The dry-seeded sowing practice in Raichur District of Karnataka state was estimated to be about 13,000 ha (Gumma et al., 2015). DSR is a common practice among farmers in West Singhbhum and Saraikela -Kharsawan Districts of Jharkhand due to the uncertainty of monsoons, water shortages and labour scarcity (Barla et al., 2021). In Jharkhand, Odisha, Chattisgarh and Madhya Pradesh, about 8% of farmers practice DSR (Malhotra, 2021).

Hindrances for the adoption of DSR

The adoption of DSR in India has been inconsistent. This is due to below-par performances of rice cultivars that were usually meant for puddle transplanted conditions. Other influential factors include poor weed control undertaken during the initial crop growth period, higher spikelet sterility in specific environments, crop lodging, iron chlorosis in some areas, nematode infestation during the initial dry period, and lesser awareness on improved DSR production technology (Bhullar and Gill, 2019; 2020).

Other significant hindrances to the adoption of DSR have been the non-availability or non-accessibility of suitable machinery for seeding rice, lack of effective herbicides and applying the technology under non-optimum conditions. DSR performs better in medium to heavy textured soils. However, in some parts of India, enthusiastic farmers raised DSR in light-textured soils (Bhullar and Gill, 2019; 2020).

Between 2010 and 2015, the area under DSR in Punjab increased continuously from a few hundred ha to 150,000 ha. However, the DSR area decreased sharply to less than 10,000 ha in 2016. The key issues identified for the decline in the DSR were - over-enthusiasm of some farmers who took up DSR in light-textured soils, the problem of weeds and the non-availability of rice varieties suited for DSR conditions.

The Punjab Agricultural University (PAU) re-visited and further refined DSR technology and, in association with the State Department of Agriculture, drew up a strategy for broader adoption of DSR, which included identifying and mapping of areas suitable for DSR, preparation of soil maps, consultation among all stakeholders and recommendation of new herbicides for the control of a broader spectrum of weeds.

Other actions included the design and development of appropriate machinery capable of sowing and applying herbicides simultaneously, introduction of short duration varieties (*Pusa Basmati 1509* and *PR 126*) and rescheduling nitrogen fertilization to match the crop's needs more effectively. With these interventions, the DSR area in the State increased again to 23,300 ha in 2019.

Adopting DSR during the pandemic: making the crisis an opportunity

The world witnessed the outbreak of the COVID-19 pandemic during the early part of 2020. The lockdown imposed by the government to minimize the spread of the virus affected the movement of people and impacted the economy significantly. The uncertainty of the situation led to what is referred to as 'Reverse migration' with millions of labours working in both urban and rural areas heading back to their homes.

The north-western part of India represents Punjab, Haryana and parts of Rajasthan and western Uttar Pradesh, where rice farming is dependent on migrant labour from Eastern Uttar Pradesh and Bihar were particularly adversely affected. The extraordinary situation forced rice farmers in this part of the country to opt for alternatives to the manual transplanting method of rice establishment that requires a minimum of 15 to 20 labour for one-hectare transplanting. Meanwhile, the labour shortage led to a sharp hike in wages, too, thus making PTR cost-prohibitive.

The SAUs in the region and the concerned state Departments of Agriculture seized the opportunity and pursued farmers to adopt DSR technology. DSR enabled rice planting at the cost of INR 12,000 to 15,000 per hectare using a hired seeding machine capable of covering 10-15 ha/day. The Punjab Government incentivized the DSR adoption and sanctioned 4,000 seeding machines in the 2020 season on a subsidized (40-50%) basis (The Hindu, 2020).

The availability of farm machinery, such as the *Lucky Seed Drill*, developed by Panjab Agricultural University (PAU), which does sowing and herbicide application, simultaneously encouraged farmers to try out the DSR technology (Singh et al., 2020). Based on five years of research and validation at the farmers' field, a novel DSR technique coined as '*Tar-wattar* DSR' was developed and recommended in April 2020 (Gill and Bhullar, 2020).

The new DSR technique involved agronomic, genetic and mechanical interventions. In this technique, pre-sowing irrigation is applied on a laser levelled field and seedbeds are prepared under *Tar-wattar* conditions (sufficiently high but workable soil moisture) by shallow cultivations and two to three plankings in the evening hours and sowing of imbibed and treated seed immediately with the *'Lucky Seed Drill'*. (Figure 1).

The significant departure from earlier practice is the delay in the first post-sowing irrigation, which is applied 21 days after sowing (Figure 2). The delayed post-sowing irrigation offers: (i) higher saving in irrigation water (15-20%), (ii) lesser weed problems, and iii) reduced incidence of nutrient deficiency, especially iron.

In 2021, the "*Lucky Seed Drill"* was fitted with a press wheel attachment that helped: (i) preventing crust formation that is encountered in case of rain after sowing, (ii) enhancing herbicide efficacy, and iii) conserving soil moisture for a more extended period (Gill and Bhullar, 2021).

Figure 1. *Lucky seed drill* machine seeding the rice seeds and spraying pre-emergence herbicides in one pass. The optimum depth of seeding and uniform herbicide application is critical for establishing DSR with adequate control of the first flush of weeds

Figure 2: The initial growth of DSR. The first irrigation to the crop is delayed to discourage weed growth and to encourage better root growth of rice seedlings

The '*Tar-wattar'* DSR technology was widely adopted in Punjab, and the area under DSR went up to 540,000 ha in 2020. and was taken up on a large scale. In the neighbouring State of Haryana also, the DSR area increased from 10,000 ha in 2019 to 25,000 ha in 2020, with many farmers adopting PAU's '*Tar-wattar'* DSR technology. Highly successful growth and establishment of the DSR crops are shown in Figures 3-5.

Figure 3. Excellent establishment of direct-seeded rice crop which was not flooded but irrigated based on crop requirement

Figure 4. Luxurious growth of direct-seeded rice in a farmers field in Punjab, India

Figure 5. The interactions amongst the farmers and scientists from the Punjab Agricultural University, Ludhiana, in a DSR farmer's field in Punjab, India

Although the primary reason for the sharp increase was labour shortages during the pandemic, the efforts of the scientists of the SAUs and the push given by the State Governments also played a significant role. DSR technology has been undergoing refinement for over five years, with a substantial number of innovative farmers adopting the technology.

This readiness has helped change the mindset of farmers who were aware of the merits of the technology but were initially cautious about adopting it. The increase in DSR area to 600,000 ha in 2021 in Punjab, despite an improvement in the labour supply, indicates farmers' confidence in the new DSR technology.

The area under DSR in Punjab is close to 20% of the total rice area. Dubbed as a 'silent revolution', this is reported to have resulted in savings of around INR 6.0 billion in monetary terms besides 30 % savings in groundwater and associated pumping costs (Singh et al., 2021).

DSR: the way forward

Considering the many positives of the DSR technology and its success in Punjab and Haryana, it is pertinent to explore possibilities of extending the acreage under DSR across the country. With this objective in view, a National Seminar on Promotion of DSR was organized by the ICAR-Agricultural Technology Application Research Institute (ATARI), Ludhiana, on 12-13 June 2021.

The event, attended by stakeholders including scientists from ICAR, SAUs, IRRI, CIMMYT, senior administrators and policymakers and farmers, took stock of the developments following the COVID-19 pandemic and discussed the DSR technology and the possibilities of its wider adoption (Singh et al. (2021a). The significant observations made at the seminar are summarised below:

- Academia should take the lead in sensitizing the various state Departments of Agriculture and policymakers on the merits of the technology.
- The most significant benefits, such as resource-use efficiency, farmers' profitability, climate resilience, lower groundwater use and lower GHG emissions, need special mention.
- DSR may not suit all ecologies. The first step would be to map areas suitable for DSR.

- Crop breeding programs may be intensified to identify and develop varieties suitable for DSR. Key attributes include early vigour, a more robust root system and greater competitiveness with weeds in the early stages of crop growth.
- The accessibility of machinery (laser leveller, machinery for seeding and spraying of herbicides) be ensured, particularly to small and medium-sized landholders, through custom hiring centres.
- Perennial weeds - purple nutsedge (*Cyperus rotundus* L.), Bermuda grass [*Cynodon dactylon* (L.) Pers.] and weedy rice - are likely to increase with continuous cultivation of DSR.
- Stale seedbed, brown manuring and other cultural practices are integrated with herbicide use for sustainable weed management.
- Scouting for herbicide-resistant weeds is to be given priority.
- The inclusion of summer moong in rice-wheat or green manuring of *Crotolaria juncea* L. are to be explored for reducing nematode infestation.
- The use of microbial inoculants for seed treatment should be explored for better nutrient cycling and reducing the losses of nitrogen.
- As farmers' "fear of failure" is one of the critical reasons for the slow or non-adoption of DSR, serious efforts are required in educating and training them.
- Labelling of the DSR produce for its low carbon footprints may be explored to boost exports.

Opportunities for upscaling DSR

Climate change is expected to increase the variability of monsoon rainfall and the risks of early or late-season drought. The DSR system increases the capacity of poor farmers to cope with climate-induced change by offering a choice of rice establishment methods and by reducing the amount of water required for crop establishment and subsequent crop growth.

The DSR technology received an uplift due to the COVID pandemic. The DSR area in Punjab increased from 235,000 in 2019 to 600,000 in 2021. The Punjab State government and the PAU have promoted DSR and kept the momentum from 2019 to 2021. The neighbouring Haryana State, too, is conscious of the problems associated with PTR and has been striving hard to promote DSR technology.

The *Tar-wattar* technology received wide publicity in local print and social media during the last two years. The PAU, partnering with other stakeholders, organized several activities, including field visits for farmers.

The National Seminar on the promotion of DSR organized in June 2021 (referred to above) attracted over 2000 participants. It successfully sensitized all the stakeholders related to the DSR technology. The scientists from other regions are expected to try out the technology in their areas in the coming years. The adoption, therefore, is expected to have a cascading effect.

In the meantime, the Prime Minister of India has released two rice varieties resistant to herbicides developed by the IARI, New Delhi, in June 2021 (Pandey, 2021). Developed through mutagenesis, these varieties (*Pusa Basmati 1979* and *Pusa Basmati 1985*) are tolerant to imidazolinone herbicides. This breakthrough research will help farmers control weedy rice- one of the most problematic weeds in DSR in many parts of the country. Punjab and Haryana states cultivate *Basmati* rice, mostly grown for export.

The new HT *basmati* rice varieties are expected to find rapid adoption. However, a similar technology (Clearfield Rice ™) has led to the rapid evolution of herbicide-resistant populations of weedy rice due to gene flow from HT rice in Malaysia in Asia and the USA. For the long-term sustainability of herbicide-tolerant technology, it is therefore essential to develop and follow a strong stewardship program to avoid/delay resistance development in weeds against HT-rice herbicides.

The ecology and production practices in eastern IGP (EIGP) - east Uttar Pradesh, Bihar and Odisha, are different. The constraints and potential of DSR adoption EIGP have been eloquently discussed by Singh et al. (2020). The crop is predominantly raised as PTR with supplemental irrigations during the initial periods of crop growth. If crop establishment is delayed, farmers face the problem of yield loss due to lateness. This will lead to delayed planting of the following wheat crop (with lower yield) and lower total system productivity.

Due to late rains, farmers had to make additional expenses on pumping water from borewells. Poor crop growth allows more weeds to increase and add to the extra weed management costs. Thus, a shift to DSR from PTR would address the direct and indirect problems related to water shortages during the initial 2-3 weeks of the crop's growth. The stale seedbed preparation with pre-sowing irrigation is followed by shallow tillage before seeding rice. Referred to as soil-mulch DSR (Dhillon et al., 2021; www.csisa.org), this simple technique has multiple benefits such as limiting evaporation losses, thereby reducing early irrigation requirement, better weed control, lower cost of cultivation and more profits.

This is almost similar to *Tar Wattar* DSR practised in Punjab. Based on the large scale farmers participatory evaluation trials in Bihar and Eastern Uttar Pradesh (N= >600), it has been reported that soil mulch DSR gave yield similar to PTR but higher than conventional DSR with sowing in dry soil followed by irrigation (**www.csisa.org**).

The DSR technology benefits from intensifying the rice-fallow cropping system (RFCS) in regions like Odisha. The early establishment through DSR facilitates the timely establishment of a succeeding wheat crop, leading to higher system productivity and profitability (**www.csisa.org**). In Odisha, dry-DSR performed better than the existing practice of *beushening* (Panneerselvam et al., 2020).

They found that the costs on establishment were USD 49 and 58 and on weed control USD 184 and 67 for the *beushening* method and DSR, respectively. That would need rebalancing the time of crop establishment and then fitting the whole system of evolution of new varieties.

At the cropping system level, DSR not only addresses the primary drivers of the rural change, such as rising scarcity of labour and water, the rising cost of cultivation and declining farmer's income, but also bring opportunity for early rice establishment.

We also believe that the dry DSR has vast potential in canal irrigated systems in peninsular India. The potential has already been captured in Raichur district of Karnataka State (in the tail-end area of *Upper Krishna* and *Tungabhadra Project* command area), where due to the canal water reaching the fields late, the farmers sow dry direct-seeded rice and later convert it as irrigated rice on the release of canal water (Rao et al., 2015).

The DSR is now spreading to Sindhanur, Gangavati areas (Gumma et al., 2015) and is becoming a widespread rice cultivation practice in Karnataka (Gurupadappa et al.,2018). Working in that area, one of us (A. N. Rao) found the farmers very enthusiastic and have successfully perfected the DSR technology, including laser levelling of the fields, dry sowing and applying herbicides using machinery and equipment much similar to the practices followed by the Punjab farmers.

International organizations, such as IRRI and CIMMYT, are also running pilots in collaboration with SAUs, State Departments of Agriculture and civil society organizations to popularise DSR technology in many parts of India. In Karnataka, they introduced the farmers to modern machinery and provided the required technical know-how. Due to their combined efforts, the area under DSR has gradually increased over the years. Presently, DSR is practised over 40,000 ha. Similar adoption is underway in the neighbouring Telangana State also.

Dry-DSR is also popular during the *Kharif* season in Nalgonda (*Nagarjuna Sagar* project area) and the Krishna and Guntur districts of Andhra Pradesh. In the State of Tamil Nādu also, a vast potential exists for farmers to adopt the DSR method under canal irrigated areas. With the initiatives such as the one made in Karnataka, it is possible to untap the technology's substantial potential to improve the farmers' profits and the environment. Agriculture in India is a State subject.

Each State could proactively explore possibilities for greater adoption of DSR. The SAUs have a pivotal role to play in testing and re-visiting the technology and fine-tuning it to suit the local conditions and scaling up the technology in collaboration with State Departments of Agriculture and other stakeholders.

The cost of establishment, irrigation and weed management in DSR compared to PTR cultivation (as an example in Punjab) is given in Table 2. Overall, there are 45-48% savings with DSR cultivation compared to PTR, with the highest contribution coming from crop establishment (65-68%), followed by irrigation (52-53%).

The weed management cost in DSR, however, is 20-38% higher than in PTR. Considering other expenses on crop production being the same in both methods of crop establishment, a farmer can expect a total saving, ranging from INR 9114 to 10192 per hectare, by adopting DSR cultivation.

Assuming a saving of INR 10,000/ha, each million ha DSR adoption would result in an economic benefit in the range of INR 10.0 billion (=USD 133 million). This, benefit is besides the significant reduction in groundwater use and GHG emission of GHGs that DSR brings about. We believe that a substantial acreage of PTR in India could be brought under DSR, with such positive social, economic and environmental effects.

Table 2 The relative investment for crop establishment, irrigation and weed management in the cultivation of DSR and PTR (per ha)

	DSR		PTR		
		Cost (INR)		Cost (INR)	Saving with DSR (%)
1. Crop establishment					
a. Tractor time (hr.)	2.0-2.5	1040-1300	2.5-4.0	1300-2080	20 to 38
b. Diesel (litres)	12.5-15.0	1050-1250	25 -30	2075-2500	49 to 50
c. labour (man-days)	2.5-5.0	1125-2250	15-20	6750-9000	75 to 83
2. Irrigations (No.)	12-16	2496-3328	25-30	5200-6240	52 to 53
3. Weed management		2500-4000		2000-2500	-20 to -38
4. Total		8211-12128		17325-22320	45 to 48

Details: Labour wages - INR 450/man-day, INR 208/ha for one irrigation, Diesel- INR 83.3/l.

Conclusions

It has been demonstrated quite emphatically that DSR has the potential to provide similar levels of productivity and greater economic returns to farmers as compared to conventional PTR. The adoption of DSR reduces the unsustainable exploitation of groundwater and minimizes GHG emissions, thereby positively assisting the environment. The Punjab and Haryana States of India used the opportunity of labour shortage following the COVID-19 pandemic in popularising DSR technology successfully.

All-out efforts should be made to reach out to more areas of the IGP and other DSR suitable areas in India. The success stories should be communicated widely with the emphasis on minimizing the cost of production to increase farmers' profits. The senior administrators and the policymakers in other parts of India need to be sensitized to promote the DSR technology.

The SAUs will have to proactively work towards fine-tuning the technology to suit the local conditions and forge a partnership with all stakeholders for its upscaling in their respective areas.

The accessibility of machinery should be ensured, particularly to small and medium farm holders through custom hiring centres. The right kind of policy support and incentives are critical in the faster upscaling of DSR in India.

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Common and chemical names of herbicides used in this paper:

Common name	Chemical name
azimsulfuron	N-[[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl]-1-methyl-4-(2-methyl-2H-tetrazol-5-yl) -1H-pyrazole -5-sulfonamide
bispyribac-sodium	2,6-bis[(4,6-dimethoxy-2-pyrimidinyl) oxy] benzoic acid
chlorimuron	2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl) amino] carbonyl] amino] sulfonyl] benzoic acid
cyhalofop-butyl	(R)-2-[4-(4-cyano-2-fluorophenoxy) phenoxy] propanoic acid
ethoxysulfuron	2-ethoxyphenyl [[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl] sulfamate
fenoxaprop-ethyl	(6)-2-[4-[(6-chloro-2-benzoxazolyl) oxy] phenoxy] propanoic acid
florpyrauxifen	4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)-5-fluoropyridine-2-carboxylic acid
halosulfuron	3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl] amino] sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid
imazethapyr	2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid
metsulfuron-methyl	2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino] carbonyl] amino] sulfonyl] benzoic acid
oxadiargyl	3-[2,4-dichloro-5-(2-propynyloxy) phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2(3H)-one
pendimethalin	N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
penoxsulam	2-(2,2-difluoroethoxy)-N-(5,8-dimethoxy [1,2,4] triazolo[1,5-c] pyrimidin-2-yl)-6-(trifluoromethyl) benzene sulfonamide
pyroxasulfone	3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl) pyrazol-4-yl] methyl sulfonyl]-5,5-dimethyl-4H-1,2-oxazole
quinclorac	3,7-dichloro-8-quinolinecarboxylic acid
triclopyr	[(3,5,6-trichloro-2-pyridinyl) oxy] acetic acid
2,4-D	(2,4-dichlorophenoxy) acetic acid