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REVIEW PAPER

Agronomic and Environmental Determinants of Direct Seeded Rice in South Asia

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Abstract

Rice (*Oryza sativa* L.) is the staple food of more than 50% of the world's population. Manual puddled transplanted rice (PTR) system is still the predominant method of rice establishment. However, due to declining water tables, increasing water scarcity, water, labor- and energy-intensive nature of PTR, high labor wages, adverse effects of puddling on soil health and succeeding crops, and high methane emissions, this production system is becoming less profitable. These factors trigger the need for an alternative crop establishment method. The direct-seeded rice (DSR) technique is gaining popularity because of its low input demand compared to PTR. It is done by sowing pre-germinated seeds in puddled soil (wet-DSR), standing water (water seeding), or dry seeding on a prepared seedbed (dry-DSR). DSR requires less water and labor (12–35%), reduces methane emissions (10–90%), improves soil physical properties, involves less drudgery and production cost (US$9–125 per hectare), and gives comparable yields. Upgraded short-duration and high-yielding varieties and efficient nutrient, weed, and resource management techniques encouraged the farmers to switch to DSR culture. However, several constraints are associated with this shift: more weeds, the emergence of weedy rice, herbicide resistance, nitrous oxide emissions, nutrient disorders, primarily N and micro-nutrients, and an increase in soil-borne pathogens lodging etc. These issues can be overcome if proper weed, water, and fertilizer management strategies are adopted. Techniques like stale bed technique, mulching, crop rotation, Sesbania co-culture, seed priming, pre-emergence and post-emergence spray, and a systematic weed monitoring program will help reduce weeds. Chemical to biotechnological methods like herbicide-resistant rice varieties and more competitive allelopathic varieties will be required for sustainable rice production. In addition, strategies like nitrification inhibitors and deep urea placement can be used to reduce N_2O emissions. Developing site and soil-specific integrated packages will help in the broader adoption of DSR and reduce the environmental footprint of PTR. The present paper aims to identify the gaps and develop the best-bet agronomic practices and develop an integrated package of technologies for DSR, keeping in mind the advantages and constraints associated with DSR, and suggest some prospects. Eco-friendly, cost-effective DSR package offers sustainable rice production systems with fewer resources and low emissions.

Keywords Direct seeded rice · Puddled transplanted rice · Greenhouse gas emissions · Resource conservation strategies · Weeds · Conservation agriculture · Crop establishment

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Extended author information available on the last page of the article

Introduction

Rice (*Oryza sativa* L.) is a major cereal crop cultivated in at least 95 countries across the globe [55] and provides staple food for more than half of the world's population [2, 205]. On a global scale, the total area under rice is 163.5 million hectares with an annual production of 758.9 million tons and productivity of 4641.5 kg/ha. In India, it is grown on about 42.5 million ha with a total production of 105.5 million tons and productivity of 3632.9 kg/ha. To meet the second Sustainable Development Goal (SDG) of the UN, which is to end hunger in all its forms by 2030 and achieve global food security, additional paddy is needed to be produced to feed the ever-increasing population. However, the possibility of an increase in area under rice is very limited in the coming future. Therefore, the only way to get this extra rice is to increase productivity. The main dare is to achieve this productivity gain with less water, labor, and chemicals to ensure sustainability.

The following are the major constraints associated with the productivity and sustainability of rice-based systems: (1) increasing scarcity of water and labor, (2) inefficient use of inputs (fertilizer, water, labor), (3) climate change and variability, (4) emerging energy crisis and hike in fuel prices, (5) multiplying cost of cultivation, and (6) other issues like rapid urbanization, migration of labor to cities, non-agricultural work preferences, and farm-related pollution [119]. Better agronomic management practices and innovations in technology are required to overcome these problems.

Asia accounts for more than 90% of rice production and consumption. Conventionally, rice in Asia is grown by the transplanting method. Rice nurseries are raised in the transplanting method, and after 20–30 days, those rice seedlings are transplanted into puddled soil. Rice grown by this method is known as puddled transplanted rice (PTR). Puddling the soil has its benefits for rice cultivation. It creates an impervious layer that helps to reduce water percolation losses, facilitates easy seedling establishment, controls weed, and creates anaerobic conditions to enhance nutrient availability [196]. However, repeated puddling damages soil aggregates, breaks capillary pores, lessens permeability in sub-surface layers, and forms hard-pan [1, 201, 203], which proves detrimental to the establishment and growth of the following crop [83]. Besides, puddling and transplanting demand large amount of water (3000–5000 L water to produce 1 kg rice] [27] and human labor, which are becoming scarce and expensive day by day, thereby increasing the cost of cultivation and making the paddy production less profitable.

Moreover, the physical drudgery in transplanting — which women primarily do — is a matter of concern. So, all the above factors trigger the search for an alternative rice crop establishment method. Direct seeded rice (DSR) seems a viable option to make this shift. DSR refers to the process of sowing rice seeds directly into the field in place of transplanting the rice seedlings from the nursery. Upgraded short-duration and high-yielding varieties and nutrient, weed, and resource management techniques encouraged the farmers to switch to DSR culture. It is widely practiced in many Asian countries: Malaysia, Sri Lanka, Vietnam, Thailand, Cambodia, and the Philippines. This review aims to develop best-bet agronomic practices so that ecological and agronomic input efficiency can be enhanced and the environmental footprint of PTR can be reduced. Types of direct seeding, reasons for adoption of DSR, advantages and constraints of

DSR, and integrated package of technologies for DSR are discussed further in this paper.

Direct Seeding

Direct seeding is the oldest known method of rice establishment. It was prevalent before the 1950s, but gradually, puddled transplanting replaced this method [75, 168, 185, 186]. Direct seeding can be done in three principal ways, which are modified with time based on technological innovations and demand for better resource-efficient practices. These direct seeding methods can be classified based on land preparation, seedbed condition, ways of sowing, and seed environment (aerobic or anaerobic) [119].

1. Wet-DSR: in this, pre-germinated seeds (radicle 1–3 mm) are broadcast or sown in lines on wet/puddled soil. When pre-germinated seeds are sown on the surface of puddled soil, the seed environment becomes aerobic, and it is called aerobic wet-DSR (surface). It can be done using a drum seeder [187]. On the other hand, when the pre-germinated seeds are drilled into puddled soil, the seed environment becomes anaerobic and is called anaerobic wet-DSR (subsurface). In this, seeds are sown inline using an anaerobic seeder with a furrow opener and closer [16]. Wet-DSR is primarily done to manage the labor shortage and is currently practiced in Malaysia, Thailand, Vietnam, the Philippines, and Sri Lanka [21, 24, 167].
2. Dry-DSR is broadcast or drilled in dry/unpuddled soil. In dry-DSR, rice is established using several different methods, including (a) broadcasting of dry seeds on unpuddled soil after either zero tillage (ZT) or conventional tillage (CT), (b) dibbled method in a well-prepared field (CT-dry-dibbledR), and (c) drilling of seeds in rows after conventional tillage (CT-dry-DSR), reduced tillage using a power-tiller-operated seeder (PTOS) (RT (PTOS)-dry-DSR), *-/zero tillage (ZT-dry-DSR), or raised beds (Bed-dry-DSR) [119]. The seedbed condition is dry (unpuddled), and the seed environment is mostly aerobic; thus, this method is known as dry-DSR. This method is traditionally practiced in rainfed upland, lowland, and flood-prone Asia areas [185, 186]. However, this method has recently been gaining importance in irrigated areas where water is becoming scarce. In dry-DSR, land preparation is done before the onset of monsoon, and seeds are sown before the wet season to take advantage of pre-monsoon rainfall for CE and early crop growth.

   Both wet-DSR and dry-DSR can reduce water and labor usage compared to CT-PTR.
3. Water seeding is broadcast in standing water. Water seeding has gained popularity in red rice or weedy rice, which is becoming a severe problem [13]. Aerial water seeding is the most common method used in California (USA), Australia, and European countries to suppress difficult-to-control weeds, including weedy rice. This method is also becoming popular in Malaysia. The rice varieties used possess good tolerance of a low dissolved oxygen level, low light, and other stress environments [16]. In addition to irrigated areas, water seeding is practiced in areas where early flooding occurs and water cannot be drained from the fields.

Method of DSR adopted varies considerably from location to location depending upon different factors like labor, land preparation (tillage), establishment methods, seed rate, water, and weed and nutrient management [116].

Drivers of Shift from Puddled Transplanting to Direct Seeding of Rice

Water Scarcity

Globally, water is becoming a scarce resource. The groundwater table is declining at an alarming rate. On the other hand, conventional rice cultivation requires substantial water. The lack of ability to recreate water calls for the need to conserve and ensure adequate water drops. It has been estimated that up to 5000 L of water is used to produce just 1 kg of rough rice [27], which is way too high. Rice consumes two to three times more freshwater than any other cereals [18, 31, 239]. Barker et al. [18] also reported that rice consumes about 50% of total irrigation water used in Asia. In India, per capita water availability decreased by 72.3% between 1951 and 2005 (5831 m^3 and 1611 m^3 in 1951 and 2015, respectively) and is likely to decline further by 77.8% till 2050 (1292 m^3 in 2050) (modified from Gardner-Outlaw and Engelman [68]). Water availability decreases because of the increasing population, declining water table, deteriorating water quality, inefficient irrigation systems, and competition from non-agricultural sectors. So, water scarcity acts as a driving force for adopting direct seeding. Since the last decade, there have been numerous efforts to find alternatives to conventional PTR [119]. Excellent water management will ensure the availability of sufficient water for crop production.

Many studies have reported the potential of DSR as a replacement for PTR. For example, an average of 67–104 mm (11–18%) irrigation water savings in wet-DSR than CT-PTR was observed under on-farm trials in the Philippines [236] while keeping the criteria of irrigation application same for both the rice establishment methods. However, in another study done in the Muda region of Malaysia by Cabangon [30], it was found that the application of irrigation water in dry-DSR was less by ~ 200 mm (40%) than CT-PTR. Likewise, in India, 10–15% water savings have been reported with dry-DSR compared to CT-PTR when the criteria of irrigation application were either the appearance of hairline cracks or tensiometer-based (− 20 kPa at 20-cm depth) [22, 96, 228, 229].

As DSR requires less water and is more tolerant of water stress than PTR, it has a more adaptive capacity to climate change. Climate change is likely to increase rainfall variability and the risk of drought and water stress in the coming future. With the growing shortage of water, dry-DSR with minimum/reduced or zero tillage further enhances the potential of this technology by saving labor [35, 104].

Labor Shortage

CT-PTR is very labor-intensive. On the other hand, Indian farming is witnessing labor scarcity [209]. Major reasons contributing to the scarcity are low wages and temporary employment in agriculture, migration of labor to cities in search of urbanized lifestyle, physical drudgery involved in farming, preference for non-agricultural work, and involvement in social welfare schemes like The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), 2005. Covid-19 pandemic–related curbs have further worsened the situation. Moreover, labor scarcity is season- and location-specific because of the mismatch in demand and supply at the right time and place. Dawe [47] reported that labor required for agricultural work is declining at the rate of 0.1–0.4%, with an average of 0.2% per year. Because of severe labor scarcity, labor wages have gone up drastically in the last few years. This has made the CT-PTR system uneconomical. All these factors urge the need for alternative practices like DSR.

DSR demands less labor as it avoids raising nurseries, uprooting seedlings, puddling, and transplanting. Instead of transplanting, which requires 25–50 person-days/ha, DSR requires about 5 person-days/ha [16, 47]. Thus, the requirement of labor in DSR is spread out over a longer period. This, in turn, avoids the problem of labor scarcity at peak season and having less dependence on hired labor. It has been reported that the labor requirements for crop establishment (CE) in direct seeding compared with transplanting decrease by more than 75% [47, 92, 167]. Depending on the season, location, and type of DSR method used, labor requirements reduced from 11 to 66% in DSR compared with CT-PTR [114, 187]. The variation in labor savings largely depends on the labor used for controlling weeds in DSR. If weeds can be managed effectively using herbicides, it can save additional labor. The newly emerging techniques of ZT-Dry-DSR report substantial labor savings, as no puddling and tillage are required in this operation. It has been reported that PTR can be substituted with wet-DSR at places where only labor/wage rate is a major limiting factor (e.g., Malaysia, Sri Lanka). But, in areas where water and labor are scarce, PTR should be replaced with dry-DSR (e.g., South Asia). Global drivers for shift from PTR to DSR are shown in Figs. 1, 2, 3, and 4.

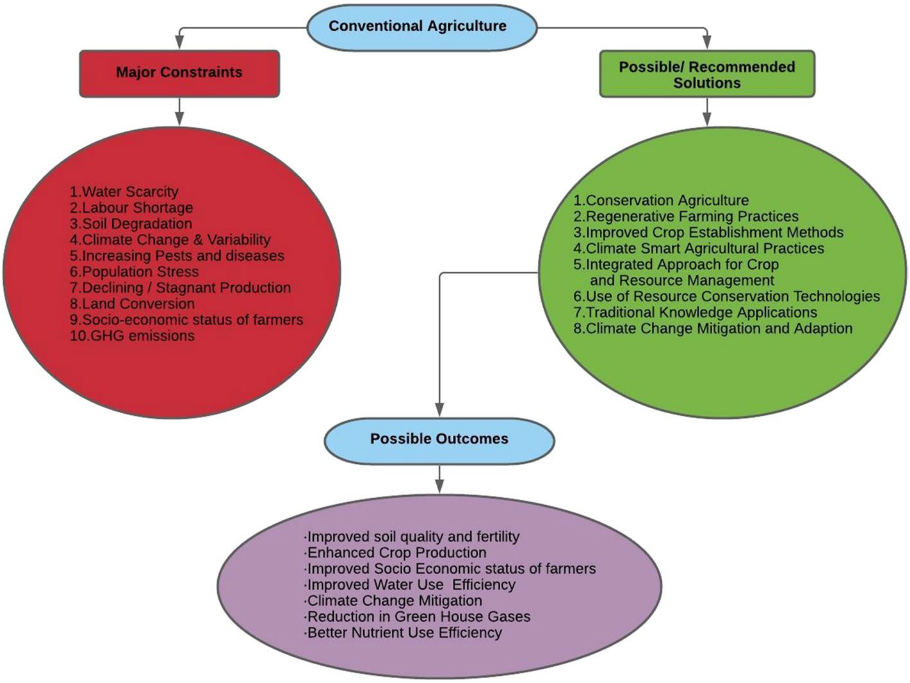

Fig. 1 An illustrative representation of major constraints and possible solutions for conventional agriculture and outcomes of emergent agronomic practices

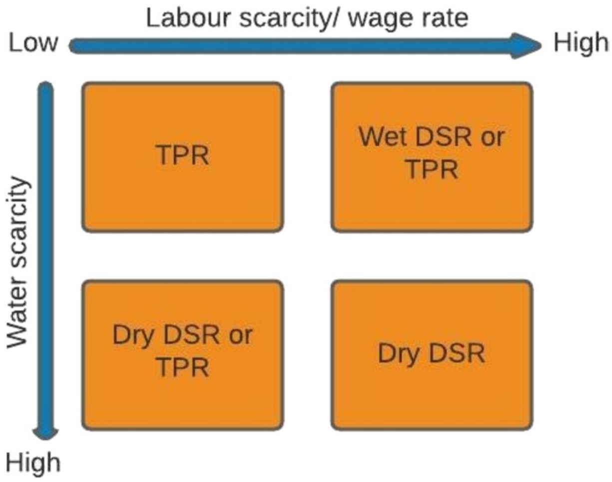

Fig. 2 Global drivers for Shift from PTR to DSR

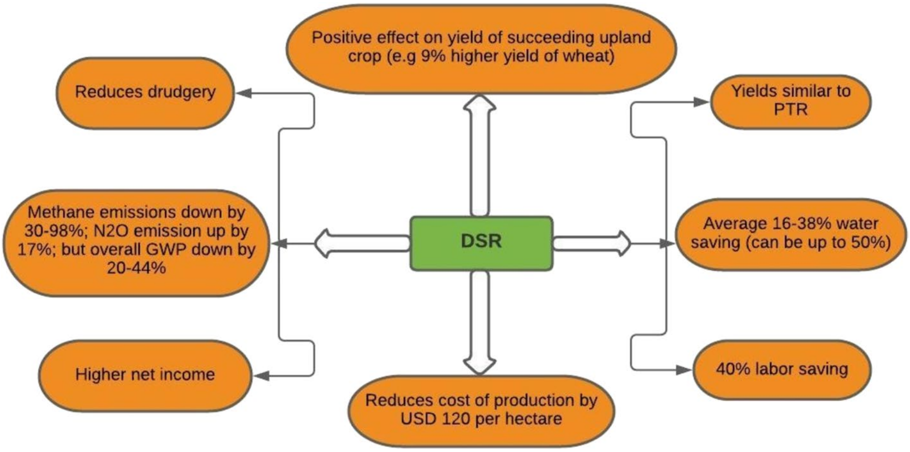

Fig. 3 Benefits of DSR adapted from: Kumar and Ladha (2011), Chakraborty et al. (2017), Padre et al. (2016)

Soil Health

Puddling has varying effects on the well-being of soil health (soil quality, especially on soil physical properties), which claims to be another reason for the shift from CT-PTR to dry-DSR on plowed soil (no puddling) or in ZT conditions, where an upland crop is grown after rice [73, 76, 119]. This is particularly relevant to the rice–wheat system, in which soil goes through the wetting and drying phenomenon [118]. Puddling breaks soil aggregates, destroys capillary pores, disperses fine clay particles, and forms hard-pan at shallow depth. Although puddling helps transplant and establish seedlings, control weeds, better water, and nutrient availability, it adversely affects the growth and yield of succeeding upland crops [69].

Numerous studies have been published that evaluated the effects of puddling in rice on succeeding wheat crops. Kumar [116] compiled and analyzed 35 such studies, out of which

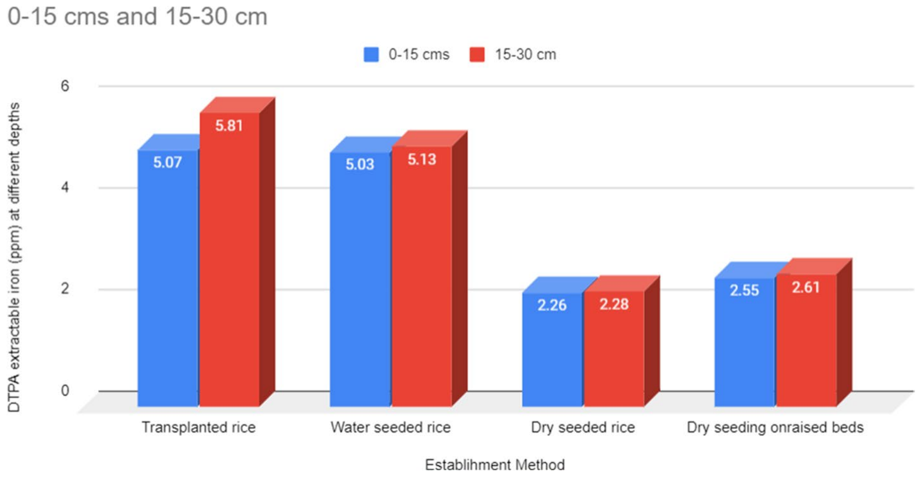

Fig. 4 DTPA-extractable iron (ppm) in the soil at 0–15 and 15–30 cm depth at maximum tillering stage (adapted from Singh et al. 2002)

28 showed adverse effects of puddling on subsequent wheat crop productivity. Five cases mentioned no impact, and only one study showed positive puddling results. The parameters considered were location, soil type, rice establishment method, number of crop cycles, rice yield, wheat yield, and percentage of change in wheat yield. In two medium-term studies carried out at Pantnagar (5-years) and Modipuram (7-years), the performance of wheat was evaluated after either puddled or dry-DSR. It was observed that the Pantnagar site had 12% higher wheat yield in dry-DSR plots than in CT-TPR in all 5 years [208, 210, 223b]. However, at Modipuram, the wheat yield was the same in the first 3 years, followed by 0.5–1.0 t/ha (9–25%) higher yield in dry-DSR plots in the later years [69]. The main reason for the lower grain yield of wheat after CT-PTR was poor root development due to the puddling done in the preceding rice crop [1, 25, 40, 89, 161].

Similarly, Gangwar [65, 66] compared the DSR-based cropping system productivity with the PTR-based cropping system productivity. He observed that the DSR-wheat, DSR-chickpea, and DSR-mustard system productivities (14.96 t/ha, 14.48 t/ha, and 13.48 t/ha, respectively) were higher than the PTR systems (13.53 t/ha, 12.12 t/ha, and 11.81 t/ha respectively). It can be understood that puddling benefits the rice crop, but it has detrimental effects on the growth and yield of the succeeding crop as it badly affects soil health [133, 224]. Therefore, it becomes imperative to find alternative methods to puddling. More attention should be paid to the regions where water availability is less and crops are grown after rice cultivation.

CA

Conservation agriculture (CA) involves minimum soil disturbance (reduced tillage or zero tillage), permanent soil covers through crop residues or cover crops (incorporation/retention), and crop diversification (sequences and rotations) for achieving higher productivity [135]. Conservation tillage (CT) involves zero or minimal tillage followed by row seeding using a drill. As stated by Ladha [119] when CT utilizes crop residue as mulch with improved crop and resource management practices, it is termed CA. Conventional agriculture (resource intensive) has led to declining/stagnating crop and factor productivity and a deteriorating resource base in cereal systems [111, 137]. Zero tillage is primarily promoted in wheat in the rice–wheat system and covers about 3 million hectares of land in Indo-Gangetic Plains (IGP) of South Asia [77, 80]. Factors responsible for rising interest and wide adoption of ZT in wheat are increased productivity (3–12%, due to timely planting), profitability by the reduction in production cost (by avoiding tillage), better resource-use efficiency, and farmer's livelihood, particularly in areas where rice harvest is delayed [51, 77, 84, 119]. Now, efforts are being made to develop ZT rice followed by ZT wheat — commonly referred to as "double-zero tillage" to explore the full potential of zero tillage.

Economics of DSR

The economic motive for farmers is to get higher profitability which can be defined as the difference between the gross economic returns and the total cost. With CT, farmers get a higher net economic return under wet or dry DSR than TPR, with 13% higher for wet DSR [33]. Under dry-DSR with ZT, the economic returns are even higher by 25.9% than TPR due to increased savings in water input and cost of cultivation. Such an increase in farmers' profitability can be explained by two reasons, a reduction of production costs and an expansion of the total revenue.

The production costs include two parts, the cost of inputs (seeds, agro-chemicals, fertilizers and pesticides, water), and the cost induced by the use of production factors (human labor and machines) in field operations (such as land preparation, sowing, irrigation, weeding, agro-chemicals applications, harvesting, threshing). Overall analysis of 77 published studies in Asian countries done by [116] shows that various methods of DSR reduced the cost of production by US$9–125/ha compared with conventional practice (TPR). According to Chakraborty [33], wet-DSR induces a reduction in cost by 2.4–8.8%. These cost reductions under DSR are mainly due to lower labor costs, tillage costs, or both.

Reduced Tillage

According to the rice establishment method, the necessity of tillage can be relatively relaxed. Under TPR, rice seedlings are transplanted into puddled soil after land preparation with wet intensive tillage, a very energy-intensive method. Tillage operations account for 15% of the total production cost in irrigated rice, and farmers in the Indo-Gangetic Plains are assumed to spend US$50–60/ha on land preparation [129]. On the contrary, under dry-DSR, seeds are sown on unpuddled soil, either after dry tillage or minimal tillage. Of course, reduced tillage significantly lowers the production cost (US$37–92/ha) [116]. According to Chakraborty [33], wet-DSR and dry-DSR have a higher grain yield than TPR under conventional tillage, and wet-DSR has the most considerable yield advantage (1.3–4.7%). The main benefits of minimum and zero tillage practices are conservation of organic matter and soil moisture, reduction in water and wind erosion, reduction in fuels and animal and human energy, and time and water required for land preparation, and possible provision of a favorable environment for biological activity [56].

Crop Intensification

Besides saving water and labor, DSR provides economic benefits by integrating an additional crop (crop intensification). This becomes the reason for the spread and rapid adoption of DSR in many regions. Furthermore, early maturity (7–11 days) of DSR than PTR allows it to incorporate another crop and fits well in different cropping systems.

In Long An Province in the Mekong River Delta region of Vietnam, DSR facilitated double cropping in place of a single crop of PTR [167]. Early harvesting of dry-DSR in August was possible due to the early establishment and short-duration varieties (95–105 days), leaving sufficient time and rainfall for another rainfed rice crop to grow. My [151] reported that some farmers could grow a third rice crop from December to February with additional irrigation. Thus, DSR is increasing gradually and steadily over different regions. Availability of new high-yielding and short-duration varieties and new herbicides for weed control made this shift technically viable [149, 167]. Rising rice production has helped increase food security, but there is a widely recognized need to assess the sustainability of such production systems [49].

GHG Emission

Agriculture contributes to the emission of greenhouse gases (GHGs) (mainly CO_2, CH_4 and N_2O), which cause global warming. Based on data from the meta-analysis by Joseph Poore and Thomas Nemecek [180], published in *Science*, crop production accounts for 27% of food emissions. About 21% of these food's emissions come from crop production for direct human consumption, and 6% comes from animal feed production. They are the direct emissions that result from agricultural production — this includes elements such as the release of nitrous oxide from fertilizers and manure, carbon dioxide from agricultural machinery, and methane emissions from rice production. Rice-based cropping systems play a significant role. GHG emissions, mainly CO_2 and CH_4 from rice fields, are substantial and sensitive to management practices. Therefore, rice is an essential target for mitigating GHG emissions [246].

Rice is among the three major crops of the world, occupying ~ 155 million ha of land. An increasing population of India will demand 25% more rice by 2025 [129]. In the Indo-Gangetic Plain of Northern India, Punjab, India, produces 50% of the nation's rice and is known as the "food bowl of India." The most common method of rice cultivation in the IGP is puddled transplanting. This flooded rice culture is the primary culprit of methane emissions because prolonged flooding results in anaerobic soil conditions. This accounts for 10–20% of total global methane emissions [86, 189]. CH_4 is produced in flooded soils due to reducing C compounds to CH_4 in limited oxygen supply. The standing water in conventional rice fields restricts oxygen from the atmosphere into the soil. A small but particular bacterial group named methanogens makes the water-saturated soil devoid of oxygen, and anaerobic conditions are formed. Therefore, methane emissions are high in conventional PTR, where standing water conditions are maintained throughout the crop growth. On the other hand, DSR fields are not continuously submerged underwater, so anaerobic conditions are not created. As a result, methane emissions are low [174].

Pathak [174] conducted a 2-year field experiment in the Jalandhar district of Punjab, India, to quantify GHG mitigation, water, and labor-saving potential of DSR with TPR. He found that the average GWP of CO_2, CH_4, and N_2O in TPR was 2.91 t/ha, and in DSR, it was 1.94 t/ha. It was also concluded that if the entire state under TPR is converted to DSR, GWP will reduce by 33%. Along with this, 3–4 irrigations were saved under DSR without yield loss. Tractor use decreased to 58% and human labor use reduced to 45% in DSR compared to TPR. This shows that by reducing GHG emissions, water, and labor (both human and machine) without reducing yield, DSR can be a feasible alternative to PTR for mitigating and adapting to climate change and increasing farmers' income [174]. A similar study was conducted at the Indonesian Agricultural Environment Research Institute (IAERI), Central Java, Indonesia. Susilawati [231] reported that CH_4 emissions were 47% less in DSR than PTR. GWP reduced by 46.4% under DSR without any significant loss of yield.

Many studies which compared CH_4 emissions from various tillage and crop establishment methods along with similar water management techniques revealed that CH_4 emissions were lower in wet (8–22%) or dry-DSR (24–79%) as compared to CT-PTR [116]. Ishibashi [91] compared ZT-dry-DSR and CT-TPR and found that the former is 20% more efficient in reducing GWP. Pathak [173] simulated for Indian conditions and found that dry-DSR on raised beds or ZT can reduce CO_2 equivalent per hectare by 40–44% compared to CT-TPR. Harada [79] reported that GWP declined by 42% in Japan by changing puddling to zero tillage.

Even in CT-PTR, CH_4 emissions vary from study to study. The reason may be individual or combined effects of climatic conditions, edaphic factors, and water management [10]. Therefore, it can be concluded that DSR is more efficient in reducing GHG emissions, mainly CH_4, if proper crop management practices are adopted and precise nutrient use employed [32]. In addition, under DSR, the dissimilatory nitrate reduction to ammonium (DNRA) pathway can reduce N_2O emissions and protect NO_3^- from leaching losses [164].

Constraints Associated with DSR

Weeds

Weeds are a major biotic constraint to the success of DSR in general and dry-DSR in particular [98, 185, 186, 215]. Competition by the weeds is not only for nutrients; the case has also been with space, light, and moisture in the entire growing season [3]. Earlier research has shown that yield loss is greater in DSR than in transplanted rice without effective weed control options [17, 185, 186]. Weeds create more problems in DSR than in puddled transplanting because (1) emerging DSR seedlings are less competitive with concurrently emerging weeds, and (2) in wet- and dry-DSR, the initial flush of weeds is not controlled due to the absence of flooding [113, 185, 186]. Failure to manage weeds in DSR leads to very low or no yield, so controlling weeds effectively in DSR is a real challenge [147, 216]. Direct seeded rice is heavily infested with weeds, so the success of DSR depends on effective weed management [36,185,186,215a, 219]. Yields were reduced by 96% in dry-DSR, 61% in wet-DSR, and 40% in the machinery-transplanted crop due to uncontrolled weeds [107, 126]. Aerobic systems are subjected to much higher weed pressure than CPTR [185, 186], in which weeds are suppressed due to prevailing anaerobic environments in flooded conditions [146]. Heavy yield losses due to lack of proper weed management can reach up to 70–100% in dry-DSR [122, 123], and this has been reported by many researchers [65, 66, 208, 210, 211, 217, 223].

Economic Consequences of Weeds

Several parameters decide the economic consequences of weeds in rice, such as infestation rate, the types of weeds, the cultivated varieties, and the measures taken to control them. Farmer's income is affected due to the following factors:

- A quantity effect due to substantial reductions in yield
- Due to the presence of weeds seeds (including red rice) in the grain, a price effect
- A cost effective, due to increased costs of production incurred by control measures such as labor, equipment, chemicals, and energy [233–235]

This reduction in farmers' income can eventually lead to the abandonment of rice production.

The Emergence of Weedy Rice

Weedy rice (*O. sativa f. spontanea*), also known as red rice, has become a severe concern in areas where rice production has shifted from transplanting to direct seeding, especially dry-DSR. The weedy rice paradox is well known but underestimated. Weedy rice is conspecific and congeneric of cultivated rice; it has both acquired and wild rice traits. Then, it is challenging to control it either traditional or biotechnologically because it promotes crop-weed hybridization and the introgression of characteristics such as herbicide resistance [233–235]. It is challenging to manage weedy rice because of its similarity with rice in genetics, morphology, and phenology. Weedy rice is highly competitive and can cause severe yield losses ranging from 15–100% [116]. Weedy rice can also reduce milling quality if mixed with rice seeds during harvesting [160]. It can also increase the cost of production. Farmers may end up using most of the labor saved by DSR to control weeds.

Vegetatively, weedy rice possesses several traits of the agricultural weed syndrome [243], such as crop mimicry, seed dispersal, seed dormancy, rapid growth, high nutrient use efficiency, and herbicide resistance. Beyond these common traits, weedy rice exhibits high genetic and phenotypic diversity [156, 188, 238]. This diversity is dependent on the ecotype and habitat.

Selective control of weedy rice has never been achieved at a satisfactory level with herbicides [155]. Therefore, FAO [54] recommends an integrated approach that encompasses preventive, cultural, mechanical, and chemical methods targeting different phases of the weedy rice cycle. Moreover, clean and certified seeds should be used [185, 186]. It was observed by Azmi and Abdullah [12] that pre-plant application of soil-incorporated moline was effective in reducing the seed bank of weedy rice. Selective control of weedy rice can be achieved from herbicide-resistant rice technologies, but the risk of gene flow poses a constraint for the long-term utility of this technology [112].

However, weedy rice control methods that can be applied under DSR are neither practical nor sustainable as they are usually thought. Indeed, weedy rice is difficult to control because of its genetic, morphological, and phenological similarities with rice. Then, the integrated weed management (IWM) strategies typically do not lead to the total eradication of the weed infestation. Incomplete control of the weed for a given year could lead to eliminating the results of several years of sound control. Weedy rice escapes of 5% or less can produce enough seeds to restore original soil seed bank population levels [62].

In addition, the IWM is not sustainable because the IWM methods are expensive, time-consuming, and are not environment-friendly since they require more fuel energy, water, and herbicide [233–235].

Changes in Weed Flora

The composition of weed flora can change drastically with a shift from CT-TPR to alternative tillage and rice establishment methods [218]. Changes in weed composition and diversity in DSR were led by the changes in rice establishment method along with water, tillage, and weed management practices [116]. DSR is infested by complex weed flora, including grasses, broadleaf weeds, and sedges. In a study conducted at Modipuram, India, Singh [218] reported that the number of species of grasses, broadleaves, and sedges in CT-PTR was 6, 4, and 4, respectively, whereas in dry-DSR, it increased to 15 grass species and 19 broadleaf species, and the number of sedge species remained unaffected. This clearly shows that some new grass and broadleaf species that were not adapted to CT-PTR appeared in dry-DSR. More species-rich vegetation and diverse weed flora were observed in dry-DSR than in CT-TPR by Tomita [237]. About 46 species were present in transplanted rice in 1989, and, after 3 years (six seasons of rice) of wet-DSR, 21 new weed species were added to the weed flora [14, 148]. Higher numbers and more diverse flora in dry-DSR could lower the efficacy of weed management strategies, including herbicides. Therefore, it is imperative to incorporate a systematic weed monitoring program and the introduction of DSR. Then, only it would be possible to develop effective integrated weed management strategies, which include identifying new herbicides that are effective against a broad spectrum of weeds.

Development of Herbicide Resistance

Increased practice of DSR also increased herbicide use for controlling weeds in rice, which resulted in the appearance of resistance in weeds against certain herbicides. The first case of herbicide resistance was seen in *F. miliacea* against 2,4-D in Malaysia in 1989. Later on, this number of resistant weed biotypes against different herbicides increased to 10. Post DSR introduction, several herbicide-resistance cases in weeds were also observed in Thailand (5), Korea (10), and The Philippines (3) [116].

Emissions of Nitrous Oxide

DSR can help reduce methane emissions, but aerobic soil conditions in DSR, especially in dry-DSR, contribute to increased nitrous oxide emissions. The biologic processes of nitrification and denitrification are the effective mechanisms of nitrous oxide emission from agricultural soils. Nitrification occurs in aerobic soil conditions, while denitrification occurs under anaerobic conditions [171]. Due to the prevailing anaerobic conditions in TPR, denitrification is the principal mechanism for N_2O emissions, whereas DSR nitrification is the primary mechanism [172]. Pathak [174] quantified the N_2O emissions from DSR and TPR fields of Punjab, India. They reported that emissions from DSR fields were slightly higher than TPR. Cumulative emission of N_2O during the entire crop duration in 2010 was 2.0–2.2 kg/ha in DSR and 1.6–1.8 kg/ha in TPR. In a study conducted in India comparing N_2O emissions from CT-TPR and different dry-DSR methods (CT-dry-DSR, bed-dry-DSR, ZT-dry-DSR), it was found that N_2O emissions were 0.31–0.39 kg N/ha in CT-TPR, which increased to 0.90–1.1 kg N/ha in CT-dry-DSR and bed-dry-DSR and 1.3–2.2 kg N/ha in ZT-dry-DSR. Similarly, a study conducted in western Japan also observed higher emissions of N_2O under ZT-dry-DSR than in CT-TPR [90]. These results suggest the need to deploy strategies to reduce N_2O emissions from dry-DSR to minimize adverse environmental impacts. Methane emission starts at redox potential of soil below − 150 mV and is stimulated at less than − 200 mV [100, 128, 245]. Nitrous oxide production increases at redox potentials above 250 mV [85]. Hou [85] suggested developing water management practices so that soil redox potential can be kept at an intermediate range (− 100 to + 200 mV) to minimize emissions of both CH_4 and N_2O. This range is high enough to prevent CH_4 production and low to encourage N_2O reduction to N_2 as the critical soil redox potential identified for N_2O production is + 250 mV [85]. The overall effect of direct-seeding methods on GWP depends on the total emissions of all three major GHGs. It has been observed that measures to reduce one source of GHG emissions lead to increases in other GHG emissions, and this trade-off between CH_4 and N_2O is a significant hurdle in devising an effective GHG mitigation strategy for rice [246]. Very few studies have compared different rice production systems in total GWP, taking all three GHGs.

Nutrient Disorders

Nutrient dynamics in DSR and TPR systems vary due to the difference in land preparation and water management techniques [104]. Nutrients needed for direct-seeded rice have faced tight competition from weeds. In DSR, soil conditions are mostly aerobic because of dry land preparation, while in PTR, the soil is mainly kept flooded and is puddled. Puddling positively impacts weed control [194] and nutrient availability [244]. Less oxygen in the rhizosphere in submerged conditions prevents oxidation of NH^{4+} and reduces leaching [108]. It also increases the availability of P [208, 210, 223, 250] and Fe [165, 230].

Deficiencies of micronutrients are of major concern in DSR. The shift from PTR to DSR reduces Zn availability to rice because of its reduced release from highly insoluble fractions in aerobic rice fields [67, 108]. Reasons for Zn deficiency are high pH, high carbonate content [127], and more bicarbonates in calcareous soils [64], which immobilize Zn due to inhibition effect [72]. Zn uptake in DSR is also affected by source and time of application [72]. When pH is below neutral in the rhizosphere, the availability of P and Zn increases because of their increased solubility [108, 195]. The availability of Fe is high in anaerobic soils because of low redox potential. However, Fe becomes a limiting factor in aerobic soils when soil pH is high. Due to unsaturated soil conditions in DSR, plants can show chlorosis because of iron deficiency. Prolonged iron deficiency may also lead to severe yield losses in DSR; hence, care should be taken to manage iron deficiency. Singh [208, 210, 223] reported that in dry-DSR, the iron content was about half of the submerged PTR and WSR treatments. The values were below the critical limit of 4.5 ppm. Therefore, appropriate nutrient management strategies need to be developed based on nutrient dynamic studies in DSR.

Increase in Soil-Borne Pathogens

Soil-borne pathogens such as root-knot nematodes (RKNs) pose a severe threat when PTR is shifted to DSR. *Meloidogyne graminicola*, a root-knot nematode, was first reported in 1963 from the Louisiana State University, Baton Rouge, USA. In a study at Tarlac, Philippines, RKNs were the most damaging pathogen for aerobic rice Apo [182]. It was reported that rice yield in untreated plots was 0.2–0.3 t /ha in 2006 and nil in 2007. However, in fields treated with nematicide dazomet, yield of 2.2 t /ha was obtained in 2006 and 2.4 t /ha in 2007. In the first year, the degree of galling in rice roots was only 0.4 in the nematicide-treated plots, whereas it was 3.4–4.4 in untreated plots. In 2007, their galling increased even in nematicide-treated fields to 2.4, whereas it was 4.8–4.9 in untreated plots. It can be concluded that pathogens are detrimental to the growth of rice.

Diseases and Insect Pests

DSR is susceptible to various diseases, and rice blast is the most common [24]. Damage due to rice blast increases under water stress conditions [23]; processes such as liberation and germination of spores and infection in rice that were causing blast are affected by the water level [106]. The crop microclimate, especially dew deposition, is affected by water management, making the environment congenial for host susceptibility [192, 197]. As influenced by water management, the changes in crop physiology also trigger host susceptibility [23]. In aerobic rice, blast resistance is the foremost important trait for breeding programs in Brazil [29].

A few other diseases and insect problems reported in DSR are sheath blight and dirty panicle [178], brown spot disease and planthoppers [197], and soil-borne pathogenic fungus *Gaeumannomyces graminis var. graminis* in Brazil without additional irrigation [181].

Lodging

Compared to PTR, DSR is more prone to lodging [200]. Lodging makes crop harvesting difficult. It also reduces yield and impairs the quality of rice both in terms of appearance and taste [130, 200]. Rice cultivars with lodging-resistant characteristics like intermediate plant heights, large stem diameters, thick stem walls, and high lignin content should be preferred and promoted [124]. Moreover, it has been observed that a wider band of sclerenchyma at the periphery of the stem [184] and more vascular bundles [34] make the cultivars more resistant to lodging. In addition, lower positioning of panicles in the plant's canopy is associated with increased lodging tolerance [88, 200]. Hill seeding, lodging-resistant cultivars, optimum N dose, seeding rates, seeding depth, and method can help overcome lodging [104]. Hill seeding is efficient because lodging resistance depends on the number of panicles in a hill and many panicles in hill-seeded rice.

Stagnant Yield

The decline in yield has been reported in direct-seeded rice [110, 242]. It may be due to various reasons viz., soil sickness [241], plant autotoxicity [43, 52, 97, 157], presence of *G. graminis* var. *graminis* in dry-DSR [181], and continuously growing DSR for more than 2 years [53].

Developing Compatible Package for DSR

DSR has excellent potential in South Asia, but its performance has not reached its full potential due to the lack of a proper production technology package. The essential prerequisites for a successful DSR and some recommendations for a successful crop are discussed in detail in the coming sections.

Land Preparation and Laser Leveling

Good field preparation is the starting point of DSR. Proper land preparation facilitates good and uniform crop establishment, aids in uniform water control and good drainage, reduces the amount of irrigation water needed, increases the area of cultivation due to fewer bunds, better input use efficiency (water, nutrients and agrochemicals), increases crop productivity, and helps in controlling weeds [95, 96, 121, 190, 207]. Lantican [121] observed the correlation between DSR yield and precision of land leveling in the Philippines. They estimated an average yield loss of 0.9 t/ha due to deficiency in land leveling, which results primarily from water stress in areas not leveled.

Studies conducted by the Rice–Wheat Consortium of the Indo-Gangetic Plains (RWC) showcased a widespread problem of poor leveling in South Asia [95]. Considerable variability of 8–15 cm in field level is observed due to traditional leveling in Indo-Gangetic Plains. This results in poor crop establishment of rice because of unequal water distribution in soil profile and inundation of newly germinating seedlings [73]. Laser-assisted precision land leveling was introduced in 2001 as a pioneer for alternative tillage and crop establishment methods in the region. It ensures better crop establishment by allowing planters/drills to place seed at a uniform distance and depth [96], resulting in consistent crop stand, precise water control, and enhanced herbicide use efficiency [39].

Crop Establishment

Optimum plant density with uniform crop emergence is crucial for attaining good yields in DSR. Good crop establishment depends on many factors, viz., soil type, seedbed preparation, sowing date, seed rate and seed preparation, planting machinery used, and depth of seeding. The soil type recommended for the direct-seeded crop is medium to heavy textured soils because it suffers from iron deficiency in light soils, which can cause significant yield losses [104]. The seedbed should be free of weeds and precisely leveled at sowing. To treat a herbicide such as a paraquat or glyphosate, it is necessary to knock down any existing annual or perennial weeds. Sowing time varies from location to location. In northern India, rice is grown during the Kharif season before the onset of the monsoon. The optimum time for sowing DSR is about 10–15 days before the onset of monsoon [73, 102, 116]. In general, seeding time for DSR should be as close as possible to the time of nursery sowing for the PTR.

Seed priming has been reported to show positive effects on the emergence, yield, and quality of dry direct seed rice [57, 58, 81]. It also improves stand establishment under variable field conditions. Seed priming techniques were tried for improving germination and crop performance of dry-DSR [125]. Various treatments included hydro-priming, water hardening, and Osmo-hardening with KCI. It was observed that mean germination time reduced and improved germination index, seedling vigor index, and germination energy. Hydro-priming was the best treatment, followed by water hardening, in improving seedling growth, leaf area index, panicles m^{-2}, and grain yield of dry-DSR. Early literature shows a high-speed rate of up to 200 kg/ha to grow DSR crops [78]. The reason may be to suppress weeds or poor germination conditions, low germination percent, damage due to rats, insects, and birds. However, based on trials in IGP, the optimum seed rate is 20–25 kg/ha for medium-fine-grain rice cultivars with 20 cm spacing between the rows and 5 cm spacing within rows [73, 76]. For basmati rice in Punjab, India, seed rates of 30, 40, and

50 kg/ha were evaluated by Sudhir-yadav [227], and they found that the seed rate of 30 kg/ha yielded the highest. For accurate and precise seeding, the crop can be drilled using a multi-crop planter with a seed–metering system (e.g., inclined plate, cupping system, or vertical plates) [73, 76]. Various seed drills used for direct seeding (viz., conventional seed cum fertilizer drill, zero till drill, inverted T-tyne zero-till seed-cum-fertilizer drill, vertical plate metering mechanism, and inclined plate metering mechanism) and machines with inclined plate metering mechanism are most suitable for DSR. These machines help maintain row to row and seed to seed spacing with negligible breakage. Seeding depth is critical for all varieties of rice. After pre-sowing irrigation, the sowing depth for dry DSR should be 2–3 cm and 3–5 cm for DSR to maximize uniform CE. As sowing is done during peak summers, it is essential to have enough moisture during the germination period to avoid moisture stress [73, 236].

Water Management

Water management at all crop growth stages is crucial, viz., seedling emergence, active tillering, panicle initiation, and flowering. Proper water management, especially during the crop establishment phase (first 7–15 days after sowing), is crucial in dry drill–seeded rice [16, 114]. To avoid seed rotting, the soil must be kept moist but not saturated from sowing to emergence. After sowing in dry soil, it is essential to provide flush irrigation to wet the soil if it is unlikely to rain, then saturating the field at the three-leaf stage [28]. This practice will ensure good rooting and seedling establishment and enhance the germination of weeds. Therefore, early weed control with an effective pre-emergence herbicide will be possible to check weed emergence and growth.

Precise land leveling is essential for the uniform spread of water and easy drainage, which is needed during the CE phase of dry-DSR. When water control and drainage are poor, the crop is likely to fail due to submergence in the early stage. Bund management also plays an important role in maintaining uniform water depth and limiting water losses via seepage and leakage [121, 240]. The bunds must be prepared as soon as possible after sowing, including compacting and plastering any holes or cracks. After CE, the following four broad water management options are available: (1) continuous flooding; (2) frequent irrigation, that is, DSR with safe alternate wetting and drying (AWD), which involves flooding the field with shallow depth (5 cm) and reirrigating a few days after water disappearance; (3) infrequent irrigation where scarcity of water limits rice yields; and (4) no irrigation under rainfed conditions [87].

Given the aim of achieving high yields of dry-DSR with less water, option 2 is preferred, but this is subject to the availability of irrigation water. Like CT-TPR, dry-DSR can also be irrigated using safe AWD to economize in water use. However, knowledge regarding optimal soil water status to implement safe AWD in dry-DSR is still limiting. Nevertheless, farmers and researchers provide many anecdotal reports indicating that a safe AWD irrigation interval in dry-DSR is longer than that in CT-TPR because of less soil cracking in the former than in the latter [87].

In a 6-year study on sandy-loam soil conducted in Modipuram, India, it was observed that dry-DSR could be irrigated safely at the appearance of soil hairline cracks [22, 69]. This study recorded an average savings of 9% irrigation water when irrigation took place on the appearance of soil hairline cracks. Another study conducted by Sudhir-Yadav [228, 229] in Punjab, India, on clay loam soil observed 33–53% irrigation water saving in dry-DSR with AWD compared with CT-TPR without compromising grain yield. Moreover, dry-DSR with residue mulch would require appropriate irrigation scheduling and water management as residue mulch would influence evaporation, infiltration, and transpiration very differently from conventional practice. A climate-smart approach for water management under different crop establishment methods is crucial to reduce water footprint in agriculture [134].

Weed Management

The success of DSR depends mainly on effective weed management, especially the integrated approach — that targets different phases of the weed cycle, as a single method may not provide adequate control and long-term sustainability. Integrated weed management (IWM) is pivotal for effective and sustainable weed control in dry-DSR [185, 186]. IWM can be categorized broadly into (a) cultural, (b) mechanical, (c) chemical, and (d) biological methods for weed control.

Cultural Methods

Hand weeding to control weedy rice can be very effective for minimizing the infestation of weedy rice, especially if it is performed after the seedling stage because weedy rice can be more easily identified than rice cultivar. It is usually taller, has more tillers, and its leaves have different colors. However, this method has its disadvantages: it is a slow, tedious, and time-consuming process, which may also induce damage to rice seedlings and mistaken removal of rice seedlings. It has been estimated that 150 to 200 labor days/ha are required to keep rice crops free of weeds, and then its economic profitability directly depends on the labor cost [101].

Proper land preparation and tillage helps in reducing weed infestation. Precise land leveling helps in better crop establishment [96] and controlling weeds through precise water control and improved herbicide efficiency [39]. It can reduce weed population up to 40%, labor requirement for weeding purposes by 75%, and weeding cost by 40% [190]. Tillage determines the vertical distribution of weed seeds in the soil profile, which affects seedling establishment that depends on seed predation, seed dormancy, seed longevity, and the potential of seedlings to emerge from a given depth [38]. Therefore, when weed load is high and control is suboptimal, conventional tillage may be a more suitable option as it can bury weed seeds below the germination zone and reduce weed problems. Zero tillage can be helpful at places where annual weeds (which reproduce primarily by seeds) are prevalent, assuming that reduced tillage does not increase weed seed production. In the case of perennial weeds, which reproduce vegetatively or through underground tubers, e.g., sedges weeds can be controlled by a non-selective herbicide such as glyphosate before crop planting. Often, land leveling is overlooked as an option for managing weeds, but it can be crucial. Therefore, more work in this area is required to clarify the exact role of land leveling in weed dynamics and composition.

Stale Seedbed Technique

The stale seedbed technique can decrease weed seed bank from the soil where a particular cropping system is followed year after year. This could be very useful in IGP, where rice–wheat is the major cropping system. It depletes 5–10% of weed seeds present in soil [207]. In this technique, single irrigation is applied 15 days before rice sowing to facilitate weed germination and emergence. After that, soil moisture is maintained at an optimum level. A nonselective herbicide (glyphosate or paraquat) or mechanical method kills emerged weeds. This helps reduce weed emergence and the number of weed seeds in the soil seed bank [185, 186]. Singh [218] reported that the stale seedbed technique in DSR reduced weed density by 53% over control. Chauhan and Johnson [37] observed better weed control when the stale seedbed technique was used with paraquat and zero-till because weed seeds placed deeper than 1 cm do not emerge. In large-scale farmer participatory trials in India, combined use of stale seedbed and pendimethalin gave effective control of weeds in DSR [222]. However, the economic impacts of the stale seedbed technique are ambiguous because delayed planting shortens the season and reduces the yield [74]. Moreover, it has adverse effects on the environment since it requires fuel energy, water, and herbicide.

Mulching

Applying mulch on soil is another way of controlling weeds in DSR. Mulching has multiple benefits, viz., conserves moisture, suppresses weeds, prevents soil erosion, adds organic matter to soils, improves soil health, and decreases fluctuations in diurnal temperature [183]. Water savings of about 20–90% were achieved from mulching done in China and India [245]. Mulches suppress weeds by providing a physical obstruction to germinating weeds [141, 142, 144], blocking sunlight, and releasing allele-chemicals in the soil [42, 248].

Kumar [115] reported that problematic weeds of DSR such as *Echinochloa crusgalli*, *E. colona*, *Dactyloctenium aegyptium*, and *Eclipta alba* were sensitive to wheat straw when used as mulch. Singh [219] also found that wheat residue mulch of 4 t/ha reduced the emergence of grass weeds by 44–47% and of broadleaf weeds by 56–72% in dry drill–seeded rice. This reduction in weed emergence resulted in 17–22% higher grain yield hence economic returns in mulched plots compared to control. Crop residue retention has also been advocated in the intensive rice–wheat system in the region because of increasing concern about decreasing soil organic matter and environmental pollution caused by the burning of crop residues [76]. Straw mulch from previous crops and post-emergence herbicides could be a promising strategy to control weeds in direct-seeded rice. Combining straw and plastic mulches with the direct-seeded rice system will help achieve the desired targets. Instead of straw burning that leads to soil health degradation and environmental pollution, residue recycling offers organic matter build-up and temporal improvement in soil health [132, 137]. This brings in the concept of circularity also in rice production systems.

Brown Manuring (Sesbania Co-culture)

In DSR, brown manuring with Sesbania can be another good option to control weeds, improve soil health, and yield higher. Sesbania is a legume used as green manure in rice cultivation either as pre-rice or inter or mixed crop with rice [218]. Seeds of Sesbania are sown at 25 kg/ha together with rice. When it is about 30–40 cm tall, after 25–30 days of growth, it is killed with 2,4-D ethyl ester at 0.50 kg/ha to produce brown manure.

Nawaz [152] evaluated five different rice–wheat cropping systems and found brown manuring with Sesbania in DSR decreased weed density by 41–56% and weed biomass by 62–75% sole DSR. Sesbania co-culture reduced broadleaf and grass weed density by

76–83% and 20–33%, respectively, and total weed biomass by 37–80% compared with a sole rice crop [219].

Sesbania followed by 2,4-D was more effective in suppressing broadleaves and sedges and less effective on grasses. Therefore, to further enhance the effectiveness of this technique, it is recommended to use pendimethalin as a pre-emergence herbicide to overcome the problem of grasses, which is otherwise difficult to control.

Other benefits of Sesbania co-culture include atmospheric nitrogen fixation and crop emergence in areas where soil crust formation is a problem [73, 218]. Despite all these benefits, Sesbania co-culture may pose risks of competition with rice if 2,4-D applications are delayed due to continuous rain or ineffective, hence increasing the cost of production. Moreover, some herbicides may also kill Sesbania. Sesbania co-culture may limit herbicide use and positively impact soil nitrogen build-up.

Selection of Cultivar

Weed-competitive cultivars can be a low cost but effective strategy to get higher yields and economic returns [4]. Varieties having good mechanical strength of coleoptile for rapid germination and higher seedling vigor to compete with weeds are best suited for direct seeding [94,256].

Better developed roots, high leaf area index, and tillering capacity were associated with weed suppressive rice cultivars [63]. Gealy and Moldenhauer [70] reported that weed-suppressive rice cultivars have twice root biomass than those of non-suppressive types. Due to higher root biomass and root proliferation, weed-suppressive cultivars competed better for resources with weeds and reduced weed loss by 44% and weed prevalence by 30% compared to non-suppressive cultivars [70]. PR 115 variety of coarse rice and Pusa Basmati 1121, Punjab Mehak 1, CSR 30, Pusa basmati 1, and Taraori basmati varieties are most suitable for direct seeding basmati rice in Haryana and Punjab.

Crop Rotation and Crop Covers

Crop rotation can be one of the most promising strategies in weed management if the crop rotation system design is based on sound agronomic knowledge, as weed population density and biomass production can be reduced significantly using a temporal diversification scheme [162]. By changing the cropping system, weed flora shifts, due to which some weeds disappear and new weeds emerge. Crop rotation helps to diversify weed management programs, decreasing the selection pressure that supports the dominance of a few weedy species in a given field [154]. Change in composition of weeds, weed density, and weed dry weight when rice–wheat cropping sequence is changed was studied by Singh [216]. They recorded minimum weed density in rice–wheat-green gram sequence followed by rice–wheat, rice-chickpea, and rice-pea sequence.

Changing rice–wheat rotation also helps in the identification of weedy rice. Singh [214] reported that by rotating rice with soybean, mungbean, Kharif maize, or cotton, weedy rice could be controlled because other herbicides and cultural practices can be used which otherwise are not used in rice. Chokkar [41] reported that introducing potato and pea in between rice and wheat could also improve weed control without herbicide applications. The results from a 2-year experimental study done by He [82] showed that increasing agricultural diversity through rotations, particularly potato-rice rotation, significantly increased rice production's social, economic, and ecological benefits.

Cover crops can be planted when the main crop is not cultivated and become part of a rotation system. They reduce weed proliferation during fallow; indeed, thick cover crop stands to compete well with weeds during the cover crop growth period and reducing light transmittance to weed seeds prevents most germinated weed seeds from completing their life cycle and reproducing. Another possible advantage is that some cover crops may also improve soil fertility through nitrogen fixation, reducing synthetic fertilizers [207].

Crop Rotation-Sustainable and Circular

When rotation sequences include crops that differ in planting and maturation dates, competitive and allelopathic characteristics, and associated management practices (e.g., tillage, cultivation, mowing, and grazing), weeds can be confronted with an unstable and frequent inhospitable environment that prevents their proliferation. Crop rotation is based on growing a series of different types of crops in the same area in sequential seasons. The planned rotation may increase to a few years or even more extended periods. Farmers usually do not follow one specific crop rotation plan. They choose alternate crops based on their requirements, possibilities, environmental conditions, and budget. By rotating the rice crop with other crops, such as soybean or cotton, it breaks the cycle of the weedy rice seeds. Such a method is widely used by rice farmers in Asia and Brazil, where HR rice varieties are widely grown [11].

Complexity and Uncertain Profitability

Although crop rotation is efficient, sustainable, and consistent with the bioeconomy, its adoption remains lower than expected [82, 176]. Two main reasons explain this situation. On the one hand, monoculture requires fewer farm implements, knowledge, and practical experience and is more straightforward than crop rotation. Moreover, some countries, e.g., Malaysia, are not self-sufficient in rice production; then, arable lands are reserved and monocropped with rice to ensure food security [191]. On the other hand, the impacts of crop rotation on economic returns are not clearly established. They depend on the time horizon (short- vs. long-term), how the rotation is organized (crop, pasture, fallow), the market price of the crops that rotated, and the various costs incurred to produce these crops. Crop rotation involves risk as in crop rotation, investing in a season consists of the input of much money to buy different seedlings of the various crops to be planted. In addition, pests and diseases from other crops can spread and infect more crops. There is also the risk of a specific crop yield not being successful. Improper implementation can cause much more harm than good. It is obligatory crop diversification because crop diversification also requires investment in different planting techniques for each unique crop that costs time and money. After all, each crop needs a different type of attention. Another limitation is that specific locations and climates are more favorable for monocultures. Other crops cannot grow well within that particular type of temperature and soil conditions other than that particular crop.

Some studies conclude that compared to monoculture, economic returns are lower in the short term (e.g., 176], while others demonstrate that crop rotation significantly increases rice's social, economic, and ecological benefit production [82]. These various conclusions show that even though crop rotation is a well-known and long-used method for maintaining or increasing crop yields, more research is needed to understand factors affecting its economic impacts and weed demography in different rotation systems.

Manual and Mechanical Methods

Controlling weeds through any physical activity that hinders the growth of weeds comes under mechanical control.

Mowing Mowing is removing or cutting shoots of weeds by using a sickle or mower. It successfully controls annual weeds while less practiced in perennial weeds because they have stored food in below-ground parts (rhizomes, stolons) and come in several flushes. Mowing must be done before flowering or seed setting to prevent the dispersal of seeds. Weed thus obtained should be buried deep or burnt to remove the viability of weed seeds [129].

Mechanical Weeder In most situations, relying only on the manual wedding is not economical or practical. The mechanical methods control weeds and yield at par with chemical control, provided they are correctly done. Mechanical weeding is not practiced in IGP due to labor and economic constraints. In DSR, rotary weeders and cono weeders for mechanical weeding have been effective in controlling weeds. Rao [185, 186] and Singh [218] have reviewed manual and mechanical methods of weed control. Singh [213] reported from Pantnagar, India, that pendimethalin at 1.0 kg/ha along with farm waste as mulch (7.5 t/ha) supplemented with one hand weeding (HW) at 45 DAS decreased weed count, weed biomass with highest weed control efficiency (91.3%) which was comparable with HW thrice at 30, 60, and 90 DAS (farmers' practice).

Chemical Methods

Labor scarcity, high labor wages, and the demand to raise yield and maintain profit on a limited land base have been the major drivers for farmers to seek alternatives to manual weeding. Herbicides are one such alternative. Effective weed management practices are essential in DSR culture, with herbicide application seemingly indispensable [15]. The trend for increased herbicide use has been reinforced by the spread of DSR [153]. Chemical control measures are generally more focused on the early stage of weed emergence and growth when weed control is more accessible. Once weeds become big, they are difficult to control [19]. In dry direct drill–seeded rice, the "critical period" of weed competition has been reported to be 15–45 days after seeding [185, 212, 253]. If weeds are suppressed effectively during this period, minimal yield losses occur. It is crucial to select the right herbicide depending upon the weed flora present in a given field. In addition, the right rate, timing, and application techniques should be used.

Preplant/Burndown Herbicides.

Preplant/burndown herbicides control existing annual and perennial weeds before rice sowing, especially under the ZT system. Glyphosate 0.5–1.0% by volume and paraquat 0.5% by volume are recommended for burndown application [76]. Glyphosate is a systemic nonselective herbicide, and it controls most annual and perennial weeds. To be effective, it should be applied when weeds are growing actively so that the herbicide is absorbed and translocated into the entire plant system. For the same reason, grazing of fields should be avoided. Light irrigation before spraying glyphosate is recommended in a situation where the weeds are under stress. Paraquat is a nonselective contact herbicide, and it should be used in fields infested with annual weeds. This herbicide should be avoided when areas are infested with perennial weeds.

Pre-emergence Herbicides

Different pre-emergence herbicides are used to control weeds in India's direct-seeded rice. Pendimethalin, oxadiargyl, and pyrazosulfuron have been reported as effective pre-emergence herbicides to control weeds in dry direct–seeded rice [73, 76, 185, 218]. Good soil moisture is essential for the activation of pre-emergence herbicides. Some common pre-emergence herbicides used in DSR are pendimethalin, butachlor, oxadiargyl, pyrazosulfron, penoxsulam, pretilachlor, thiobencarb, flufenacet, anilofos. These herbicides, along with recommended dose, are listed in the table. Singh [220] evaluated three pre-emergence herbicides pendimethalin 1.0 kg/ha, butachlor 1.0 kg/ha, and oxadiargyl 0.09 kg/ha and found weed density after application of these herbicides were 10–13, 15, and 16–23 plants/m^2, respectively, compared to 51 plants/m^2 in weedy check at Taraori location. Kaur [105] evaluated seven pre-emergences (pendimethalin 0.75 g/ha, butachlor 1.50 kg/ha, thiobencarb 1.50 kg/ha, anilofos 0.375 kg/ha, pretilachlor 0.75 kg/ha, oxadiargyl 0.09 kg/ha, and pyrazosulfuron-ethyl 0.015 kg/ha) herbicides for their efficacy against weeds in DSR.

Post-emergence Herbicides

In DSR, more than one flush of weeds occurs during crop duration. Pre-emergence herbicides gave effective control during the early stage of crop growth and post-emergence herbicides during the second flush of weeds. If weeds are not controlled properly, they can cause a significant qualitative and quantitative loss in grain yield. A single herbicide cannot give effective weed control throughout the crop growth period, so sequential herbicide application is made. Some common post-emergence herbicides used in DSR are bispyribac-sodium, fenoxaprop-p-ethyl, ethoxysulfuron, chlorimuron-ethyl, metsulfuron-metyl, and acifluorfer, 2,4-D. These herbicides, along with recommended dose, are listed in the table. Continuous use of a single herbicide on a long-term basis should be avoided; rather, it should be rotated with another herbicide with a different mode of action to prevent/delay resistance development. Tank mixtures of herbicides can be used when two or more herbicides are compatible with broadening the weed control spectrum so that each herbicide controls the weeds missed by the other one Table 1.

From Chemical to Biotechnological Method: Herbicide (IMI) — Resistant Rice Varieties

In countries where DSR is widely adopted, herbicide use increased steadily, resulting in resistance in weeds against certain herbicides. Selective control of weedy rice was never achieved satisfactorily with herbicides, such as the application of non-selective herbicides before and after the emergence of weedy rice, but before planting rice. Indeed, the application of pre-emergence (antigerminative) herbicides provides weedy rice control, but it is phytotoxic if applied less than 15 days before crop sowing. Moreover, the physiological similarity of weedy rice to cultivated rice makes it challenging to use post-emergence herbicides in rice fields. Rather than an IWM, herbicide-resistant (HR after that) rice technologies offer opportunities for selective control of weedy rice [36, 50, 71, 214]. Two non-genetically modified herbicide-resistant rice cultivars are commercialized; the Clearfield

Table 1 List of Pre-emergence and Post-emergence herbicide spray and recommended doses

Sl. No	Pre- emergence herbicides		Post- emergence herbicides		
	Name	Dose (kg/ha)	Name	Dose (kg/ha)	Time of applicaton (DAS)
1	Pendimethalin	0.75 -1.0	Bispyribac-sodium	0.025	25–30
2	Oxadiargyl	0.09—0.1	Fenoxaprop-pethyl	0.06–0.075	25–30
3	Pyrazosulfron	0.015–0.020	Ethoxysulfron	0.015–0.0175	25–30
4	Butachlor	1.0–1.50	Chlorimuronethyl + metsulfron-methyl	0.002–0.004	25–30
5	Penoxsulam	0.03	Acifluorfer	0.6	20–30
6	Pretilachlor	0.40–0.75	2,4-D	1	30
7	Thiobencarb	1.25			
8	Flufenacet	0.08			
9	Anilofos	0.375			

rice and the Provisia rice systems, both developed by BASF, were launched in the early 2000s and 2018.

Clearfield rice is a group of cultivars that encompasses imidazolinone-resistant rice (IMI-rice). Imidazolinone is a broad-spectrum group of herbicides that can be applied pre- or post-emergence. It inhibits some enzymes (ALS) involved in producing amino acids when applied. Without the latter, the plant cannot synthesize proteins and slowly dies. Since Clearfield adoption from the early 2000s (e.g., in the USA, Europe, Brazil, and Malaysia), weedy rice infestation has decreased, and increases in rice production have been reported, for instance, up to 50% in Brazil [131]. In Malaysia, this system introduced in 2010 has increased yield production by 5 to 8 times [138]. HR weeds are an ongoing challenge worldwide, and Provisia™ Rice System provides a tool to weedy rice becoming resistant to the Clearfield technology. The system allows farmers to safely apply the broad-spectrum Provisia herbicide for post-emergence control of a wide range of weeds, including weedy rice. It complements the Clearfield production system for rice because farmers can rotate different herbicide modes of action for sustainable management of resistant rice types and annual grasses. However, weedy rice — as most weeds — evolves to become herbicide-resistant, according to the usual "treadmill of herbicide resistance." Since weedy rice is now resistant to Clearfield, it will inevitably become resistant to Provisia in the future [50].

Biological Method (Allelopathy)

Studies have shown that rice plants and weeds also compete through allelopathy. Kato-Noguchi [103] identified 3-hydroxy-β-ionone and 9-hydroxy-4-megastigmen-3-one as main allelochemicals in Kartik-shail and BR 17, two high-yielding rice cultivars of Bangladesh. The allelopathic potential of 111 rice cultivars on weeds in the Philippines was studied by Olofsdotter [157] who reported that the dry weight of weeds reduced up to 34% after 8 weeks of seeding. The reduction in weed's dry weight is due to allelochemicals released by these rice cultivars [158].

The allelopathic potential of many rice cultivars like BR17 against *Echinochloa crus-galli* and *E. colo-num* had already been reported in various studies [59, 60, 93]. Several rice cultivars through the release of allelochemical had been found to suppress predominant weeds of rice, such as *E. crus-galli* [97, 198], *Cyperus difformis* [198], and *Sagittaria montevidensis* [198, 199].

Seal and Pratley [198] evaluated the allelopathic multi-weed suppression of 27 different rice cultivars against five major aquatic weeds of Australia and found that cultivar Amaroo inhibited *Alisma-taceae* weeds by an average of 97%, whereas *Echinochloa crus-galli* was inhibited by 72%.

Not much work is done in India to exploit the rice's allelopathic property for weed control in DSR. Cultivars with improved allelopathic potential can be developed, competing better with weeds and lowering herbicides' dependence. So, there is a broad scope to identify, develop, and exploit cultivars with higher allelopathic potential in proper cropping systems.

It can be summarized that the components of integrated strategies for weed control in DSR are crucial for the adoption and scaling of this technology in South Asia.

Assessment of Weed Management Sustainability in Rice

The Sustainable Rice Platform (SRP 2015) is a multi-stakeholder partnership (established in 2011 and co-convened by UN Environment and the International Rice Research Institute) to promote resource-use efficiency and sustainability both on-farm and throughout the rice value chain. It is developing a range of tools to promote sustainable rice cultivation, including standards [225] related to priorities defined in a set of 12 performance indicators [226].

Standards are based on 41 requirements under eight significant themes: integrated pest management (IPM). The latter includes one provision (no. 18.1) about weed management, which impacts 4 of the 12 performance indicators: profitability, productivity, biodiversity, and food safety. Requirement no. 18.1 "weed management" lists standard preventive weed control methods and the conditions for appropriate use of herbicides that all belong to what is usually called IWM. The SRP Standard seeks to encourage IWM that combines preventive weed control actions and punctual curative weed control actions when preventive methods are not effective on their own [225]. Preventive control methods help manage conditions to avoid weed build-up and include resistant varieties, crop rotation, or intercropping. Curative weed control methods help treat weed build-up and can consist of mechanical control, biological control, and chemical control (e.g., synthetic herbicides). Herbicides are used only if and when action thresholds are exceeded, and the severity of the weed is expected to cause significant damage or loss.

Fertilizer Management

Not much work on fertilizer management has been done for DSR than CT-PTR. Due to aerobic conditions and alternate wet and dry cycles, there is less availability of several micronutrients such as Zn and Fe and other nutrients including N [179]. Also, nitrogen losses are higher in dry-DSR than in CT-PTR due to nitrification/denitrification, volatilization, and leaching [46, 150, 175, 211].

General recommendations for NPK fertilizers are similar to those in PTR, except that a slightly higher N (22.5–30 kg/ha) dose is suggested in DSR [69]. This is to balance the higher losses and lower availability of N from soil mineralization at the early stage and the longer duration of the crop in the main field in dry-DSR. Earlier studies conducted in Korea indicated that 40–50% more N fertilizer should be applied in dry-DSR than in CT-TPR [170, 255], although higher N application also leads to disease susceptibility and crop lodging. Split applications of N are recommended to maximize grain yield, increase N uptake, and reduce N losses. It ensures the supply of N to match crop demand at critical growth stages. Since more N is applied in dry-DSR than in CT-PTR and losses are higher, more efficient N management for dry-DSR is needed.

Slow-release (SRF) or controlled-release N fertilizers (CRFs) offer options to reduce N losses because of their delayed-release pattern, which may match crop demand in a better way [206]. The one-shot application also reduces the labor cost. CRF improves N use efficiency and yield compared to untreated urea [61], but their use is limited because of their high cost. They are four to eight times costlier than conventional fertilizers [204].

Split application of K has also been suggested for direct seeding in medium-textured soil [177]. Deficiency of Zn and Fe is more common in aerobic/non-flooded rice systems than in flooded rice systems [202, 208, 210, 223a, 44, 163, 254, 216]. Therefore, micronutrient management is critical in dry-DSR. A total of 25–50 kg/ha zinc sulfate is recommended [5–9]. For iron, it has been observed that foliar application is superior to soil application [6–9, 45].

Significance of DSR in Circular Economy

Due to the early maturity of DSR, it gives the chance to include an additional crop in the system, which can help economically and help in crop rotation and improve soil fertility and help reduce weeds. As far as the circular economy is considered, DSR harvest can reach markets about 15 days early. This market can give incentives to reuse post-harvest products like straw, husk, and bran, adding value to the circularity. Instead of burning the straw, it can be used, which farmers usually burn to clear land for the next crop. This will help reduce carbon dioxide emissions and preserve soil microbiology. So, it is a win–win situation both for farmers and the environment. These crop residues can be used to produce, for instance, new bio-fertilizer through composting new materials for healthy buildings and energy (e.g., biofuels). The rice, duck, and fish-integrated farming is another well-known system for which circular principles are present. All agricultural practices, such as tillage, pesticide application, harvesting, threshing, can potentially be concerned by the circular economy. Weed management in rice that should easily fit the sustainability criteria and the circularity principles but require additional research and development. Bioherbicides seem to be a sustainable option to fulfill the circularity principle. Eco-friendly, cost-effective DSR package offers sustainable rice production systems with fewer resources and low emissions.

Conclusions

This study identified that DSR is feasible both technically and economically compared to PTR. Moreover, with proper conservation and management strategies, DSR adoption will likely increase in the coming future, provided weed control in DSR, especially the control of weedy rice, should be at the center of any strategy aiming to improve the sustainability of rice production in the long run. Eco-friendly, cost-effective DSR package offers sustainable rice production systems with fewer resources and low emissions.

A few important conclusions that have emerged from this review are as follows.

- First, DSR is a more resource-efficient, climate-resilient, and sustainable alternative agricultural system, but many agronomic DSR practices have become inefficient because of the lack of mechanization, precision application, and proper education. So, adopting adequate management practices is very important.
- The primary bottleneck experienced with direct seeding is the infestation of weeds. Pre-emergence and post-emergence herbicides can be vital in controlling weeds, but environment friendlier weed control methods must be sought and substantially reduce the cost of weed management for farmers. Techniques like stale bed technique, mulching, crop rotation, Sesbania co-culture, seed priming, and systematic weed monitoring program will help to reduce weeds. However, a single weed control method is not viable, so an integrated approach based on climatic conditions, edaphic factors, and weed flora are critical. Furthermore, given the drawbacks associated either with IWM or the use of herbicide-resistant rice varieties, development of competitive and allelopathic rice varieties for increased rice competitiveness must be targeted.
- The selection of a proper cultivar is very crucial. As DSR is aerated rice, dry and wet conditions responsive rice varieties should be promoted.
- Poor stand establishment is another hindrance in the wide-scale adoption of DSR. More practical seed priming techniques can help to solve the issue.
- Effective management strategies, well-developed biotechnological and genetic approaches, and a better understanding of pest and disease dynamics will help resolve blast and root-knot nematode infestation in DSR [136].
- New resource conservation technologies (RCTs) like laser land leveling, short-duration cultivars, irrigation scheduling based on soil matric potential (SMP), crop diversification and raised bed planting should be recommended based on sites and soils.

Future Research Outlook

- On the research front, new and improved rice varieties suitable for DSR are required.
- Despite many integrated approaches, additional research on weed management, especially weedy rice control, is required for comprehensive spectrum weed control.
- More efforts are needed to study the nutrient dynamics in soils under DSR as the availability of micronutrients, mainly Fe and Zn, reduces DSR. Also, research is required on soil ecology in rice soils.
- According to the climatic edaphic factors and resources available locally, there is a need to develop a site-specific package of production technologies for different rice production systems. Anticipatory research and development strategies need to be framed for a place where DSR will be practiced.
- To combat higher N_2O emissions in DSR, there is a need to monitor GHG emissions. However, not many studies quantify the emissions and study the combined effect of all three GHGs (CO_2, CH_4, and N_2O) in rice systems. Therefore, baseline data to develop better management strategies is lacking. Furthermore, more approaches like nitrification inhibitors and deep urea placement can be worked out to reduce the emissions hence, global warming.

- Intense convincing has to be done to the various stakeholders in rice production. They include the policymakers and farmers. Their understanding of the benefits will enhance its wide spread. Another green revolution in direct-seeded rice with better management techniques is the need of the hour.

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References

1. Aggarwal GC, Sidhu AS, Sekhon NK, Sandhu KS, Sur HS (1995) Puddling and N management effects on crop response in a rice-wheat cropping system. Soil Till Res 36:129–139
2. Ainsworth EA (2008) Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. Global Change Bio 14(7):1642–1650
3. Alia N, Durrani S, Abbas M, Ullah I, Ishfaq M, Akbar N, Rehman A, Waheed A (2018) Different approaches in direct seeded rice system to avert weed infestation: review. Intl J Scie Eng Res 9(6):1538–1558
4. Andrew KS, Storkey J, Sparkes DL (2015) A review of the potential for competitive cereal cultivars as a tool in integrated weed management. Weed Res 55:239–248
5. Anonymous (2008) Package and practices of Kharif Crops. CCS Haryana Agricultural University, Hisar, Haryana
6. Anonymous (2010a) Micronutrient deficiencies in Indian soils and field usable practices for their correction Indian Institute of Soil Science, Bhopal www.iiss.nic.in/ Recommendations1.pdf
7. Anonymous (2010b) Annual report of Department of Agronomy (2009–10) Punjab Agricultural University, Ludhiana
8. Anonymous (2016a) Area and production of rice in India. http// www.indiastat.com
9. Anonymous (2016) Package of practices for Kharif Crops. Punjab Agricultural University, Ludhiana
10. Aulakh MS, Wassmann R, Rennenberg H (2001) Methane emissions from rice fields: quantification, mechanisms, role of management, and mitigation options. Adv Agron 70:93–260
11. Avila L, Noldin J, Mariot C et al (2021) Status of weedy rice (Oryza sativa L.) infestation and management practices in Southern Brazil. Weed Sci 69(5):536–546
12. Azmi M, Abdullah MZ (1998) A manual for the identification and control of Padi Angin (Weedy Rice) in Malaysia. MARDI Publication, Serdang, Malaysia, p 18p
13. Azmi M, Johnson DE (2009) Crop establishment options for lowland irrigated rice in relation to weed infestation and grain yield. J Trop Agri Food Sci 37:111–117
14. Azmi M, Mashor M (1995) Weed succession from transplanting to direct-seeding method in Kemubu rice area. Malaysia J Biosci 6:143–154

15. Azmi M, Chin DV, Vongsaroj P, Johnson DE (2005) Emerging issues in weed management of direct-seeded rice in Malaysia, Vietnam, and Thailand. In: Toriyama K, Heong KL, Hardy B (ed) Rice is life: scientific perspectiveS for the 21st Century. International Rice Research Institute, Los Baños, Philippines and Japan International Research Center for Agricultural Sciences, Tsukuba, Japan pp 196–198
16. Balasubramanian V, Hill, JE (2002) Direct seeding of rice in Asia: emerging issues and strategic research needs for the 21st century. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (ed) Direct seeding: research strategies and opportunities. International Rice Research Institute, Los Baños, Philippines pp 15–39
17. Baltazar AM, De Datta SK (1992) Weed manag rice Weed Abstr 41:495–508
18. Barker R, Dawe D, Tuong TP, Bhuiyan SI, Guerra LC (1998) The outlook for water resources in the year 2020: Challenges for research on water management in rice production. In: Assessment and Orientation towards the 21st Century, 7–9 September 1998 proceedings of 19th Session of the International Rice Commission, Cairo, Egypt, FAO pp 96–109
19. Bastiaans L, Paolini R, Baumann DT (2008) Focus on ecological weed management: what is hindering adoption? Weed Res 48(6):481–491
20. Bhatt R, Singh P, Hossain A, Timsina J (2021) Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy Water Environ 19(3):345–365
21. Bhuiyan SI, Sattar MA, Khan MAK (1995) Improving water use efficiency in rice irrigation through wet seeding. Irrig Sci 16:1–8
22. Bhushan L, Ladha JK, Gupta RK, Singh S, Tirol-Padre A, Saharawat YS, Gathala M, Pathak H (2007) Saving of water and labor in rice-wheat systems with no-tillage and direct seeding technologies. Agron J 99(5):1288–1296
23. Bonman JM (1992) Durable resistance to rice blast disease-environmental influences. Euphytica 63:115–123
24. Bonman JM, Leung H (2004) Breeding for durable resistance to rice blast disease- dream or reality? Phytopathol 93:S113 Publication No. P-2003–0110-SSA. American Phytopathol Soc Ann Meeting
25. Boparai BS, Singh Y, Sharma BD (1992) Effect of green manuring with Sesbania aculeata on physical properties of soil and on growth of wheat in rice–wheat and maize–wheat cropping systems in a semiarid region of India. Arid Soil Res Rehab 6:135–143
26. Bouman BAM (2009) How much water does rice use? Rice Today 8:28–29
27. Bouman BAM, Tuong TP (2001) Field water management to save water and increase its productivity in irrigated rice. Agric Water Manage 49:11–30
28. Bouman BAM, Lampayan RM, Tuong TP (2007) Water management in irrigated rice: coping with water scarcity. International Rice Research Institute, Los Baños, Philippines, 54p
29. Breseghelo F, de Morais OP, Ferreira CM (2006) Upland rice in Brazil: breeding, adoption and management. In: Paper Presented at Aerobic Rice Workshop held at International Rice Research Institute, Los Baños, Philippines
30. Cabangon RJ, Tuong TP, Abdullah NB (2002) Comparing water input and water productivity of transplanted and direct-seeded rice production systems. Agric Water Manage 57(1):11–31
31. Carrigere Valle´ SD (2007) More crop per drop. Rice Today 6(2):10–13
32. Cassman KG (1999) Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proceed Nat Academy Sci, USA 96(11):5952–5959
33. Chakraborty D et al (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci Rep 7(1):1–11
34. Chaturvedi GS, Misra CH, Singh CN, Pandey CB, Yadav VP, Singh AK., Divivedi JL, Singh BB, Singh RK (1995) Physiological flash flooding. International Rice Research Institute, Los Baños, Philippines, pp 79–96
35. Chaudhari SK, Bardhan G, Kumar P, Singh R, Mishra AK, Rai P, Singh K, Sharma DK (2015) Short-term tillage and residue management impact on physical properties of a reclaimed sodic soil. J Indian Soc Soil Sci 63(1):30–38
36. Chauhan BS, Yadav A (2013) Weed management approaches for direct seeded rice in India: a review. Ind J Weed Sci 45(1):1–6
37. Chauhan BS, Johnson DE (2010) The role of seed ecology in improving weed management strategies in the tropics. Adv Agron 105:221–262
38. Chauhan BS, Gill G, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust J Exp Agric 46:1557–2157
39. Chauhan BS (2012) Weed ecology and weed management strategies for dry-seeded rice in Asia. Weed Techno 26:1–13

40. Chenkual V, Acharya CL (1990) Effect of rice–wheat and maize–wheat rotations on soil physical properties including soil–water behavior in an acidic Alfisol. J Indian Soc Soil Sci 38:574–582
41. Chhokar RS, Sharma RK, Singh RK, Gill SC (2008) Herbicide resistance in little seed canary grass (Phalaris minor) and its management proceedings of the 14th Australian Agronomy Conference, Adelaide, South Australia, pp 106
42. Chou CH (1999) Roles of allelopathy in plant biodiversity and sustainable agriculture. Crit Rev Plant Sci 18:609–636
43. Chou CH (1980) Allelopathic researches in the subtropical vegetation in Taiwan. Physiol Ecol 5:222–234
44. Choudhury BU, Bouman BAM, Singh AK (2007) Yield and water productivity of rice-wheat on raised beds at New Delhi. India Field Crops Res 100:229–239
45. Datta SP, Saharan N, Rattan RK (2003) Micronutrient fertilizers, sources and methods of application In: Das DK and Saha D (ed) Integrated micronutrient management for sustainable agriculture. BCKV, West Bengal, India. pp 71–89
46. Davidson EA (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers JE, Whitman WB (eds) Microbial production and consumption of greenhouse gases: methane, nitrogen oxides and halomethanes. The American Society Microbiol, Washington, DC, pp 219–235
47. Dawe D (2005) Increasing water productivity in rice-based systems in Asia- past trends, current problems, and future prospects. Plant Prod Sci 8:221–230
48. De Datta SK (1981) Principles and practices of rice production. John Wiley and Sons, New York
49. Devkota KP et al (2020) Assessing alternative crop establishment methods with a sustainability lens in rice production systems of Eastern. J of Cleaner prod, India, p 244
50. Durand-Morat A, Nalley LL (2019) Economic benefits of controlling red rice: a case studyof the United States. Agronomy 9(8):422
51. Erenstein O, Laxmi V (2008) Zero tillage impact in India's rice-wheat systems: a review. Soil Till Res 100:1–14
52. Fageria NK, Baligar VC (2003) Upland rice and allelopathy. Commun Soil Sci Plant Anal 34(9–10):1311–1329
53. Fageria NK, Souza NP (1995) Response of rice and common bean crops in succession to fertilization in cerrado soil. Pesquisa Agropecuaria Brasileira 30:359–368
54. FAO (2009) FAOSTAT Database. Food and Agriculture Organization of the United Nations, Rome, Italy
55. FAO (2017) FAOSTAT Database. Food and Agriculture Organization of the United Nations, Rome, Italy.
56. FAO (2020a) Sustainable Rice Systems (online). http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/sustainablerice-systems/en/ accessed 25 January 2020
57. Farooq M, Basra SMA, Wahid A (2006) Priming of field-sown rice seed enhances germination, seedling establishment, allometry and yield. Plant Growth Regul 49:285–294
58. Farooq M, Basra SMA, Tabassum R, Afzal I (2006) Enhancing the performance of direct seeded fine rice by seed priming. Plant Prod Sci 9:446–456
59. Farooq M, Jabran K, Cheema ZA, Wahid A, Siddique KHM (2011) The role of allelopathy in agricultural pest management. Pest Manag Sci 67:493–506
60. Farooq M, Jabran K, Rehman H, Hussain M (2008) Allelopathic effects of rice on seedling development in wheat, oat, barley and berseem. Allelo J 22:385–390
61. Fashola OO, Hayashi K, Wakatsuki T (2002) Effect of water management and polyolefin-coated urea on growth and nitrogen uptake of indica rice. J Plant Nutr 25(10):2173–2190
62. Ferrero A (2003) Weedy rice, biological features and control. In: Labrada R (ed): Weed Management for Developing Countries, Addendum 1, FAO (online). http://www.fao.org/3/Y5031E/y5031e09.htm#bm9
63. Fofana B, Rauber R (2000) Weed suppression ability of upland rice under low input conditions in West Africa. Weed Res 40:271–280
64. Forno DA, Yoshida S, Acher CJ (1975) Zinc deficiency in rice. Plant Soil 42(3):537–550
65. Gangwar KS, Gill MS, Tomar OK, Pandey DK (2008) Effect of crop establishment methods on growth, productivity and soil fertility of rice (*Oryza sativa L.*)- based cropping systems. Ind J Agron 53:102–106
66. Gangwar KS, Tomar OK, Pandey DK (2008) Productivity and economics of transplanted and direct-seeded rice (*Oryza sativa L.*)- based cropping systems in Indo-Gangetic plains. Ind J Agric Sci 78:655–658
67. Gao XP, Zou CQ, Fan XY, Zhang FS, Hoffland E (2006) From flooded to aerobic conditions in rice cultivation: consequences for zinc uptake. Plant Soil 280:41–47

68. Gardner-Outlaw T, Engelman R (1997) Sustaining water, easing scarcity: a second update. Population Action International, Washington, DC, p 19
69. Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H (2011) Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron J 103(4):961–971
70. Gealy DR, Moldenhauer KA (2012) Use of 13C isotope discrimination analysis to quantify distribution of barnyardgrass and rice roots in a four-year study of weed-suppressive rice. Weed Sci 60:133–142
71. Gealy DR, Mitten DH, Rutger JN (2003) Gene flow between red rice (Oryza sativa) and herbicide-resistant rice (O. sativa) implications for weed management. Weed Technol 17(3):627–645
72. Giordano PM, Mortvedt JJ (1972) Rice response to Zn in flooded and non-flooded soil. Agron J 64:521–524
73. Gopal R, Jat RK, Malik RK, Kumar V, Alam MM, Jat ML, Mazid MA, Saharawat YS, McDonald A, Gupta R (2010) Direct dry seeded rice production technology and weed management in rice based systems. Technical Bulletin. International Maize and Wheat Improvement Center(CIMMYT), New Delhi, India, 28pp
74. Gressel J (2002) Preventing, delaying and mitigating gene flow from crops – rice as an example. Proceedings of the Seventh International Symposium on the Biosafety of Genetically Modified Organisms, Beijing, China, pp.50–64
75. Grigg DE (1974) The agricultural systems of the world: an evolutionary approach. Cambridge University Press, Cambridge, UK
76. Gupta RK, Ladha JK, Singh S, Singh R, Jat ML, Saharawat Y, Singh VP, Singh SS, Singh G, Sah G, Gathala M, Sharma RK (2006) Production technology for direct seeded rice, Technical Bulletin Series 8. In: Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, 14p.
77. Gupta R, Seth A (2007) A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic Plains (IGP). Crop Prot 26:436–447
78. Guyer R, Quadranti M (1985) Effect of seed rate and nitrogen level on the yield of direct wet-seeded rice. Proceedings of the 10th Asian-Pacific Weed Science Society Conference. Chiangmai, Thailand, pp 304–311
79. Harada H, Hitomi K, Hayato S (2007) Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: Life-cycle inventory analysis. Soil Sci Plant Nutr 53:668–677
80. Harrington LW, Hobbs PR (2009) The Rice-Wheat Consortium and the Asian Development Bank: a history. In: Ladha JK, Singh Y, Erenstein O, Hardy B (ed) Integrated Crop and Resource Management in the Rice-Wheat System. Int Rice Res Institute, Los Baños, Philippines, pp 3–67
81. Harris D, Tripathi RS, Joshi A (2002) On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice. In: Pandey S , Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (ed) Direct seeding: research strategies and opportunities. Proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities, 25–28, January 2000, Bangkok, Thailand,. Int Rice Res Institute, Los Baños, Philippines. Pp 231–240
82. He D-C, Ma Y-L, Li Z-Z, Zhong CS, Cheng ZB, Zhan J (2021) Crop rotation enhances agricultural sustainability: from an empirical evaluation of eco-economic benefits in rice production. Agriculture 11(2):91
83. Hobbs PR, Gupta RK (2000) Sustainable resource management in intensively cultivated irrigated rice–wheat cropping systems of the Indo-Gangetic Plains of South Asia: Strategies and options. International Conference on Managing Natural Resources for Sustainable Production in 21st Century, 14–18 February 2000. New Delhi, India, pp 584–592
84. Hobbs PR, Gupta RK (2003) Resource-conserving technologies for wheat in the rice-wheat system. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (ed) Improving the productivity and sustainability of rice–wheat systems: issues and impacts. ASA Special Publication Number 65. ASA-CSSASSSA, Madison, Wisconsin, USA. Pp 149–172
85. Hou AX, Chen GX, Wang ZP, Van Cleemput O, Patrick WH Jr (2000) Methane and nitrous oxide emissions form a rice field in relation to soil redox and microbiological processes. Soil Sci Soc Am J 64:2180–2186
86. Houghton JT, Meira Filho LG, Callander BA, Harris N, Katterberg A, Maskell K (1996) IPCC report on climate change: the science of climate change. WG1 Contribution to the IPCC Second Assessment Report on Methane Emission from Rice Cultivation. Cambridge University Press, Cambridge, UK
87. Humphreys E, Kukal SS, Christen EW, Hira GS, Singh B, Yadav S, Sharma RK (2010) Halting the groundwater decline in north-west India- which crop technologies will be winners? Adv Agron 109:155–217

88. IRRI (1994) Program Report for 1993. International Rice Research Institute, Los Baños, Philippines
89. Ishaq M, Hassan A, Saeed M, Ibrahim M, Lal R (2001) Subsoil compaction effects on crops in Punjab. Pakistan. I. Soil physical properties and crop yield. Soil Till Res 59:57–65
90. Ishibashi E, Yamamoto S, Akai N, Tsuruta H (2007) The influence of no-tilled direct seeding cultivation on greenhouse gas emissions from rice paddy fields in Okayama, Western Japan. 4. Major factors controlling nitrous oxide emission from rice paddy fields under no-till direct seeding cultivation. Jpn J Soil Sci Plant Nutr 78:453–463
91. Ishibashi E, Yamamoto S, Akai N, Tsuruta H (2009) The influence of no-tilled direct seeding cultivation on greenhouse gas emissions from rice paddy fields in Okayama, Western Japan. 5. Annual emission of CH_4, N_2O and CO_2 from rice paddy fields under different cultivation methods and carbon sequestration into paddy soils. Jpn J Soil Sci Plant Nutr 80:123–135
92. Isvilanonda S (2002) Development trends and farmers' benefits in the adoption of wet seeded rice in Thailand. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (ed) Direct seeding: research strategies and opportunities proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities 25–28 January 2000, Bangkok, Thailand. Int Rice Res Institute, Los Baños, Philippines, pp 115–124
93. Jabran K, Farooq M (2013) Implications of potential allelopathic crops in agricultural systems. In: Cheema ZA, Farooq M, Wahid A (eds) Allelopathy, Current Trends and Future Applications. Springer, Berlin, Heidelberg, pp 349–385
94. Jannink JL, Orf JH, Jordan NR, Shaw RG (2000) Index selection for weed-suppressive ability in soybean. Crop Sci 40:1087–1094
95. Jat ML, Chandna P, Gupta R, Sharma SK, Gill MA (2006) Laser land leveling: a precursor technology for resource conservation. In: Rice-Wheat Consortium Technical Bulletin 7. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India,48 p
96. Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar V, Sharma SK, Kumar V, Gupta RK (2009) Evaluation of precision land levelling and double zero-till systems in the rice-wheat rotation: Water use, productivity, profitability and soil physical properties. Soil Till Res 105:112–121
97. Jensen LB, Courtois B, Shen L, Li Z, Olofsdotter M, Mauleon RP (2001) Locating genes controlling allelopathic effects against barnyard grass in upland rice. Agron J 93:21–26
98. Johnson DE, Mortimer AM (2005) Issues for integrated weed management and decision support in direct-seeded rice. In: Toriyama K, Heong KL, Hardy B (ed) Rice Is Life: Scientific Perspectives for the 21st Century. International Rice Research Institute, Los Baños, Philippines and Japan Int Res Center for Agricultural Sci, Tsukuba, Japan, pp 211–214
99. Joshi E, Kumar D, Lal B, Nepalia V, Gautam P, Vyas AK (2013) Management of direct seeded rice for enhanced resource - use efficiency. Plant Know J 2:119–134
100. Jugsujinda A, Delaune RD, Lindau CW (1996) Factors controlling carbon dioxide and methane production in acid sulfate soils. Water Air Soil Pollut 87:345–355
101. Juraimi AS, Uddin MK, Anwar MP, Mohamed MTM, Ismail MR, Man A (2013) Sustainable weed management in direct seeded rice culture: a review. Aust J Crop Sci 7(7):989
102. Kamboj BR, Kumar A, Bishnoi DK, Singla K, Kumar V, Jat ML, Chaudhary N, Jat HS, Gosain DK, Khippal A, Garg R, Lathwal OP, Goyal SP, Goyal NK, Yadav A, Malik DS, Mishra A,Bhatia R (2012) Direct seeded rice technology in Western Indo-Gangetic Plains of India: CSISA Experiences. CSISA, IRRI and CIMMYT, pp 16
103. Kato-Noguchi H, Salam MA, Suenaga K (2011) Isolation and identification of potent allelopa-thic substances in a traditional Bangladeshi rice cultivar Kartikshail. Plant Prod Sci 14(2):128–134
104. Kaur J, Singh A (2017) Direct seeded rice: prospects, problems/constraints and researchable issues in India. Curr Agri Res J 5(1):13–32
105. Kaur S, Singh S (2015) Bio-efficacy of different herbicides for weed control in direct-seeded rice. Ind J Weed Sci 47(2):106–109
106. Kim CK (1987) Disease dispersal gradients of rice blast from point source. Kor J Plant Prot 3:131–136
107. Kim HH, Pyon JY (1998) Weed occurrence and yield loss due to weeds in different direct seeded rice paddy fields. Kor J Weed Sci 18(1):12–19
108. Kirk GJD, Bajita JB (1995) Root induced iron oxidation, pH changes and zinc solubilization in the rhizosphere of lowland rice. New Phytopathol 131:129–137
109. Kirk GJD, Solivas JL, Begg CBM (1994) The rice root–soil interface. In: Kirk GJD (ed) Rice roots: Nutrient and Water Use. Int Rice Res Institute, Los Baños, Philippines, pp 1–10
110. Kreye C, Bouman BAM, Castan˜eda AR, Lampayan RM, Faronilo JE, Lactaoen AT, Fernandez L (2009) Possible causes of yield failure in tropical aerobic rice. Field Crops Res 111:197–206

111. Kumar P, Chaudhari SK, Singh A, Singh R, Mishra AK, Singh K, Sharma DK (2021) Effect of tillage and residue management in rice-wheat system. Indian J Agric Sci 91(2):283–286
112. Kumar V, Bellinder RR, Brainard DC, Malik RK, Gupta RK (2008) Risks of herbicide-resistant rice in India: A review. Crop Prot 27:320–329
113. Kumar V, Bellinder RR, Gupta RK, Malik RK, Brainard DC (2008) Role of herbicide-resistant rice in promoting resource conservation technologies in rice–wheat cropping systems of India: a review. Crop Prot 27:290–301
114. Kumar V, Ladha JK, and Gathala MK (2009) Direct drill-seeded rice: a need of the day. Annual Meeting of Agronomy Society of America, Pittsburgh, November 1–5, 2009
115. Kumar V, Singh S, Chhokar RS, Malik RK, Brainard DC, Ladha JK (2013) Weed management strategies to reduce herbicide use in zero-till rice-wheat cropping systems of the Indo-Gangetic Plains. Weed Tech 27:241–254
116. Kumar V, Ladha JK (2011) Direct seeding of rice: recent developments and future research needs. Adv Agron 111:297–413
117. Ladha JK (2011) Direct-seeded rice culture in Sri Lanka. Field Crops Res 121:53–63
118. Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B, Singh Y, Singh Y, Singh P, Kundu AL, Sakal R, Ram N et al (2003) How extensive are yield declines in long-term rice–wheat experiments in Asia? Field Crops Res 81:159–180
119. Ladha JK, Kumar V, Alam MM, Sharma S, Gathala M, Chandna P, Saharawat YS, Balasubramanian V (2009) Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In: Ladha JK,Singh Y, Erenstein O, Hardy B (ed) Integrated Crop and Resource Management in the Rice–Wheat System of South Asia. International Rice Research Institute, Los Baños, Philippines, pp 69–108
120. Ladha JK, Pathak H, Tirol-Padre A, Dawe D, Gupta RK (2003). Productivity trends in intensive rice-wheat cropping systems in Asia. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (ed) Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. ASA, CSSA, SSSA, Madison, WI, ASA Special Publ 65, pp 45–76
121. Lantican MA, Lampayan RM, Bhuiyan SI, Yadav MK (1999) Determinants of improving productivity of dry-seeded rice in rainfed lowlands. Exp Agric 35:127–140
122. Lee MH, Kim JK, Kim SS, Park ST (2002) Status of dry-seeding technologies for rice in Korea. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, and Hardy B (ed) Direct Seeding: Research Strategies and Opportunities. Int Rice Res Institute, Los Baños, Philippines, pp 161–176
123. Lee MH, Kim JK, Kim SS and Park ST (2002) Status of dry-seeding technologies for rice in Korea. In: Pandey *et al.* (ed) Direct Seedling: Research and Strategies and Opportunities proceedings of the International Workshop on Direct Seeding in Asian Rice Systems: Strategic Research Issues and Opportunities, 25–28 Jan., 2000, Bangkok, Thailand. IRRI, pp 161–176
124. Mackill DJ, Coffman WR, Garrity DP (1996) Rainfed low land rice improvement. International Rice Research Institute, Manila, Philippines, 242p
125. Mahajan G, Timsina J (2011) Effect of nitrogen rates and weed control methods on weeds abundance and yield of direct-seeded rice. Arch Agro Soil Sci 57(3):239–250
126. Maity SK, Mukherjee PK (2008) Integrated weed management in dry direct-seeded rice (*Oryza sativa* L.). Ind J Agro 53(2):116–120
127. Mandal B, Hazra GC, Mandal LN (2000) Soil management influences on zinc desorption for rice and maize nutrition. Soil Sci Soc Am J 64:1699–1705
128. Masscheleyn PH, Delaune RD, Patrick WH Jr (1993) Methane and nitrous oxide emission from laboratory measurements of rice soil suspension: effect of soil oxidation-reduction status. Chemosphere 26:251–260
129. Matloob A, Khaliq A, Chauhan BS (2015) Weeds of direct-seeded rice in Asia: problems and opportunities. Advan Agro 130:291–336
130. Matsue Y, Mizuta K, Furuno K, Yoshida T (1991) Studies on palatability of rice grown in northern Kyushu. Jpn J Soil Sci Pl Nut 60:490–496
131. Merotto A Jr, Goulart IC, Nunes AL, Kalsing A, Markus C, Menezes VG, Wander AE (2016) Evolutionary and social consequences of introgression of nontransgenic herbicide resistance from rice to weedy rice in Brazil. Evol Appl 9(7):837–846
132. Mishra AK, Chaudhari SK, Kumar P, Singh K, Rai P, Sharma DK (2014) Consequences of straw burning on different carbon fractions and nutrient dynamics. Indian Farming 64:11–12
133. Mishra AK, Mahinda AJ, Shinjo H, Jat ML, Singh A, Funakawa S (2018) Role of conservation agriculture in mitigating soil salinity in Indo-Gangetic Plains of India. In: Gupta SK, Goyal MR, Singh A (ed) Engineering Practices for Management of Soil Salinity. Apple Academic Press Inc., pp. 87–114

134. Mishra AK, Padbhushan R, Biswal S, Sharma S (2020) Climate smart approach for water management in summer paddy under different establishment methods in Odisha. National Seminar on Climate Smart Agriculture for Enhancing Farm Profitability, 28–29 January, 2020
135. Mishra AK, Shinjo H, Jat HS, Jat ML, Jat RK, Funakawa S (2016) Farmer 's perspective on adaptation and up-scaling of conservation agriculture based management practices in Indo-Gangetic plains of India. In: Madarasz Balazs [Hungarian Academy of Sciences], Andrienn T [Hungarian A. of Sciences] (ed) International Conference on Conservation Agriculture and Sustainable Land Use. Szarka, Laszlo Csaba (Hungarian Academy of Sciences), Budapest, Hungary, pp. 40–46
136. Mishra AK, Arya R, Tyagi R, Grover D, Mishra J, Vimal SR, et al. (2021) Non-judicious use of pesticides indicating potential threat to sustainable agriculture. Sustainable Agriculture Reviews 50: Emerging Contaminants in Agriculture, 383–400
137. Mishra AK, Roohi, Mishra S, Grover D, Mishra J (2021) Precise nutrient management in agroecosystems and associated environmental challenges. In: Contemporary Environ Challenges India, 203–241
138. Mispan MS et al (2019) Managing weedy rice (Oryza sativa L.) in Malaysia: challenges and way forward. J Res Weed Sci 2:149–167
139. Mitchell J, Fukai S, Basnayake J (2004) Grain yield of direct seeded and transplanted rice in rainfed lowlands of South East Asia. Proceedings of 4th International Crop Science Congress, 26 September–October 2004, Brisbane, Queensland, Australia
140. Mohanty S (2014) Rice in South Asia Rice Today 13(2):40–41
141. Mohler CL (1996) Ecological bases for the cultural control of annual weeds. J Prod Agric 9:468–474
142. Mohler CL, Callaway MB (1991) Effects of tillage and mulch on emergence and survival of weeds in sweet corn. J Appl Ecol 29:21–34
143. Mohler CL, Galford AE (1997) Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage. Weed Res 37:147–155
144. Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of Vicia villosa Roth and Secale cereale L. residue. Weed Res 33:487–499
145. Moody K (1977) Weed control in multiple cropping. In: Cropping Systems Research and Development for the Asian Rice Farmer. International Rice Research Institute, Los Baños, Laguna, Philippines, pp 281–293
146. Moody K (1983) The status of weed control in Asia. FAO Plant Prot Bulletin 30:119–120
147. Moody K, Mukhopadhyay K (1982) Weed control in dry seeded rice-problems, present status, and research direction. In: Rice Research Strategies for the Future. International Rice Research Institute, Manila, Philippines, pp 147–158
148. Mortimer AM, Hill JE (1999) Weed species shifts in response to broad spectrum herbicides in subtropical and tropical crops. Brighton Crop Prot Conf 2:425–437
149. Mortimer AM, Riches CR, Mazid M, Pandey S, Johnson DE (2008) Issues related to direct seeding of rice in rainfed cropping systems in northwest Bangladesh. In:Singh Y, Singh VP, Chauhan B, Orr A, Mortimer AM, Johnson DE, Hardy B (ed) Direct seeding of rice and weed management in the irrigated rice-wheat cropping system of the Indo-Gangetic Plains. International Rice Research Institute, Los Baños, Philippines, and Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India
150. Musa MM (1969) Some aspects of nitrogen transformation in Gezira soil. In:Siddiq MA, Hughes LC (ed) Cotton Growth in Gezira Environment pp 29–38
151. My TV, Tuong TP, Xuan VT, Nghiep NT (1995) Dry seeding rice for increased cropping intensity in Long An Province, Vietnam. In: Vietnam and IRRI, a Partnership in Rice Research. Ministry of Agriculture and Food Industry, Vietnam and International Rice Research Institute, Los Baños, Philippines, pp 111–122
152. Nawaz A, Farooq M, Lal R, Rehman A, Hussain T, Nadeem A (2017) Influence of Sesbania brown manuring and rice residue mulch on soil health, weeds and system productivity of conservation rice–wheat systems. Land Degra Devel 28:1078–1090
153. Naylor R (1994) Herbicide use in Asian rice production. World Devel 22:55–70
154. Neve P, Barney JN, Buckley Y et al (2018) Reviewing research priorities in weed ecology, evolution and management: a horizon scan. Weed Res 58:250–258
155. Noldin JA, Chandler JM, Ketchersid ML, McCauley GN (1999) Red rice (*Oryza sativa* L.) biology. II. Ecotype sens herbicides Weed Technol 13:19–24
156. Olajumoke B et al (2016) Competitive ability of cultivated rice against weedy rice biotypes – a review. Chilean J of Agri Res 6(2):243–252
157. Olofsdotter M (2001) Rice—a step toward use of allelopathy. Agron J 93:3–8
158. Olofsdotter M, Jensen L, Courtois B (2002) Improving crop competitive ability using allelopathy-an example from rice. Plant Breed 121:1–9

159. Olofsdotter M, Navarez D, Moody K (1995) Allelopathic potential in rice (*Oryza sativa* L.). Ann Appl Bio 127:543–560
160. Ottis BV, Smith KL, Scott RC, Talbert RE (2005) Rice yield and quality as affected by cultivar and red rice (*Oryza sativa* L.) density. Weed Sci 53:499–504
161. Oussible M, Crookstan RK, Larson WE (1992) Subsurface compaction reduces the root and shoot growth and grain yield of wheat. Agron J 84:34–38
162. Owen MD (2016) Diverse approaches to herbicide-resistant weed management. Weed Sci 64:50–584
163. Pal S, Datta SP, Rattan RK, Singh AK (2008) Diagnosis and amelioration of iron deficiency under aerobic rice. J Plant Nutr 31:919–940
164. Pandey CB, Kumar U, Kaviraj M, Minick KJ, Mishra AK, Singh JS (2020) DNRA: a short-circuit in biological N-cycling to conserve nitrogen in terrestrial ecosystems. Sci Total Environ 738:139710
165. Pandey NC, Samantaray RN, Mohanty SK (1985) Nutrient changes in direct- seeded submerged rice soils with varying nutrio-environments. Plant Soil 88:299–306
166. Pandey S, Velasco LE (1999) Economics of alternative rice establishment methods in Asia: a strategic analysis. In: Social Sciences Division Discussion Paper, International Rice Research Institute, Los Baños, Philippines
167. Pandey S, Velasco L (2002) Economics of direct seeding in Asia: patterns of adoption and research priorities. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (ed) Direct Seeding: Research Strategies and Opportunities. International Rice Research Institute, Los Baños, Philippines, pp 3–14
168. Pandey S, Velasco L (2005) Trends in crop establishment methods in Asia and research issues. In: Toriyama K, Heong KL, Hardy B (ed) Rice Is Life: Scientific Perspectives for the 21st Century. International Rice Research Institute, Los Baños, Philippines and Japan International Research Center for Agricultural Sciences, Tsukuba, Japan, pp 178–181
169. Parihar SS (2004) Effect of crop-establishment method, tillage, irrigation and nitrogen on production potential of rice-wheat cropping system. Indian J Agron 49:1–5
170. Park ST, Son Y, Lee SK, Chung KS (1990) Studies on major cultivation methods for dry direct seeding. Res Rep RDA (Rice) 32:18–28
171. Pathak H (1999) Emissions of nitrous oxide from soil. Curr Sci 77(3):359–369
172. Pathak H, Saharawat YS, Gathala M, Ladha JK (2011) Impact of resource-conserving technologies on productivity and greenhouse gas emission in rice-wheat system. Greenhouse Gas Sci Technol 1:261–277
173. Pathak H, Saharawat YS, Gathala MK, Mohanty S, Ladha JK (2009) Simulating environmental impact of resource-conserving technologies in the rice-wheat system of the Indo-Gangetic Plains. In: Ladha JK, Singh Y, Erenstein O, and Hardy B (ed) Integrated Crop and Resource Management in the Rice-Wheat System of South Asia. International Rice Research Institute, Los Baños, Philippines, pp 321–333
174. Pathak H, Sankhyan S, Dubey DS, Bhatia A, Jain N (2013) Dry direct-seeding of rice for mitigating greenhouse gas emission: field experimentation and simulation. Paddy Water Environ 11:593–601
175. Patrick WH Jr, Wyatt R (1964) Soil nitrogen loss as a result of alternate submergence and drying. Soil Sci Soc Am J 28:647–653
176. Perotti VE, Larran AS, Palmieri VE, Martinatto AK, Permingeat HR (2020) Herbicide resistant weeds: a call to integrate conventional agricultural practices, molecular biology knowledge and new technologies. Plant Sci 290:110255
177. PhilRice (The Philippine Rice Research Institute) (2002) Integrated nutrient management for rice production. In: Rice Technology Bulletin No. 45. The Philippine Rice Research Institute, Maligaya, Nueva Ecija, Philippines, pp 24
178. Pongprasert S (1995) Insect and disease control in wet-seeded rice. In: Moody K (ed) Constraints, Opportunities, and Innovations for Wet-seeded Rice, Discussion Paper Series No.10. International Rice Research Institute, Los Baños, Philippines, Thailand pp 118–132
179. Ponnamperuma FN (1972) The chemistry of submerged soils. Adv Agron 24:29–96
180. Poore J, Nemecek T (2018) Reducing food’s environmental impacts through producers and consumers. Sci 360(6392):987–992
181. Prabhu AS, Filippi MC, Arau´jo LG, Faria JC (2002) Genetic and phenotypic characterization of isolates of *Pyricularia grisea* from the rice cultivars Epagri 108 and 109 in the State of Tocantins. Fitopatol Bras 27:566–573
182. Prasad R (2011) Aerobic rice systems Adv Agron 111:207–247
183. Qin J, Hu F, Li D, Li H, Lu J, Yu R (2010) The effect of mulching, tillage and rotation on yield in non-flooded compared with flooded rice production. J Agro & Crop Sci 196:397–406

184. Ramaiah K, Mudaliar SD (1934) Lodging of straw and its inheritance in rice (Oryza sativa L.). Ind J Agric Sci 4:880–894
185. Rao AN, Nagamani A (2007) Available technologies and future research challenges for managing weeds in dry-seeded rice in India. Proceed of the 21st Asian Pacific Weed Sci Soc Conference,2–6 October 2007, Colombo, Sri Lanka, pp 391–491
186. Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM (2007) Weed management in direct-seeded rice. Adv Agron 93:153–255
187. Rashid MH, Alam MM, Khan MAH, Ladha JK (2009) Productivity and resource use of direct-(drum)-seeded and transplanted rice in puddled soils in rice-rice and rice-wheat ecosystem. Field Crops Res 113:274–281
188. Rathore M, Singh R, Kumar B, Chauhan B (2016) Characterization of functional trait diversity among Indian cultivated and weedy rice populations. Sci Rep 6(1):1–9
189. Reiner W, Milkha SA (2000) The role of rice plants in regulating mechanisms of methane emissions. Biol Fertil Soils 31:20–29
190. Rickman JF (2002) Manual for laser land leveling. Rice–Wheat Consortium Technical Bulletin Series 5. In: Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India
191. Ruzmi R, Ahmad-Hamdani M, Abidin M, Roma-Burgos N (2021) Evolution of imidazolinone-resistant weedy rice in Malaysia: the current status. Weed Sci 1–11. https://doi.org/10.1017/wsc.2021.33
192. Sah DN, Bonman JM (2008) Effects of seed bed management on blast development in susceptible and partially resistant rice cultivars. J Phytopathol 136:73–81
193. Saharawat YS, Bhagat S, Malik RK, Ladha JK, Gathala M, Jat ML, Kumar V (2010) Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Res 116:260–267
194. Sahid IB, Hossain MS (1995) The effects of flooding and sowing depth on the survival and growth of five rice-weed species. Plant Prot Quart 10:139–142
195. Saleque MA, Kirk GJD (1995) Root induced solubilization of phosphate in the rhizosphere of low land rice. New Phyto 129:325–336
196. Sanchez PA (1973) Puddling tropical soils. 2. Effects water loss Soil Sci 115:303–308
197. Savary S, Castilla NP, Elazegui FA, Teng PS (2005) Multiple effects of two drivers of agricultural change, labour shortage and water scarcity, on rice pest profiles in tropical Asia. Field Crops Res 91:263–271
198. Seal AN, Pratley JE (2010) The specificity of allelopathy in rice (Oryza sativa L). Weed Res 50(4):303–311
199. Seal AN, Pratley JE, Haig T, Lewin LG (2004) Screening rice varieties for allelopathic potential against arrowhead (*Sagittaria montevidensis*), an aquatic weed infesting Australian Riverina rice crops. Crop Pasture Sci 55(6):673–680
200. Setter TL, Laureles EV, Mazaredo AM (1997) Lodging reduces yield of rice by self-shading and reductions in canopy photosynthesis. Field Crops Res 49:95–106
201. Sharma PK, De Datta SK (1985) Effect of puddling on soil physical properties and processes. In: Soil Physics and Rice. International Rice Research Institute, Los Baños, Philippines, pp 217–234
202. Sharma PK, Bhushan L, Ladha JK, Naresh RK, Gupta RK, Balasubramanian BV, Bouman BAM (2002) Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic medium textured soi. In: Hengsdijk BAM, Hardy B, Bindraban PS, Tuong TP, Ladha JK, Bouman H (ed) Water- Wise Rice Production. International Rice Research Institute, Los Baños, Philippines, pp 223–235
203. Sharma PK, Ladha JK, Bhushan L (2003) Soil physical effects of puddling in rice-wheat cropping systems. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (ed) Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. ASA, CSSA, SSSA, Madison, WI, ASA Special Publication 65, pp 97–113
204. Shaviv A, Mikkelsen RL (1993) Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation: a review. Fert Res 35:1–12
205. Shimono H (2011) Earlier rice phenology as a result of climate change can increase the risk of cold damage during reproductive growth in northern Japan. Agri Ecosys Environ 144(1):201–207
206. Shoji S, Delgado J, Mosier A, Miura Y (2001) Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Commun Soil Sci Plant Anal 32:1051–1070
207. Singh S, Singh R, Mishra AK, Updhayay S, Singh H, Rahgubanshi AS (2018) Ecological perspectives of crop residue retention under the conservation agriculture systems. Trop Ecol 59(4):589–604
208. Singh AK, Choudhury BU, Bouman BAM (2002a) Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong

TP, Ladha JK (ed) Water-Wise Rice Production. International Rice Research Institute, Los Baños, Philippines, pp 237–246

209. Singh A, Nandal DP, Punia SS, Malik P (2018) Integrated weed management in direct seeded rice in Trans Indo-Gangetic plains of India- a review. J Appl Nat Sci 10(2):779–790
210. Singh DK, Singh AK (2002) Groundwater situation in India: Problems and perspective. Water Res Dev 18:563–580
211. Singh GR, Singh TA (1988) Leaching losses and use efficiency of nitrogen in rice fertilized with urea supergranules. J Ind Soc Soil Sci 36:274–279
212. Singh G, Singh RK, Singh VP, Singh BB, Nayak R (1999) Effect of crop weed competition on yield and nutrient uptake by direct seeded rice (*Oryza sativa* L.) in rainfed lowland situation. Ind J Agron 44:722–727
213. Singh, G., Singh VP, Singh Y, Singh KM, Mortimer M, Johnson DE, White JL (2003) Efficacy of herbicides alone and in combinations in direct seeded rice Biennial Conference ISWS, 12–14 March, G.B. P.U.A. & T., Pantnagar, pp 03
214. Singh K, Kumar V, Saharawat YS, Gathala M, Ladha JK (2013) Weedy rice: an emerging threat for direct seeded rice production systems in India. J Rice Res 1:106
215. Singh S, Bhushan L, Ladha JK, Gupta RK, Rao AN, Sivaprasad B (2006) Weed management in dry-seeded rice (*Oryza sativa* L.) cultivated in the furrow-irrigated raised-bed planting system. Crop Prot 25:487–495
216. Singh S, Bhushan L, Ladha JK, Gupta RK, Rao AN, Shivprasad B (2008) Weed management in aerobic rice systems under varying establishment methods. Crop Prot 27(3–5):660–671
217. Singh S, Singh G, Singh VP, Singh AP (2005) Effect of establishment methods and weed management practices on weeds and rice in rice-wheat cropping system. Ind J Weed Sci 37(1–2):51–57
218. Singh S, Chhokar RS, Gopal R, Ladha JK, Gupta RK, Kumar V, Singh M (2009) Integrated weed management: a key to success for direct-seeded rice in the Indo-Gangetic Plains. In: Ladha JK, Singh Y, Erenstein O, Hardy B (ed) Integrated Crop and Resource Management in the Rice-Wheat System of South Asia. International Rice Research Institute, Los Baños, Philippines, pp 261–278
219. Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN, Sivaprasad B, Singh PP (2007) Evaluation of mulching, intercropping with Sesbania and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). Crop Prot 26:518–524
220. Singh V, Jat ML, Ganie ZA, Chauhan BS, Gupta RK (2016) Herbicide options for effective weed management in dry direct seeded rice under scented rice-wheat rotation of western Indo Gangetic Plains. Crop Prot 81:168–176
221. Singh K, Kumar V, Saharawat YS, Gathala MK, Ladha JK, Chauhan BS (2013) Weedy rice: an emerging threat for direct-seeded rice production systems in India. J of Rice Res 1(1):106
222. Singh VP, Singh G, Singh SP, Kumar A, Singh Y, Johnson DE, Mortimer M (2005a) Effect of rice wheat establishment methods and weed management in irrigated rice–wheat production system. In: Workshop on Direct Seeded Rice in the Rice–wheat System of the Indo-Gangetic Plains, 1–2 February 2005, G.B. Pant University of Agriculture and Technology, Pantnagar, U.S. Nagar, Uttaranchal, India, pp. 12
223. Singh Y, Bhardwaj AK, Singh SP, Singh RK, Chaudhary DC, Saxena A, Singh V, Singh SP, Kumar A (2002) Effect of rice (*Oryza sativa* L.) establishment methods, tillage practices in wheat (*Triticum aestivum*) and fertilization on soil physical properties and rice–wheat system productivity on a silty clay Mollisol of Uttaranchal. Indian J Agric Sci 72:200–205
224. Srivastava K, Jat H, Meena M, Choudhary M, Mishra AK, Chaudhari SK (2016) Long term impact of different cropping systems on soil quality under silty loam soils of Indo-Gangetic plains of India. J Appl Nat Sci 82:584–587. https://doi.org/10.31018/jans.v8i2.841
225. The SRP standard for sustainable rice cultivation (Version 2.1), Sustainable Rice Platform. Bangkok. Available at: http://www.sustainablerice.org. Accessed on January 06, 2021
226. The SRP performance indicators for sustainable rice cultivation (Version 2.1), Sustainable Rice Platform. Bangkok. Available at http://www.sustainablerice.org. Accessed on January 06, 2021
227. Sudhir-Yadav G, Gill MS, Kukal SS (2007) Performance of direct-seeded basmati rice in loamy sand in semi-arid sub-tropical India. Soil Till Res 97:229–238
228. Sudhir-Yadav GG, Humphreys E, Kukal SS, Walia US (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 1. Crop performance Field Crops Res 120:112–122
229. Sudhir-Yadav HE, Kukal SS, Gill G, Rangarajan R (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 2. Water balance and water productivity. Field Crops Res 120:123–132
230. Surendra S, Sharma SN, Rajendra P, Singh S, Prasad R (2001) The effect of seeding and tillage methods on productivity of rice–wheat cropping system. Soil Till Res 61:125–131
231. Susilawati HL, Setyanto P, Kartikawati R, Sutriadi MT (2019) The opportunity of direct seeding to mitigate greenhouse gas emission from paddy rice field. In: IOP Conf Ser Earth Environ Sci 393(1):012042
232. Svizzero S (2020) Weedy rice and the sustainability of alternative establishment methods. Int J Sus Dev 23(1–2):86–102

233. Svizzero S (2021) On the sustainability of direct-seeded rice. In: Keswani C (ed) Agro-Based Bioeconomy: Reintegrating Trans-disciplinary Research and Sustainable Development Goals. CRC Press, USA, pp 93–108
234. Svizzero S (2021) Agronomic practices and biotechnological methods dealing with the occurrence, dispersion, proliferation and adaptation of weedy rice (Oryza sativa f. spontanea). Int J Pest Mgmnt https://doi.org/10.1080/09670874.2021.1944697
235. Svizzero S (2021) Sustainability, efficiency and circularity of weedy rice management strategies. Circular Econ Sustain. https://doi.org/10.1007/s43615-021-00087-0
236. Tabbal DF, Bouman BAM, Bhuiyan SI, Sibayan EB, Sattar MA (2002) On-farm strategies for reducing water input in irrigated rice: case studies in the Philippines. Agric Water Manage 56:93–112
237. Tomita S, Nawata E, Kono Y, Nagata Y, Noichana C, Sributta A, Inamura T (2003) Differences in weed vegetation in response to cultivating methods and water conditions in rainfed paddy fields in northeast Thailand. Weed Biol Manage 3:117–127
238. Tseng TM (2013) Genetic diversity of seed dormancy and molecular evolution of weedy red rice, theses and dissertations, pp 595 (online). http://scholarworks.uark.edu/etd/595. Accessed on 1 February 2020
239. Tuong TP, Bouman BAM, Mortimer M (2005) More rice, less water Integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod Sci 8:231–241
240. Tuong TP, Wopereis MCS, Marquez JA, Kropff MJ (1994) Mechanisms and control of percolation losses in irrigated puddled rice fields. Soil Sci Soc Am J 58:1794–1803
241. Ventura W, Watanabe, (1978) I. Growth inhibition due to continuous cropping of dryland rice and other crops. Soil Sci Plant Nutri 24:375–389
242. Vermeulen H (2007) Evaluation of the aerobic rice technology: three years of experiments in the Philippines. Internship Thesis, Plant Production Systems (WUR), International Rice Research Institute, Los Baños, Philippines
243. Vigueira CC, Olsen KM, Caicedo AL (2013) The red queen in the corn: agricultural weeds as models of rapid adaptive evolution. Heredity 110(4):303–311
244. Wade LJ, George T, Ladha JK, Singh U, Bhuiyan SI, Pandy S (1998) Opportunities to manipulate nutrient-by-water interactions in rainfed lowland rice systems. Field Crops Res 56:93–112
245. Wang Z, Delaune RD, Masscheleyn PH, Patrick WH Jr (1993) Soil redox and pH effects on methane production in a flooded rice soil. Soil Sci Soc Am J 57:382–385
246. Wassmann R, Neue HU, Ladha JK, Aulakh MS (2004) Mitigating greenhouse gas emissions from rice–wheat cropping system in Asia. Environ Dev Sustain 6:65–90
247. Weerakoon WMW, Mutunayake MMP, Bandara C, Rao AN, Bhandar DC, Ladha JK (2011) Direct-seeded rice culture in Sri Lanka: lessons from farmers. Field Crops Res 121(1):53–63
248. Weston LA (1996) Utilization of allelopathy for weed management in agroecosystems. Agron J 88:860–866
249. Willet IR (1991) Phosphorous dynamics in acid soils that undergo alternate flooding and drying. In: Deturck P, Ponnamperuma FN (ed) Rice Production on Acid Soils of the Tropics. Institute of Fundamental Studies, Sri Lanka, pp 43– 49
250. Yadav S, Gill MS, Kukal SS (2007) Performance of direct-seeded basmati rice in loamy sand in semi-arid subtropical India. Soil Till Res 97:229–238
251. Yadav S, Humphreys E, Kukal SS, Gill G, Rangarajan R (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 2. Water balance and water productivity. Field Crops Res 120:123–132
252. Yaduraju NT, Mishra JS (2004) Weed management in rice with special orientation to export. In: SAARC RICE EXPO 2004. Maharashtra Chamber of Commerce and Industry and Rice Exporters Association of Pakistan, Mumbai, India, pp 111–115
253. Yadvinder-Singh, Brar NK, Humphreys E, Singh B, Timsina J (2008) Yield and nitrogen use efficiency of permanent bed rice-wheat systems in northwest India: effect of N fertilization, mulching and crop establishment method. In: Humphreys E, Roth CH (ed) Permanent Beds and Rice-Residue Management for Rice-Wheat Systems in the Indo-Gangetic Plain. ACIAR Proceedings No. 127, Australian Centre for International Agricultural Research, Canberra, Australia, pp 62–78
254. Yun YD, Park TS, Oh YJ (1993) Establishment of dry seeding cultivation method. Annual Research Report 1993 (Rice). National Crop Experiment Station, Suwon, Korea.
255. Zhao D, Atlin G, Bastiaans L, Spiertz J (2006) Developing selection protocols for weed competitiveness in aerobic rice. Field Crops Res 97:272–285

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