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Irrigation Management Strategies to Increase Crop-Water Productivity and Grain Quality of Direct Seeded Rice in North West IGP: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Due to its great productivity and profitability, rice (*Oryza sativa* L.) is farmed in alluvial irrigated tracts of northwest India. For half of the world's population as well as in our country, rice serves as the main source of calories. However, excessive groundwater use in rice farming has resulted in an alarming decline in water table, indicating overuse of groundwater. Therefore, it is necessary to investigate alternative, resource-conserving methods that can sustain rice production. Direct seeded rice presents a compelling option when the future of rice production is in jeopardy due to worldwide water constraint and rising labour costs. The oldest method of crop establishment in this regard, direct seeded rice (DSR), is becoming more and more well-liked constraints minimal input requirements. It has certain benefits, including labour savings, a reduction in water and manpower requirements, early crop maturity, cheap production costs, improved soil physical conditions for crops, a reduction in methane emissions, and greater options for being the best match in various cropping systems. For dry-seeded rice, management strategies that cut irrigation water use and boost crop-water production are needed. Some of the interventions in this respect include cultivars with short growing seasons, tillage, and irrigation scheduling. High crop-water productivity is ensured with optimal yields thanks to irrigation scheduling that aims to eliminate over- or under-irrigation. Tillage changes the edaphic environment of the soil, which impacts crop development. Because of their shallow root systems, rice plants are unable to use the water in the deeper layers of the soil. In order to increase the deep root growth of rice cultivars, deep tillage has become the preferable method. The present research evaluates irrigation management options to raise crop-water productivity and grain quality of DSR in northwest IGP based on the available evidence.

Keywords: Direct seeded rice; irrigation; water productivity; tillage.

ABBREVIATIONS

DAS : Date after Sowing
DSR : Direct Seeded Rice
GWP : Global Warming Potential
CF : Conventional Flooding
I : Irrigated
R : Rainfed
WT : Water Table
SM : Soil Moisture
PTR : Puddled Transplanted Rice
ZT : Zero Tillage
MT : Minimum Tillage
CT : Conventional Tillage
GHG : Green House Gas
DDS : Dry Direct Seeding
WDS : Wet Direct Seeding
USD : United States Dollar

1. INTRODUCTION

With more than 70% of all global water withdrawals going to irrigated agriculture, it is clear that this sector is the major freshwater consumer. Rice is irrigated with more than half of all irrigation water. The most significant staple food in Asia is rice, which accounts for 35–80% of all caloric intake. Food security faces a major challenge from rising food consumption, and both the present and the future depend heavily on irrigation management measures to boost crop productivity. Water scarcity, however, is posing a growing threat to this ecosystem. The causes vary by region and include worsening quality (chemical pollution, salinization), depleting resources (e.g., dropping groundwater tables, silting of reservoirs), and rising rivalry from other industries like urban and industrial customers. When compared to other crops, rice uses water far less efficiently. 1 kilogramme of rough rice requires, on average, 2500 litres of water, ranging from 800 to more than 5000 litres [1]. An additional 14 million ha of land might be irrigated with a 10% increase in irrigation efficiency. In order to increase water productivity without decreasing the productivity of other factors, primarily land (i.e., yield), labour, and fertiliser, various management practises of rice cultivation must change simultaneously. This is because solely reducing water use in puddle transplanted rice (PTR) led to a proportional reduction in yield [2]. Although transplanting is the most popular way of growing rice, a change to less demanding alternative methods that aim to boost crop-water productivity is essential due to the growing water shortage, labour shortage, and higher pay during peak seasons. The hunt for such alternative crop establishment techniques that can boost water productivity is prompted by the growing water shortage, the water-loving character of rice agriculture, and rising labour costs [3]. The difficulty lies in creating cutting-edge technology and manufacturing methods that would enable rice production to remain constant or even increase in the face of dwindling water supplies [4]. To lessen the amount of water needed for rice, irrigation management techniques like direct seeded rice are popular. Only direct seeded rice (DSR) is a practical solution to reducing wasteful water flows. Instead of transplanting seedlings from a nursery, DSR refers to the process of starting a rice crop from seeds sowed in the field. Since the 1950s, it has been acknowledged as the primary way of growing rice in developing nations70. Any method that could reduce water consumption without affecting rice harvest would undoubtedly be appreciated [5]. Pre-germinated seed can be sown directly into the ground using one of three methods: wet seeding, water seeding, or dry planting into a prepared seedbed. Farmers were urged to switch from the conventional approach of transplanting to DSR culture by improved short duration and high producing varieties, nutrient management systems, and weed control methods. In addition to reducing greenhouse gas emissions and improving the growth of subsequent crops, direct seeding has other benefits as well [6]. One of the most promising methods for conserving water and labour is the direct-seeding of the crop on non-puddled, non-flooded fields [7]. When we used early maturing crop cultivars under DSR, the amount of irrigation water needed was similarly decreased [8]. Furthermore, by using only the necessary amount of water in an irrigated direct seeded rice culture, water use efficiency on the farm can be raised without noticeably reducing yields [9]. The main constraints forcing growers to switch to water-saving dry direct seeded rice (DDSR) are a paucity of water, electricity, and labour. Rice is grown using DDSR in fields that are dry and free of puddles [10]. In comparison to TPR (Traditional rice cultivation), DDSR has numerous advantages, including efficient water use, mechanization-friendliness [11], and higher economic returns [12]. It may also guarantee early maturity [11], maintain higher production and quality [13], and increase stand establishment. Additionally, it makes it easier to sow the following wheat crop on time and prevents edaphic conflict, boosting the sustainability of the rice-wheat cropping system [14]. Direct seeded rice (DSR) produces a yield that is equivalent to that of flooded TPR while requiring less water input than standard TPR [15,16]. When managed appropriately, DSR has a better yield potential than TPR, according to Ali et al. [17]. Qureshi et al. [18] observed a yield penalty in DSR as compared to TPR, which is in contrast to these findings. Given that rice output decreases as the soil dries below saturation, this yield penalty may be caused by water stress [19].

2. DIRECT SEEDED RICE IN NORTH WEST IGP

2.1 Why Direct-Seeded Rice?

Table 1. List of the various factors that led to the switch from PTR to DSR

Major Reasons	Other Reasons
• Water scarcity • Water-guzzling puddled transplanted rice • Increasing demand and competition for water from non-agricultural sector • Water wise-direct seeding practice • The rising cost and scarcity of labour at peak periods	• Adverse effects of puddling • Rising interest in conservation agriculture • Best fit in cropping system

2.2 Different Direct Seeding Techniques

The earliest known method of establishing rice is direct seeding. Before the 1950s, it was widely used, but over time, puddled transplanting took its place [20-24]. There are three main methods for direct seeding, which are adjusted over time based on technology advancements and the need for improved resource-efficient practises. The land preparation, the state of the seedbed, the sowing techniques, and the kind of seed environment (aerobic or anaerobic) can all be used to classify these direct seeding procedures [19].

Rice can be produced using three main techniques:

- Transplanting,
- Dry-DSR and
- Wet- DSR.

These approaches differ from others either in the way crops are established (tillage) or in the way the ground is prepared. In Asia, particularly in the tropical regions, transplanting is the predominant method of crop establishment. This technique involves ponding the ground and transplanting seedlings cultivated in nurseries. Direct seeding is the practise of sowing seeds directly into the main field as opposed to transplanting rice seedlings. This can be done both dry and wet. The earliest method of growing rice is direct seeding, which was eventually replaced by transplanting [6].

1. Dry Direct Seeded Rice:

In Dry-DSR, rice is established using a variety of techniques, such as

(i) broadcasting dry seeds on unpuddled soil after either ZT or CT
(ii) using the 'dibbled method' in a field that has been well-prepared, and
(iii) drilling seeds in rows after CT, MT using a power tiller-operated seeder, ZT, or raised beds. In both CT and ZT situations, a seed-cumfertilizer drill is employed, which drills the seeds and applies fertiliser after preparing the ground or in ZT conditions.

2. Wet Direct Seeded Rice

Pre-germinated seeds (radicle 1- 3 mm) are sown on or into puddles of soil using the wet-DSR technique. The term "aerobic Wet-DSR" refers to the seed environment created when pregerminated seeds are placed on the surface of puddled soil. Pregerminated seeds are usually planted or drilled into soggy soil, which creates an anaerobic Wet-DSR environment. Using a drum seeder81 or an anaerobic seeder with a furrow opener and closure, seeds can be broadcasted or sown in line in wet-DSR under aerobic and anaerobic conditions (Maharaj et al. 2016)

3. DSR v/s Transplanted Rice

Based on the following parameters, the effectiveness of various direct seeding methods of rice (DSR) was compared to that of conventional puddled transplanted rice (CT-PTR).

- Effect on succeeding crops
- Grain Yield
- Irrigation Water Applied and Water Use Efficiency
- Labour Use
- Greenhouse Gas (GHG) Emissions
- Economics [25]

2.3 Actual Advantages of DSR

When compared to the traditional methods of puddling and transplanting, direct seeding of rice has the potential to offer farmers and the environment a number of advantages. The following is a list of the different advantages:

- Reduces manpower costs (1-2 vs. 25–30 for PTR).
- Early crop maturity by 7–10 days permits timely planting of succeeding crops
- Easier and faster planting makes it possible to sow within the allotted time frame.
- More effective water use and increased resistance to water stress.
- Greater profitability, particularly when irrigation facilities are guaranteed.
- Better soil's physical characteristics.
- Less methane emission: DDS<WDS< PTR [6].

Fig. 1. Global factors driving the switch from PTR to DSR

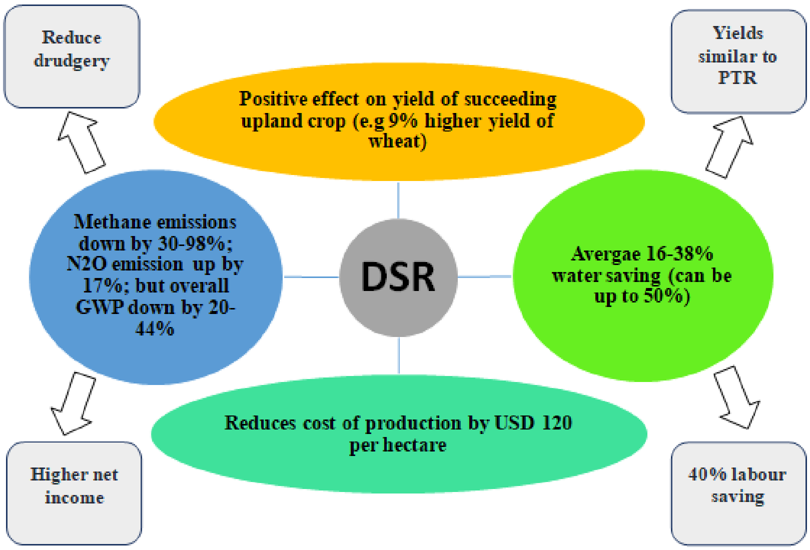

Fig. 2. Advantages of DSR adapted from: (Kumar and Ladha, [26]) and (Chakraborty et al., [27])

2.4 Rice Water Productivity and Use Efficiency Improvement

Future challenges will include feeding a growing population and providing for their water needs. To achieve global food security, agricultural water resource use must be sustainable [28]. There are three methods to handle the issue of food scarcity brought on by water scarcity:

- Water scarcity in the region can be addressed by importing water in the form of food through virtual water commerce,
- Increasing water availability through wastewater recycling,
- Improving water productivity through higher yields or better water usage, or both [29].

The major goals of all three strategies are to improve agricultural water usage efficiency, maximise the utilisation of available rainfall, and utilise irrigation water as effectively as possible. India needs to increase water efficiency in agriculture if it is to meet the country's rising food demand. This can be done using a variety of methods and tools, such as:

(i) Improving and enhancing irrigation and drainage systems
(ii) Creating and lining field channels and waterways
(iii) Levelling and shaping land
(iv) Building field drains
(v) Combining the use of surface and groundwater
(vi) Introducing and enforcing rotational water distribution systems (warabandis)
(vii) Creating plans for supplying inputs such as credit, seeds, and fertiliser.
(viii) improving existing extension, instruction, and demonstration programmes in farmers' fields to save freshwater and boost irrigation effectiveness [30]

Table 2. Water-saving rice production DSR method

	DSR
Water saving (%)	~ 15
Percolation	Low
Weed	More
Suitable ecosystem	R
CH4 emission	Low
N2O emission	More
GWP	Low
Irrigation	Normal Irrigation
Irrigation depth (cm)	< 5
Suitable soil	All
Labour requirement	Low
Energy input	Low
Cost	Low

2.5 Direct Seeded Rice (DSR) Cultivation Techniques that Conserve Water

Raising nurseries for transplantation is not done in direct seeded rice (DSR) agriculture. In the event of water scarcity or a monsoon that is delayed, DSR allows the farmer the freedom to engage in direct paddy seeding. In the North-West IGP region, direct sowing can be used to grow both coarse and basmati rice whenever practical. Depending on the type of soil, the initial irrigation can be applied 7–10 days after sowing in DSR if the crop has already been established during pre-sowing irrigation. It is necessary to maintain optimal moisture (irrigation at 2–3-day intervals) during the active tillering period, or 30-45 days after sowing (DAS), and the reproductive phase, or panicle emergence to grain filling stage, in order to harvest the highest yields from DSR crops. In a six-year study on sandy-loam soil in Modipuram, it was found that dry DSR can be irrigated safely when soil hairline cracks first form [31]. In studies at both experimental stations and on-farm, direct seeded rice (DSR) on raised beds used 12–60% less water and produced 10% more grain than puddle transplanted rice [32].

2.6 DSR Research Gaps in the NW IGP

There are numerous advantages attributed to DSR, including labour and energy savings, better plant stand, improved soil fertility, better water relations, soil organic matter accumulation, decreased soil compaction, increased soil biodiversity, resilience to climate change, and greenhouse gas mitigation. These advantages are all said to interact intricately to boost rice productivity and systems' sustainability in the irrigated ecology of northwest India. Dry-seeded rice has a variety of potential advantages, including increased labour and water productivity with several off-farm advantages and improved food security for millions of Indians as a result of higher rice output. For it to be sustainable, weeds, nitrogen management, and resistance to novel biotic and abiotic pressures must be addressed first [33].

The primary barriers to the promotion of DSR are the change in weed flora, smaller sinks, emergence of volunteer rice seedlings, and poor crop emergence, especially when the field is not levelled and rain falls right after sowing. The development of criteria for identifying traits that are likely to be most useful for weed management in direct seeding is urgently needed. These traits include tolerance for early submersion and seed germination in anaerobic conditions for uniform crop establishment, high and early seedling vigour with rapid leaf area development during the early vegetative stage for weed suppression, cultivars with an allelopathic effect, and herbicide-resistant rice cultivars.

In order to increase the sink size in DSR, research is also required to close the physiological gaps for improved nutrient uptake under moisture stress. Low post-anthesis assimilate input in DSR restricts grain filling. Additionally, the shallow surface soil in which the roots of DSR are placed prevents transplanting, which leads to a relatively low intake of N. Finding agronomic techniques for nutrient-efficient genotype identification is urgently needed to support more effective and long-lasting agro-management solutions in DSR.

It is crucial to solve the major issue of rice's low to moderate nutrient-use efficiency, which ranged between 25 and 40% for both nitrogen (N) and phosphorus (P). One of the most crucial mechanisms in DSR is water mining, or the maximisation of water uptake from deeper soil layers. The roots are essential for the uptake of water and nutrients and serve as sensors for the soil's water and nutrient status. The effectiveness with which plants collect soil moisture from deep layers during the gap between two rainfall events and irrigation is crucial for maintaining the crops' water and nutrient needs. To increase yield stability under these pressures in DSR, agronomic measures are required. The most often accepted target feature for increasing water usage efficiency in DSR at the moment is sufficient root length and surface area in the deep soil layer. In order to increase root zone development and resistance to lodging under low soil moisture, DSR will concentrate on root zone investigation. In order to achieve high water use efficiency in DSR, agronomic efforts are also required to reduce evapotranspiration losses with the use of soil amendments. In addition to having little water available, the DSR has little iron, phosphorus, or nitrogen. An effort would be made to identify genotypes or to increase the plasticity of genotypes with superior root systems, which can better absorb N, P, and Fe and produce better crops [34].

Understanding the differences in N usage efficiency (NUE) across rice genotypes suited to DSR and describing the differences in N absorption and utilisation between N-efficient and N-inefficient rice are important. According to some recent studies, some rice cultivars may be able to absorb more NO2 than NH4 + at high N levels. This is significant for rice that is dry-direct seeded because rice roots may aerate the

Table 3. WUE and water productivity of direct-seeded rice

S. No.	% Water Saving or WUE or Water Productivity	Reference
1	Compared to transplanted rice, which received 0.29 to 0.39 kg grain m-3 irrigation water, DSR had water productivity that ranged from 0.40 to 0.46. When compared to transplanted rice, the water productivity under DSR is 17.9–27.5% higher.	[3]
2	Input for irrigation was lowered by 30 to 50% when using DSR with 20 kPa, and water productivity rose without affecting productivity.	[39]
3	In comparison to transplanted rice, which has a water productivity of 1.1 kg grain m-3 under sandy loam soil, DDSR has a water productivity of 1.4 kg grain m-3 and conserves 8–12% of water.	[10]

rhizosphere by releasing oxygen (O2), and this action encourages nitrification, or the process by which ammonium is converted to nitrate. In order to compare NUE between different rice cultivars, it is necessary to assess the effectiveness of nitrate absorption as well as the activity of key enzymes involved in the N-assimilation pattern. Finding the physiological underpinnings of variation in N-efficient and N-inefficient cultivars is necessary. Rice is much more sensitive to Fe shortage than other graminaceous plants because it secretes far fewer deoxy-mugineic acids as a Phyto siderophore even in Fe deficiency [35]. The rice crop has occasionally failed completely as a result of severe chlorosis brought on by Fe shortage [36]. Due to the fact that soil-derived Fe is not readily available in reduced form, this issue is made worse in DSR. Strong breeding and agronomic efforts are therefore required to solve this problem.

Most reports assert that DSR reduces methane emissions compared to conventional methods of puddled transplanted rice. Despite the fact that DSR can lower CH4 emissions, higher aerobic soil conditions can actually raise N2O emissions. At redox potentials greater than 250 mV, nitrous oxide production rises. Therefore, efforts to lower N2O emissions from DSR are needed to reduce any negative effects on the environment. The trade-off between CH4 and N2O emissions is a significant barrier to reducing the hazards of global warming. Therefore, solutions must be developed to lower DSR emissions of both CH4 and N2O at the same time.

In order to reduce emissions of both CH_4 and N_2O, DSR will concentrate on creating agronomic and water management practises that allow soil redox potential to be maintained in the intermediate range (-100 to +200 mV). However, many of these gaps are not well supported by the experimental data that are available. Therefore, it is crucial to close this knowledge gap through research in order to create the best management practises for DSR that can be long-term adjusted in accordance with local demands and conditions. This will give researchers a solid scientific foundation on which to undertake their investigations into the development of efficient and long-lasting agronomic practises for DSR in NW-IGP and the establishment of suitable information systems to enable better decision-making. Research including a comprehensive strategy and practical application is clearly needed to stop these problems.

3. RECOMMENDATIONS TO BOOST DIRECT-SEEDED RICE'S CROP-WATER PRODUCTIVITY

1. Growing DSR on soil with a thick to medium texture
2. Do laser levelling in the field
3. Non-basmati cultivars should be sown in the first fortnight of June and basmati cultivars should be sown in the second fortnight of June for high quality and crop water production in DSR.
4. A direct seeded rice drill with a seed metering device or inclined plates planter should be used to sow the crop.
5. When sowing in medium-textured soil, do it when the earth is dry and irrigate the field right away. Vattar conditions developed in this soil three days after sowing (DAS), and a pre-emergence herbicide was applied within three DAS.
6. If the soil is heavy, plant the crop in a vattar condition. In heavy soil, vattar condition does not appear within 3 DAS if irrigation is applied right away after dry seeding; therefore, in such soil, it is advised to sow the crop in vattar condition and apply pre-emergence herbicide right away to maximise the efficacy of pre-emergence herbicide.
7. A seed rate of 15 to 30 kg ha^{-1} is ideal for DSR.
8. Before planting, seeds should soak in water for 10 to 12 hours.

9. The recommended seeding depth is 2 to 3 cm.
10. The DSR has a row spacing of roughly 20 cm.
11. To effectively control weeds in DSR, it is advised to apply bispyribac (Nominee Gold) 10 SC (100 ml/acre) 20–30 days after sowing, followed by a pre-emergence treatment of pendimethalin (Stomp) 30 EC (1000 ml/acre) three days after sowing. Pendimethalin efficiently controlled Leptochloa but bispyribac was ineffective against it.
12. Pyrasufuron ethyl 10 WP (60 g/acre) can be utilised as an alternative to pendimethalin for more efficient Leptochloa management.
13. Use Azimsulfuron 50 DF (16g/acre) instead of Bispyribac if Cyperus rotundus and broad leaf weeds are a serious problem in the field.
14. A flat fan nozzle should be used for herbicide spraying. The wrong nozzle choice could result in ineffective weed management. Avoid "swinging" the pesticide when applying it.
15. Use 150 litres of water per acre to make spray solution and 200 litres of water per acre to apply herbicide post-emergence.
16. For direct seeded rice to provide a larger yield, fertiliser must be applied properly and on time. N should be applied in four splits (15, 30, 45, and 60 days after planting) for medium duration cultivars (140 d). On the basis of a soil test, fertilisers should be administered.
17. Depending on the soil and weather circumstances, the crop should be irrigated every 4-5 days for the first irrigation in heavy textured soil and every 5-6 days for medium textured soil. The following irrigation should be administered at 15 DAS [37,38].

4. CONCLUSION

The ways for managing irrigation to boost agricultural water productivity and DSR grain quality have been the main subject of this review. Although direct planting reduces the need for irrigation, grain output varies based on time, rainfall pattern, crop management, and soil type. The most promising techniques involve using cutting-edge, site-specific tactics and technologies to improve water management in order to close the yield gap. In DSR, water productivity is high and exceeds transplanting values by more than 25%. By using good management techniques, comparable yields of DSR (2.2-8.7 t/ha) can be attained. In addition to being site- and location-specific, direct seeded rice's success depends on timely irrigations, foliar applications of micronutrients, and effective weed control programmes to improve the region's declining soil fertility, underground water levels, and poor farmers' ability to support themselves. DSR, which uses less water for labour and has lower production costs than PTR, has emerged as an effective, commercially viable, and environmentally promising substitute. Additionally, supporting technologies like mechanised seeding, proper water-nutrient-weed management, and mechanised harvesting and threshing may make it possible for suitable DSR technologies to be expanded and adopted on a broad scale.

DATA AVAILABILITY STATEMENT

In this investigation, no new data were collected or analysed.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Bouman BAM. How much water does rice use? Rice Today. 2009;8:28-9.
2. Mallareddy M, Thirumalaikumar R, Balasubramanian P, Naseeruddin R, Nithya N, Mariadoss A et al. Maximizing water use efficiency in rice farming: A comprehensive review of innovative irrigation management technologies.Water. 2023;15(10):1802.
3. Gill MS, Dhingra KK. Growing of basmati rice by direct seeding method in Punjab. Indian Farmer's digest. 2002;13:141.
4. Singh PK, Naresh RK, Bhatt R, Tiwari H, Singh O, Singh A et al. Efficient crop management strategies to improve crop resilience and crop-water productivity enhancement under direct seeded rice

cultivation system in adverse climatic conditions: A review; 2023.
5. Sharma A, Bharti A, Saha A, Sharma J, Bhagat R, Jamwa S. Influence of various water saving techniques on yield and water productivity of irrigated rice: A review. Int J Curr Microbiol Appl Sci. 2021;10(1):1993-2004.
6. Kaur J, Singh A. Direct seeded rice: Prospects, problems/constraints and researchable issues in India. Curr Agri Res Jour. 2017;5(1):13-32.
7. Singh R, Mahajan G, Bhullar MS. Direct seeded rice in North-West India–opportunities, scope and research gaps. Ludhiana: ICAR-Agricultural Technology Application Research Institute. 2016;52.
8. Gill MS, Kumar A, Kumar P. Growth and yield of rice (*Oryza sativa* L.) cultivars under various methods and ties of sowing. Indian J Agron. 2006;51:123-7.
9. Dahiya S. Management of irrigation water in direct seeded rice (*Oryza sativa* L.)-A review. In: Compendium of abstracts, Third International Conference on Bioresource and Stress Management. Jaipur: Rajsthan. 2017;17.
10. Ishfaq M, Akbar N, Anjum SA, ANWAR-IJL-HAQ M. Growth, yield and water productivity of dry direct seeded rice and transplanted aromatic rice under different irrigation management regimes. J Integr Agric. 2020;19(11):2656-73.
11. Farooq M, Siddique KHM, Rehman H, Aziz T, Lee D, Wahid A. Rice direct seeding: experiences, challenges and opportunities. Soil Till Res. 2011;111(2):87-98.
12. Bhushan L, Ladha JK, Gupta RK, Singh S, Tirol-Padre A, Saharawat YS et al. Saving of water and labour in a rice–wheat system with no-tillage and direct seeding technologies. Agron J. 2007;99(5):1288-96.
13. Ishfaq M, Akbar N, Khan I, Anjum SA, Zulfiqar U, Ahmad M et al. Optimizing row spacing for direct seeded aerobic rice under dry and moist fields. Pak J Agric Res. 2018;31(4):291-9.
14. Anjum SA, Akbar N, Ashraf U, Khan I, Shakoor A, Ishfaq M et al. Interactive effect of rice production systems and tillage systems in rice-wheat cropping system. Pak J Sci. 2019;71:21-7.
15. Jehangir WA, Masih I, Ahmed S, Gill MA, Ahmad M, Mann RA et al. Sustaining crop water productivity in rice–wheat systems of South Asia: A case study from Punjab Pakistan. Draft working [paper]. Lahore, Pakistan: International Water Management Institute; 2005.
16. Liu H, Hussain S, Zheng M, Peng S, Huang J, Cui K et al. Dry direct-seeded rice as an alternative to transplanted-flooded rice in Central China. Agron Sustain Dev. 2015;35(1):285-94.
17. Ali A, Erenstein O, Rahut DB. Impact of direct rice-sowing technology on rice producers' earnings: Empirical evidence from Pakistan. Dev Stud Res. 2014;1(1):244-54.
18. Qureshi AS, Masih I, Turral H. Comparing land and water productivities of transplanted and direct dry seeded rice for Pakistani Punjab. J Appl Irrig Sci. 2004;41:47-60.
19. Sudhir-Yadav , Humphreys E, Kukal SS, Gill G, Rangarajan R. Effect of water management on dry seeded and puddled transplanted rice: Part 2: Water. Field Crops Res. 2011;120(1):123-32.
20. Guyer R. Quadranti M. In: Efect of seed rate and nitrogen level on the yield of direct wet-seeded rice. Proceedings of the 10th Asian-Pacific weed science society conference. Thailand: Chiangmai. 1985;304-11.
21. Grigg DE. The agricultural systems of the world: an evolutionary approach. Cambridge, UK: Cambridge University Press; 1974.
22. Pandey S, Velasco L. Trends in crop establishment methods in Asia and research issues. In: Toriyama K, Heong KL, Hardy B, editors. Rice Is Life: Scientific Perspectives for the 21st. Los Baños, Philippines: Century. International Rice Research Institute and Tsukuba, Japan: Japan International Research Center for Agricultural Sciences. 2005;178-81.
23. Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. Weed management in direct-seeded rice. Adv Agro; 2007.
24. Rao AN, Nagamani A. Available technologies and future research challenges for managing weeds in dry-seeded rice in India. Proceed of the 21st Asian Pacifc Weed Sci Soc Conference,Oct 2-6 2007, Colombo, Sri Lanka. 2007;391-491.
25. Joshi R. Management interventions to enhance water productivity in dry-seeded rice (*Oryza sativa* L.). Int J Agric Environ Biotechnol. 2016;9(1):69-83.

26. Kumar S, Narjary B, Kumar K, Jat HS, Kamra SK, Yadav RK. Developing soil matric potential based irrigation strategies of direct seeded rice for improving yield and water productivity. Agric Water Manag. 2019;215:8-15.
27. Chakraborty D, Ladha JK, Rana DS, Jat ML, Gathala MK, Yadav S et al. A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci Rep. 2017;7(1):9342.
28. Du T, Kang S, Zhang J, Davies WJ. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. J Exp Bot. 2015;66(8):2253-69.
29. Fereres E, Orgaz F, Gonzalez-Dugo V. Reflections on food security under water scarcity. J Exp Bot. 2011;62(12):4079-86. doi: 10.1093/jxb/err165, PMID 21624976.
30. Chaudhary A, Venkatramanan V, Kumar Mishra A, Sharma S. Agronomic and environmental determinants of direct seeded rice in South Asia. Circular Economy and Sustainability. 2022:1-38.
31. Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK et al. Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron J. 2011;103(4):961-71.
32. Gupta RK, Naresh RK, Hobbs PR, Ladha JK. Adopting conservation agriculture in the ricewheat system of the Indo-Gangetic Plains: new opportunities for saving water. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK, editors. Water wise rice production. Proceedings of the international workshop on water wise rice production, Apr 8-11, 2002, Los Baños, Los Baños, Philippines, Philippines. International Rice Research Institute; 2002.
33. Sandhu N, Yadav S, Kumar Singh V, Kumar A. Effective crop management and modern breeding strategies to ensure higher crop productivity under direct seeded rice cultivation system: a review. Agronomy. 2021;11(7):1264.
34. Kumar V, Ladha JK. Direct seeding of rice. Adv Agron. 2011;111:297-413.
35. Mori S, Nishizawa N, Hayashi H, Chino M, Yoshimura E, Ishihara J. Why are young rice plants highly susceptible to iron deficiency? Plant Soil. 1991;130(1-2):143-56.
36. Katyal JC, Sharma BD. A new technique of plant analysis to resolve iron chlorosis. Plant Soil. 1980;130:143-56.
37. Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN. Weed management in aerobic rice system under varying establishment methods. Crop Prot. 2008;27(3-5): 660-71.
38. Rajinder-Pal G, Mahajan G, Sardana V, Sharma N, Chauhan BS. Grain quality of dry-seeded rice in response to sowing dates and genotypes. Int J Plant Prod. 2018;12(2):95-106.
39. Yadav S, Humphreys E, Kukal SS, Gill G, Rangarajan R. Effect of water management on dry seeded and puddled transplanted rice, Part 2, Water balance and water productivity. Field Crops Res. 2011;120:123–132.

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