Field Crops Research 322 (2025) 109739

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Dry direct-seeded and broadcast rice: A profitable and climate-smart alternative to puddled transplanted *aus* rice in Bangladesh

Sharif Ahmed [a,*], Virender Kumar [b], Asad Uz Zaman [c], Mahbubur Rahman Dewan [c], Amina Khatun [c], Khaled Hossain [d], Sudhanshu Singh [e], Jagadish Timsina [f], Timothy J. Krupnik [d]

[a] *International Rice Research Institute, Banani, Dhaka 1201, Bangladesh*
[b] *International Rice Research Institute, Leguna, Los Banōs 4031, Philippines*
[c] *Bangladesh Rice Research Institute, Gazipur 1700, Bangladesh*
[d] *International Maize and Wheat Improvement Center (CIMMYT), Gulshan-2, Dhaka, Bangladesh*
[e] *International Rice Research Institute, New Delhi 110008, India*
[f] *International Fertilizer Development Centre, Muscle Shoals, Alabama, USA*

ARTICLE INFO

Keywords:
Tillage and crop establishment methods
Landscape positions
Climate-smart agriculture (CSA)
Resource-conservation
Yield-scaled emissions

ABSTRACT

Context: Dry direct-seeded rice (DSR) has been identified as a potential crop establishment method to reduce labor, water, and energy use, as well as the carbon footprint and is considered as a climate-smart practice for rice production. However, the economic feasibility and farmers' adoption of DSR will likely depend on its productivity compared to the dominant practice of puddled transplanted rice (PTR). Tillage and crop management practices, landscape position, and rice cultivars are also likely to influence DSR productivity, profitability, energy use, and global warming potential (GWP). While numerous studies have compared the performance of DSR with PTR, none have evaluated DSR across different landscape positions to identify the most suitable landscape for expansion of DSR.

Methods: We conducted multilocation and multi-year trials comparing the performance of spring '*aus*' season rice establishment methods (machine drilled DSR, broadcasted DSR, and PTR) using three rice varieties (BRRI dhan83, BRRI dhan85, and Binadhan-19) under three landscape positions (highland, medium highland, and lowland) in three distinct districts and agroecological zones of Bangladesh. We evaluated productivity, profitability, energy use efficiency (EUE), energy productivity (EP), GWP, and yield-scaled emissions of each of these tillage and crop establishment systems.

Results: Our results showed that the DSR had a similar or slightly lower yield (2–8 %) than PTR, but with lower labor use (15–47 %), lower production cost (US$ ~150 ha^{-1}), and higher net profit. Drill-DSR yielded similar to PTR under highlands and medium highlands, but as 9–16 % lower when grown on lowlands. EUE and EP were 15–40 % higher in DSR than in PTR due to lower energy requirements. Higher energy use in PTR primarily resulted from extra energy required for nursery raising, transplanting, puddling, and irrigation. DSR was associated with lower GWP and yield-scaled emissions of 56 to 66 % compared to PTR.

Conclusions: This study suggests that DSR can be a more environmentally sound, economically viable, and climate-smart production system, found more suitable for highland and medium-highland environments. However, for the widespread adoption of DSR in Bangladesh and South Asia as a whole, the nuiances of landscape position should be considered and appropriate technological, social, and policy-level interventions will be necessary.

1. Introduction

Climate change is a major threat to agriculture, food security, and livelihoods of millions of globally (IPCC, 2019). Agricultural production will be impacted by increasing temperatures, changes in rainfall patterns, and variations in the frequency and intensity of extreme climatic events such as floods and droughts (Lobell et al., 2012; Singh et al., 2013; Prasanna, 2014). Sustainable food production will require

---

* Corresponding author.
E-mail address: s.ahmed@irri.org (S. Ahmed).

https://doi.org/10.1016/j.fcr.2025.109739
Received 6 May 2024; Received in revised form 20 November 2024; Accepted 2 January 2025

reductions in greenhouse gas (GHG) emissions from agriculture and better resilience to the risks posed by climate change.

Rice is the main staple food crop globally, providing a primary source of energy for over half of the world's population (Fukagawa and Ziska, 2019; Mohidem et al., 2022). Worldwide, rice is grown on more than 164 million hectares, of which around 90 % is in Asia alone (FAO, 2022; Shahbandeh, 2022). The estimated impacts of historical and future climate change indicate up to 35 % yield loss in rice depending on locations, future climate scenarios, and the range of climate change projection (Porter et al., 2014). On the other hand, rice fields emit large quantities of methane (CH_4) and nitrous oxide (N_2O) gases, which have high global warming potential (GWP) due to their high radiative effects (Xu et al., 2022b). Paddy rice contributes about 10 % of agricultural GHG emissions and about 20 % of total methane emissions from agriculture (IPCC, 2014; Smartt et al., 2016).

Bangladesh is the fourth largest rice-producing country in the world. Rice is the first ranked crop grown on 75 % of the total cropped area covering 15.44 million hectares with a total paddy (rough rice) production of 52 million tons (BBS, 2022). In Bangladesh, puddled transplanted rice (PTR) is the dominant tillage and crop establishment method, though it is highly labor and water-intensive, has a high cost of cultivation, and emits large amounts of GHGs. Around 0.48 million tons of CH_4 are emitted from rice cultivation annually (Khan et al., 2015). Researchers and policymakers in Bangladesh are increasingly concerned with the potential impacts of climate change on rice yield and the impacts of rice cultivation on GHG emissions. Therefore, alternative tillage, crop establishment, and management strategies which emit less CH_4 from rice cultivation are increasingly prioritized to mitigate climate change (Sapkota et al., 2021). Dry or wet direct-seeded rice (DSR) could be an alternative to the PTR grown under flooded conditions to minimize CH_4 emissions (Li et al., 2019). In contrast to PTR where seedlings are transplanted into wet-tilled soil, DSR seeds are sown directly into tilled or non-tilled soil, often by machine-aided drilling. DSR fields experience alternating wetting and drying conditions without standing water, particularly in the early season, reducing the development of reduced soil conditions favoring CH_4 emission (Wang et al., 2012; Yang et al., 2012). A study from China reported that the GWP of dry DSR and wet DSR is respectively 76.2 % and 60.4 % lower compared to conventional PTR (Tao et al., 2016). Ko and Kang (2000) reported reductions in CH_4 emissions by 8 % on a wet and 33 % on a dry soil in South Korea while Corton et al. (2000) showed 16–54 % reductions in CH_4 in DSR compared to PTR in the Philippines. Wassmann and Aulakh (2000) reported a 16–92 % reduction from DSR than PTR in several Asian countries and Susilawati et al. (2019) reported 47 % such reduction in Indonesia. In India, Joshi et al. (2013) reported 30–38 % reductions under DSR than PTR while in Bangladesh, Borna et al. (2022) found 15–25 % reductions under wet-DSR with AWD compared with PTR.

On-going research in Asia also suggests that the labor-intensive PTR is progressively becoming less profitable as labor costs grow and energy costs increase. Combined with environmental concerns, research is increasingly geared towards identifying potential alternative methods of crop establishment to PTR (Kumar and Ladha, 2011; Yuan et al., 2017b; Krupnik et al., 2022; Magar et al., 2022; Timsina et al., 2022). Dry or wet DSR could be a profitable and sustainable option for rice establishment/cultivation, especially under uncertain rainfall and water-scarce environments, and under high labor costs conditions, therefore it is considered a climate-smart (CSA) agricultural production practice. CSA is a comprehensive approach designed to transform and reorient agricultural systems whose goal is to sustainably enhance agricultural productivity while also increasing resilience to climate change and minimizing greenhouse gas emissions (Lipper et al., 2014). The core principles of CSA include optimizing resource use, enhancing carbon storage in soils, and promoting biodiversity (Zheng et al., 2024). DSR demonstrates these principles through its innovative cultivation techniques, which require less water and energy compared to traditional PTR. DSR minimizes soil disturbance, thereby enhancing soil health and carbon sequestration, which contribute to improved resilience against climate-induced stresses such as drought (Chaudhary et al., 2022). DSR does not require much irrigation water during its sowing and establishment allowing its timely planting which can help to reduce the risk of crop failure during adverse weather conditions (Ahmed et al., 2014). Additionally, it significantly reduces methane emissions by limiting the duration of flooded fields, which are common in PTR (Chaudhary et al., 2022).

Despite such benefits, many studies in Asia have reported lower yields of DSR than of PTR due to patchy crop stands, poor management, and higher weed and root-knot nematode infestation (Yadav et al., 2011; Kumar et al., 2015; Liu et al., 2015). Xu et al. (2019) conducted a meta-analysis of 53 studies comparing the yield of DSR and PTR from 1980–2017. They showed that DSR yield was 12 % lower than PTR and yield loss in DSR was highly variable relative to PTR depending on management practices, soil types, and climate conditions. In India, Singh et al. (2005) conversely reported similar yields of DSR and PTR when management practices were optimum for both crops. Alam et al. (2019) recorded similar yields for *aman* DSR and PTR in on-station trials, while Bari and Ahmed (2018) reported no significant differences for direct-seeded and transplanted *aus* rice in on-farm research in Bangladesh. Other studies focus less on yield, and more on DSR's potential to save labor, water and total cost of production, with respective measurements ranging from 20–30 %, 10–40 %, and 10–30 %, respectively for these variables (Kumar et al., 2015; Liu et al., 2015; Hussain et al., 2021).

The scope for DSR in Bangladesh lies mainly for '*aus rice*' which is currently grown under both direct seeding and transplanting conditions in the pre-monsoon *aus* season (usually sown in April-May and harvested in July–August). *Aus* is practiced on about 10 % of the country's total rice area, albeit farmers' yields are low due to the use of local varieties and poor management. The lack of significant early season rainfall in the *aus* season enables farmers to sow by broadcasting and/or establishing the crop by sowing with a seed drill, after which starter irrigation can be applied to encourage germination and the established crops can make better use of early-season rainfall. Due to the dependence of *aus rice* on pre-monsoon rains, the start of the *aus* season is generally late, resulting in a late start and late harvest of *aman* rice. However, due to the development of 2-wheel tractors and seeders (Krupnik et al., 2013), rice can now be drilled early and rapidly. DSR could also be affected by its cultivation in different landscapes characterized by variations in elevation and drainage (Da Silva and Silva, 2008; Hao et al., 2010; Ran et al., 2018). Ly et al. (2012) reported a large variation in rice yield across regions and villages, as well as within villages due to landscape differences and management practices. In Bangladesh, most of the *aus* rice cultivars are developed for transplanted conditions, and as such may not perform well under direct-seeded conditions.

Despite potential benefits of DSR in terms of reducing water requirements and GHG emissions, improving soil health, and increasing resiliency to climate variability, there are no sufficient studies comparing GHG emissions and GWP (indicators of climate change) of DSR as compared with PTR, especially in a large rice producing country like Bangladesh. Therefore, this study was designed to evaluate the performance of three rice varieties under three landscape positions and three establishment methods in terms of yield, labor and water requirement, economics, energy productivity, and GHG emission and GWP. We sought to: (i) to identify the appropriate landscape positions suitable for DSR grown in the *aus* season, (ii) to quantify the impact of DSR on yield, profitability, energy use, and yield-scaled GHG emission and GWP as compared to PTR, and (iii) to identify suitable rice *aus* varieties compatible with DSR.

2. Materials and methods

2.1. On-farm experimental location, soil, and climate

On-farm experiments were conducted in the 2019, 2020, and 2021 *aus* seasons (mid-April to 1st week of August) in three districts (Jhenaidah, Faridpur, Dinajpur) representing three agro-ecological zones (AEZs 11, 12 and 13) in Bangladesh. AEZs are broad units based on physiography (landforms and parent materials), soil, depth and duration of seasonal flooding, and agro-climatology (Ahmed et al., 2018). All three locations cultivated transplanted Aman rice from the last week of July to the first week of November, following the Aus rice. Before Aus, onions were grown in Jhenaidah and Faridpur, while wheat was cultivated in Dinajpur from November to March. Farmer-managed trials were conducted in 18 farmers' fields per district (Fig. 1; Table 1).

***Jhenaidah*:** The trial locations under this district belong to AEZ 11 (*High Ganges River Floodplain* -HGRF), which has predominantly high to mediumlands (Ahmed et al., 2018). On-farm trials were conducted in Ghusaidanga village, Sarutia union, Shailkupa upazila in 2019, 2020 and 2021. Soils of AEZ 11 are silty loam and silty clay loam on the upper parts of floodplain ridges and dark grey clay in the basins. The predominant soil types are Calcareous Dark Grey Floodplain and Calcareous Brown Floodplain. Organic matter content is low in the brown ridge soils while it is high in the dark grey soils. In general, topsoils are slightly acidic to slightly alkaline, but there has been a significant lowering of soil pH in the highlands and strongly acidic in some places in recent years. Subsoils are slightly alkaline (Ahmed et al., 2018). Mean annual rainfall is about 1100 mm and the mean annual temperature is about 26.1 °C.

***Faridpur*:** The trial locations under this district belong to AEZ 12 (*Lower Ganges River Floodplain* - LGRF) which has predominantly medium-low to mediumlands. Experiments were conducted in Goalkandi village, Koijuri union, Faridpur upazila in 2020 and 2021. Soils of AEZ 12 are silty clay loam to heavy clay on lower sites and silt loams and silty clay loams on the ridges. Soil types predominantly include calcareous brown floodplain and calcareous dark grey. Organic matter content is low in ridges and moderate in the basins. The general fertility level is medium (Ahmed et al., 2018). The mean annual rainfall is about

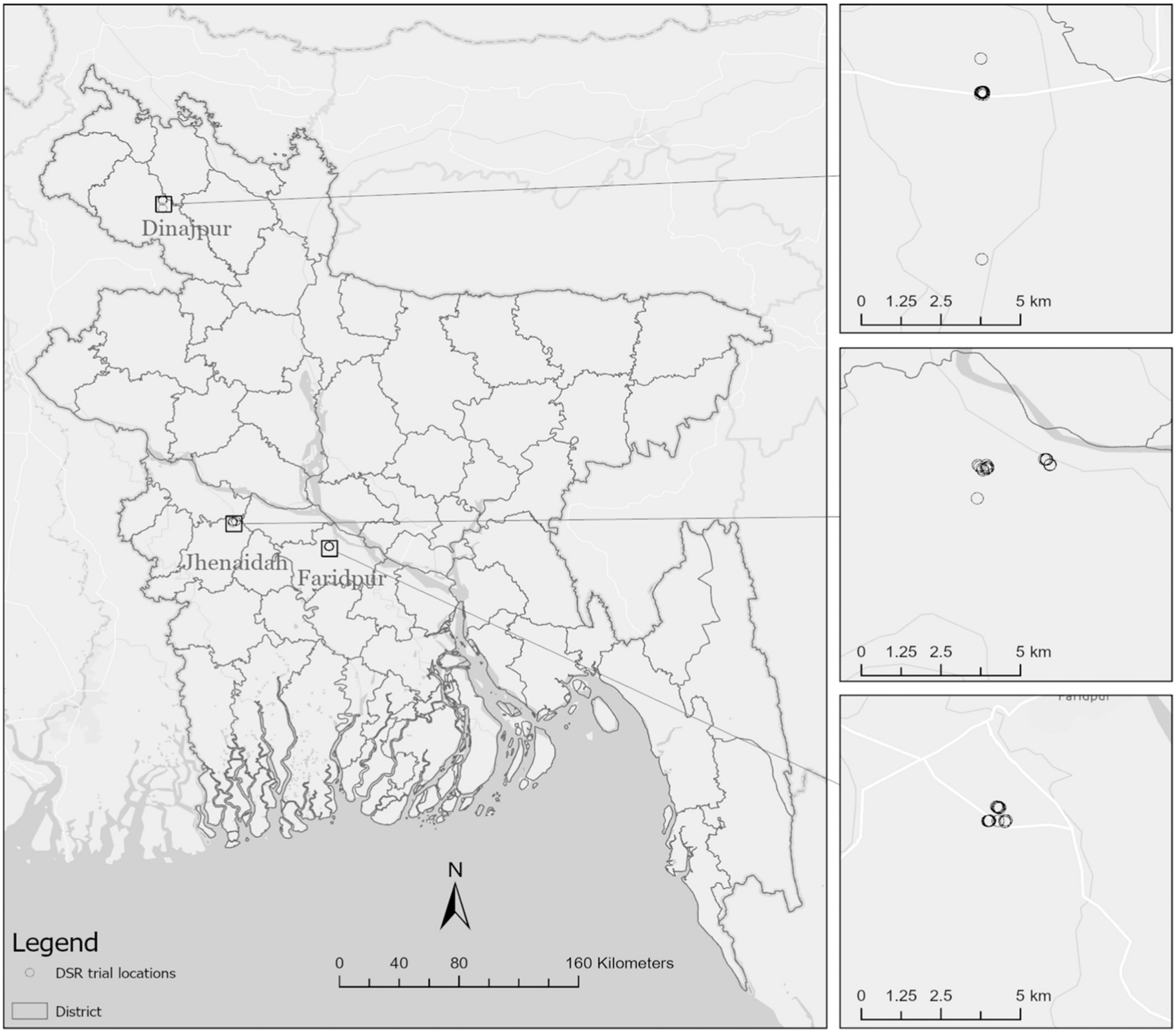

Fig. 1. Map of Bangladesh showing trial locations in Jhenaidah, Faridpur, and Dinajpur districts representing three agroecological zones (locations of all farmers' trials are shown but may overlap due to scale).

Table 1
Soil physical and chemical properties at 0-15 and 15-30 cm soil depth in three trial locations (district) and three landscape positions. Values indicate the mean data of six farmers' fields with standard errors.

District	Land type	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	pH	Organic carbon (%)	Total N (%)
Jhenaidah	High	0–15	40 ± 0.5	44 ± 1.2	16 ± 0.9	Loam	7.6 ± 0.07	1.08 ± 0.07	0.09 ± 0.006
		15–30	40 ± 1.7	43 ± 1.1	17 ± 1.3	Loam	7.8 ± 0.08	0.62 ± 0.02	0.05 ± 0.007
	Medium	0–15	40 ± 0.3	47 ± 1.4	13 ± 1.4	Silty Loam	7.8 ± 0.05	1.09 ± 0.87	0.09 ± 0.008
		15–30	46 ± 1.3	40 ± 1.6	14 ± 1.2	Sandy Loam	7.9 ± 0.03	0.41 ± 0.05	0.04 ± 0.007
	Low	0–15	43 ± 0.7	43 ± 1.9	16 ± 0.5	Loam	7.7 ± 0.08	1.03 ± 0.08	0.08 ± 0.007
		15–30	46 ± 1.5	40 ± 0.9	14 ± 0.9	Sandy Loam	7.8 ± 0.06	0.66 ± 0.02	0.06 ± 0.003
Faridpur	High	0–15	35 ± 3.0	43 ± 2.0	22 ± 1.0	Loam	7.1 ± 0.05	1.24 ± 0.03	0.11 ± 0.002
		15–30	37 ± 3.3	43 ± 1.8	20 ± 1.6	Loam	7.2 ± 0.90	0.87 ± 0.03	0.08 ± 0.003
	Medium	0–15	36 ± 4.8	42 ± 3.0	22 ± 1.8	Loam	6.7 ± 0.13	1.14 ± 0.15	0.10 ± 0.010
		15–30	34 ± 3.8	44 ± 2.8	22 ± 1.2	Loam	6.9 ± 0.16	1.07 ± 0.15	0.09 ± 0.011
	Low	0–15	40 ± 4.3	40 ± 2.8	21 ± 1.9	Loam	6.9 ± 0.09	1.31 ± 0.14	0.12 ± 0.012
		15–30	37 ± 3.9	40 ± 2.4	22 ± 1.7	Loam	7.0 ± 0.07	1.11 ± 0.07	0.09 ± 0.010
Dinajpur	High	0–15	65 ± 4.4	20 ± 1.1	15 ± 1.3	Sandy loam	6.1 ± 0.09	0.92 ± 0.06	0.09 ± 0.005
		15–30	68 ± 3.7	21 ± 2.1	11 ± 1.6	Sandy loam	6.2 ± 0.06	1.01 ± 0.04	0.06 ± 0.004
	Medium	0–15	70 ± 3.1	20 ± 1.4	10 ± 0.9	Sandy loam	6.0 ± 0.04	0.96 ± 0.09	0.08 ± 0.005
		16–30	65 ± 2.5	20 ± 2.5	15 ± 1.5	Sandy loam	6.1 ± 0.06	1.04 ± 0.06	0.07 ± 0.004
	Low	0–15	40 ± 2.6	18 ± 1.3	42 ± 3.5	Clay loam	6.1 ± 0.05	1.23 ± 0.03	0.09 ± 0.002
		15–30	42 ± 3.9	19 ± 2.1	39 ± 2.7	Clay loam	5.9 ± 0.03	1.12 ± 0.02	0.08 ± 0.003

Textural class: hydrometer method based on Stokes' law; pH: electrochemical method using a pH meter; Organic carbon: Walkley-Black chromic acid wet oxidation method; Total N: Kjeldahl method; the values after ± in columns indicate standard errors of mean.

1300 mm and the mean annual temperature is ~25.3 °C.

Dinajpur: Trials were established in AEZ 3 (*Tista Meander Floodplain* - TMF) which has predominantly medium highlands. Experiments were conducted in Fatehjongpur village, Fatehjongpur union, Chrirbandor upazila in 2020 and 2021. Soils of AEZ 3 are loamy on floodplain ridges, silty clay loam in mediumland, and heavy silt loam on the lower landscape positions. Most areas have broad floodplain ridges and almost level basins. The overall soil fertility level is low to medium with adequate moisture holding capacity (Ahmed et al., 2018).

Prior to experimentation, soil samples at 0–15 and 16–30 cm depths were collected from each field from five spots (four from four corners and one from the middle) and bulked for each depth. Soil texture with sand (%), silt (%) and clay (%), pH, organic carbon and total nitrogen were determined (Table 1).

2.2. Experimental design and treatments

Experiments were conducted at farmers' fields in a split-plot design with crop establishment methods in main plots (drill-seeded DSR, broadcast seeding DSR, and PTR), and rice varieties in sub-plots (BRRI dhan83, BRRI dhan85, and Binadhan-19). Within each AEZ, these treatments were evaluated in three landscape positions characterized by the Government of Bangladesh (Uddin et al., 2019) for their differences in water accumulation after heavy rain during the *aus* season in each AEZ: (i) Highland (i.e., no water accumulation), (ii) Medium highland (i.e., water accumulates and remains flooded for less than a month) and (iii) Lowland (i.e., water accumulates and for more than a month). Main plot sizes ranged from 360 to 450 m^2 and sub-plots from 120–150 m^2.

The varieties included in the study were newly released with yield potential from 4.0- 5.5 t ha^{-1} and a duration of 105 to 115 days. BRRI dhan83 was released for dry DSR with bold grain, BRRI dhan85 for transplanting with medium bold grain, and Binadhan-19 for both dry DSR and PTR with slender and thin grain (BRRI, 2020; Anonymous, 2022). Each year, the study was conducted on the same 18 farmers' fields (six farmers' fields with each landscape position) within each district representing different AEZs and thus resulting in a total of 54 farmers' fields in 2020 and 2021. In 2019, experiments were conducted only in one district/AEZ 11, so the total on-farm sites were 18 only. Each farmer's field was considered as a single dispersed replication.

2.3. Crop establishment and management

Immediately after harvesting the previous crop by early April, farmers participating in the trials either tilled their land using a rotavator or left it undisturbed until the trials started. At all sites, rice sowing (either in the main or nursery field) was completed between 15 to 25 April. the land preparation, fields were divided into three equal parts for the main plot treatments (establishment methods. During the sowing/transplanting, sub-plots were prepared. The buffer distance between main plots was 1 m; between subplots 0.75 m was maintained. In all fields, rice seeds were either sown for drill seeding and broadcasting (DSR) or soaked up on the same day for nursery raising. PTR plots were established with 21 days old rice seedlings.

2.3.1. Drill seeding

A Dongfeng two-wheel power tiller operated seeder (PTOS) was used in non-tilled soil to sow rice seeds continuously by performing the three operations (tillage, seeding, and seed coverage) in a single pass. Seeds were sown in six rows per pass at 45 kg ha^{-1} maintaining a row-to-row distance of 20 cm.

2.3.2. Broadcast seeding

Prior to rice seeding, plots were dry cultivated with two to three passes of Dongfeng two-wheel tractor drawn rotavator followed by manual levelling. Seeds were then manually broadcasted at 80 kg ha^{-1} and covered by a hand pulled leveller.

2.3.3. Manual transplanting

Seedlings established in nurseries at 30 kg ha^{-1} equivalent. The treatment plots were prepared with three Dongfeng two-wheel tractor drawn rotavator passes in flooded soil followed by levelling. 2–4 irrigations were required for puddling and transplanting operations, depending on the sites, LP, and locations. Twenty-day-old seedlings were uprooted and immediately transplanted into puddled soil using 2–3 seedlings $hill^{-1}$ and at 20 by 20 cm hill-to-hill spacing.

2.3.4. Fertilizer application

Site-specific recommended amounts of fertilizers for higher yield goal were applied (FRG, 2018). Rates for Jhenaidah and Faridpur were similar (triple super phosphate or TSP 75 kg ha^{-1}, muriate of potash or MoP 75 kg ha^{-1}, Gypsum 50 kg ha^{-1}, ZnSO4 3.3 kg ha^{-1} and Urea 245 kg ha^{-1}) but that for Dinajpur was different (TSP 75 kg ha^{-1}, MoP 90 kg ha^{-1}, Gypsum 50 kg ha^{-1}, ZnSO4 3.3 kg ha^{-1} and Urea 260 kg ha^{-1}). All fertilizers except urea were applied basally before sowing; urea was topdressed in three splits at 20 %, 40 %, and 40 %, respectively, at 15 days after emergence (DAE), 25–30 DAE, and 45–50

DAE. For PTR, all fertilizers were applied during puddling except urea which was top-dressed in three splits: 30 %, 35 %, and 35 %, respectively at 10–12 days after transplanting (DAT), 25–30 DAT, and 40–45 DAT.

2.3.5. Water management

In DSR, light irrigation was given immediately after sowing to enhance germination and emergence, followed by irrigation applied regularly to avoid hairline soil cracking. In PTR, standing water was maintained from 10–15 DAT followed by alternate wetting and drying.

2.3.6. Weed and other pest management

In DSR, the pre-emergence herbicide pendimethalin was applied at 1000 g a.i. ha^{-1} at 1–2 days after the first irrigation/seeding followed by a tank mixture of bispyribac-sodium (25 gm a.i. ha^{-1}) and ethoxysulfuron (20 gm a.i. ha^{-1}) at 15–25 DAE. In PTR, the pre-emergence herbicide acetachlor+bensulfurnmethyl was applied at 1100 g a.i. ha^{-1} at 2–3 DAT. In DSR, 2–3 manual weedings were done as required to mitigate weed competition at 25–30 DAE, 40–45 DAE, and 55–60. In PTR, 1–2 manual weeding was done at 20–25 DAT and 35–40 DAT. Some fields had sheath rot (*Sarocladium oryzae*) and rice bugs (*Leptocorisa acuta*) and were managed by the application of hexaconazole 5 % and malathion 57 EC respectively.

2.4. Data collection

2.4.1. Irrigation

Water pumped from shallow tube wells was estimated by recording the time required to fill a 125 L bucket. For more accurate measurements at each location, we performed three estimations and then calculated the average time and water amount. The volume of water applied in each irrigation application was calculated by multiplying the duration of irrigation at the same pump rate with water discharge after which all irrigations were summed. To measure the fuel consumption of the pump, we tested the amount burnt per hour.

2.4.2. Crop data

For DSR, plant number m^{-2} was recorded from randomly placed 50-cm by 60-cm quadrat from three locations within each treatment plot at 10 DAE. Plants were not counted for PTR because the hill numbers were fixed. The date to 50 % flowering was determined by the daily count of the number of panicles in which anthesis had commenced from three fixed 50-cm by 60-cm quadrats for DSR and three permanent locations of six hills for PTR.

The date to physiological maturity (PM) was recorded when about 80 % of the grains had turned to yellow-golden color. The crop was harvested when most of the leaves had senesced. Immediately prior to harvest, yield components were recorded from randomly placed three 50-cm by 60-cm quadrats outside the yield measurement areas. For DSR, all rice plants from the sampling area were cut at the base of the plants and for PTR eighth hills were selected randomly from each sampling area. All three samples for DSR were mixed and all eight hills for PTR were mixed composite them after which panicle numbers were counted. They were then threshed manually and only stubbles, but not unfilled grains, were cleaned.

Grain weight was recorded using a digital balance. Fifty gramm samples were taken from each plot for counting filled and unfilled grains, filled and unfilled grains panicle^{-1}, and floret fertility (%). For rice grain and straw yield measurements, samples were taken from two 3 m by 2 m (6 m^2) fixed areas from the center of the plots. Grains were threshed using a mechanical thresher, cleaned, and grain weight was recorded. Immediately after weighing, grain moisture (was determined using a digital moisture meter as the average of three random measurements and yield at 14 % moisture content was computed. For straw yield, first, the fresh weight was measured after threshing. Then a 100 gm subsample was oven-dried at 70 °C for three days and converted to t ha^{-1} on an oven dry basis.

2.5. Economic analysis

All variable costs (except harvesting and threshing which was similar for all treatments) were considered for the economic analysis. These consisted of tillage for land preparation, seed, fertilizer, herbicide, insecticide, fungicide, irrigation, etc., and labor cost (based on measured person-days ha^{-1} through direct measurement by farmers and confirmed in focus group discussions) for land preparation, seeding/transplanting, irrigation, fertilizer and pesticide application, and weeding. The hours (h) required to complete each operation was recorded for each treatment and 8 h was considered equivalent to 1 person-day. Labor costs were calculated using the local wage rate For irrigation costs, charges were calculated using the local rate (cost/hour) plus the cost of labor used for irrigation application. For drill seeding, costs were calculated based on the machinery service providerss rental fees for 33 decimals of land (0.13 ha). Farmgate grain sale prices and local straw sale prices were collected from a minimum of three local markets, averaged, and used to calculate gross income. Additional gross returns for DSR (drill seeding and broadcasting) was calculated by multiplying the additional yield (yield of DSR – yield of PTR) by the market price of rough rice. Any and all additional costs were estimated by subtracting the total management cost (inputs + labor) for DSR from the total management cost for PTR (total management cost for PTR– total management cost for DSR). Net returns for DSR was calculated by the difference between added gross return and added cost for a treatment contrasted with PTR.

2.6. Energy analysis

To estimate the total energy used in each crop establishment method under the different landscape positions and varieties, the energy equivalent (MJ unit^{-1}) for each input was used from the published conversion coefficients (Table 2). The total energy input (TEI: MJ ha^{-1}) to produce a crop was calculated with Eq. 1:

$$TEI = EL + EE + EI + EW + EO \quad (1)$$

Table 2
Inputs and outputs, and energy equivalent used for various treatments.

Variables	Unit	Energy equivalent (MJ unit^{-1})	Ref.
Inputs			
Human labor	Person-hr	1.96	Singh, (2002); Yadav et al., (2013)
Fuel (diesel)	Litre	56.30	Singh, (2002); Kumar et al., (2013)
Farm machinery	Hr	158.30	Barut et al., (2011)
Chemical fertilizers			
N	Kg	66.14	Lal, (2004); Shahin et al., (2008)
P_2O_5	Kg	12.40	Esengun et al., (2007), Shahin et al., (2008)
K_2O	Kg	11.20	Esengun et al., (2007); Shahin et al., (2008)
Gypsum	Kg	10.00	Nassiri and Singh, (2009)
Zn sulphate	Kg	20.90	Nassiri and Singh, (2009)
Seed	Kg	15.20	Rahman and Rahman, (2013); Wang et al., (2015)
Irrigation	m^3 ha^{-1}	1020.00	Acaroğlu and Aksoy (2005)
Herbicide	Kg	238.00	Turhan et al., (2008)
Pesticide	Kg	199.00	Gundogmus, (2006)
Fungicide	Kg	92.00	Turhan et al., (2008)
Outputs			
Grain yield	Kg	14.70	Shahin et al., (2008); Kumar et al., (2013)
Straw yield	Kg	13.10	Singh and Mittal, (1992)

where, EL is the energy (labor + machine) for land preparation; EE is the energy (labor) for crop establishment (sowing/transplanting), EI is the energy (fuel + labor) from irrigation; EW is the energy (herbicide+labor) from weed management and EO is the energy (inputs) from all other crop production-related inputs. Total energy output (TEO: MJ ha^{-1}) produced from grain and straw was computed with Eq. 2:

$$TEO = [(\ Grain\ yield \times energy\ factor) + (\ Straw\ yield \times energy\ factor)] \tag{2}$$

Here, the energy factor is the specific conversion factor for grain or straw yield. Additional parameters were computed with Eqs. 3–6.

$$Net\ energy (NE : MJ\ ha^{-1} = Total\ energy\ output - total\ energy\ input \tag{3}$$

$$Energy\ use\ efficiency (EUE) \quad = Energy\ output / energy\ input \tag{4}$$

$$Specific\ energy (SE) \quad = Energy\ input / grain + straw\ yield \tag{5}$$

$$Energy\ productivity (EP) \quad = Yield\ of\ rice / energy\ input \tag{6}$$

2.7. Global warming potential and yield-scaled emissions

To assess of global warming potential (GWP) and yield-scaled emissions, we employed the CCAFS' Mitigation Options Tool (CCAFS-MOT) combined with data collected as described in Sections 2.3, 2.4, 2.5. This tool simulates GHG emissions associated until the farm-gate using empirical models (Feliciano et al., 2017). We applied measured plot-level data on inputs and crop management with associated soil and climate data to generate simulations in a scripted R version of the CCAFS-MOT (R Core Team, 2020).

The emissions of CH_4, N_2O, and CO_2 were estimated from Yan et al. (2005), which calculates CH_4 emissions under floodwater and irrigation conditions as a function of soil pH, climate variables, and the application of organic amendments or residue. N_2O from fertilizer was calculated based on Stehfest and Bouwman (2006). CO_2 emissions from nutrients and irrigation are estimated from the IPCC (2019) in the CCAFS-MOT, while the production and transportation of fertilizers are estimated with the Ecoinvent Center's (2007) database. Using Ogle et al. (2005) and Smith et al. (1997), the tool also models soil C from residue management. Based on Powlson et al. (2016), soil C responses from tillage management were calculated. All GHGs were converted into CO_2-equivalent (CO_2eq) using 100-year GWPs of 34 and 298 for CH_4 and N_2O, respectively (IPCC, 2013). Following Pittelkow et al. (2014) yield-scaled emissions were calculated for each treatment as:

$$Yield - scaled\ emissions = \frac{Total\ GWP(kgCO_2 \quad ha^{-1})}{Grain\ yield(kgha^{-1})} \tag{7}$$

2.8. Statistical analysis

Data were analyzed with JMP Pro 13 (SAS Institute Inc., Cary, NC) using the Fit Model Function to complete ANOVAs determining the significance of fixed effects, with farmer replicate treated as a random factor and each year assessed independently. Tukey's honestly significant difference test was applied to compare the mean values at the 5 % probability level. Each treatment combination was subsequently compared within and across landscape positions and tillage and establishment methods. To understand the trade-offs among grain yield, labor used, costs and profits, and energy and environmental parameters derived in this study, radial diagrams were constructed (after standardizing the data on a 0–1 scale). Box plots for plant stand establishment and added net return were used to show visually describe variability in the data.

3. Results

3.1. Plant stand establishment

Plant stand establishment in DSR was affected by location, landscape position, establishment method and variety (Fig. 2). DSR broadcasting had always had higher establishment success than drilling. Across locations and landscape positions, initial plant density ranged from 45 to 225 seedlings m^{-2} (mean 127) and from 75 to 320 seedlings m^{-2} (mean 175) under drilling and broadcasting, respectively. Across locations, DSR establishment methods and varieties, mean initial plant density was 165, 172, and 131 seedlings m^{-2} on high, medium and lowlands. Across locations, establishment methods, and landscape positions, plant density was greatest under BRRI dhan85 (172 m^{-2}) followed by Binadhan-19 (156 m^{-2}) and BRRI dhan83 (140 m^{-2}). Under transplanted rice, seedling numbers ranged from 60–70 m^{-2} in 25 hills m^{-2} (data not presented).

3.2. Grain and straw yield

In 2019, rice grain and straw yields were significantly affected by landscape position and variety, but not by establishment method nor by interactions (Table 3). Grain and straw yield were 4–7 % and 13–14 % higher on high and mediumlands compared to lowlands. The highest grain and straw yields were recorded for BRRI dhan83 which had 8–9 % greater grain yield than BRRI dhan85 and Binadhan-19 Similarly, BRRI dhan83 produced 11 to 18 % higher straw yield compared to BRRI dhan85 and Binadhan-19, though BRRI dhan85 and Binadhan-19 did not differ in grain or straw yield.

In 2020 and 2021, rice grain and straw yields were significantly affected by location (L), landscape position (LP), establishment method (EM), and variety (V) (Table 3**)**. There was a significant interaction effect of four-factor and L × V interaction suggesting the influence of landscape position, establishment method and variety varied by location. Additionally, the effect of the establishment method varied by landscape position and varietal effect by establishment method as demonstrated by significant interactions effect of LP × EM and EM × V.

In 2020, grain yield was 14 % higher in Jhenaidah and Faridpur as compared to Dinajpur. In 2021, grain yield in different locations decreased in the following order: Faridpur (5.12 t ha^{-1}) > Jhenaidah (4.82 t ha^{-1}) > Dinajpur (4.12 t ha^{-1}) (Table 3). Considering landscape position, the highest grain and straw yields were consistently recorded on mediumland. During 2020 and 2021, rice yields were on average 4–5 % higher under mediumlands than in high and lowlands (Table 3**)**. Straw yield was also highest under mediumland.

Within crop establishment methods, on average rice grain yield was 3–5 % higher in 2020 and 5–6 % higher in 2021 under PTR than under drill or broadcast DSR (Table 3). Straw yield has the same trend. Grain yields under drilled and broadcast DSR however did not differ. BRRI dhan83 yielded the highest followed by BRRI dhan85 and Binadhan-19. BRRI dhan83 yielded 16–18 % higher than Binadhan-19. BRRI dhan85 produced 9–12 % higher yield than Binadhan-19.

The interaction effect of location, landscape position and establishment method on grain yield showed that on high and mediumlands, drill DSR yielded similar to PTR in all locations and in both years except in Faridpur in 2021 where PTR yield was higher (Table 4). Broadcast DSR yielded similarly on highlands in all years and locations except in Jhenaidah in 2020, where drilled DSR yielded more. In all locations, drill DSR had a higher yield than broadcast DSR, but only by a small margin of 4 % in 2020. Yields were similar in 2021, though in lowlands, PTR outperformed both DSR methods in both years.

3.3. Yield components and growth duration

In 2019, panicle density differed significantly by LP, EM, and V but not by their interactions (Table 5). Across EM and V, the highest panicle

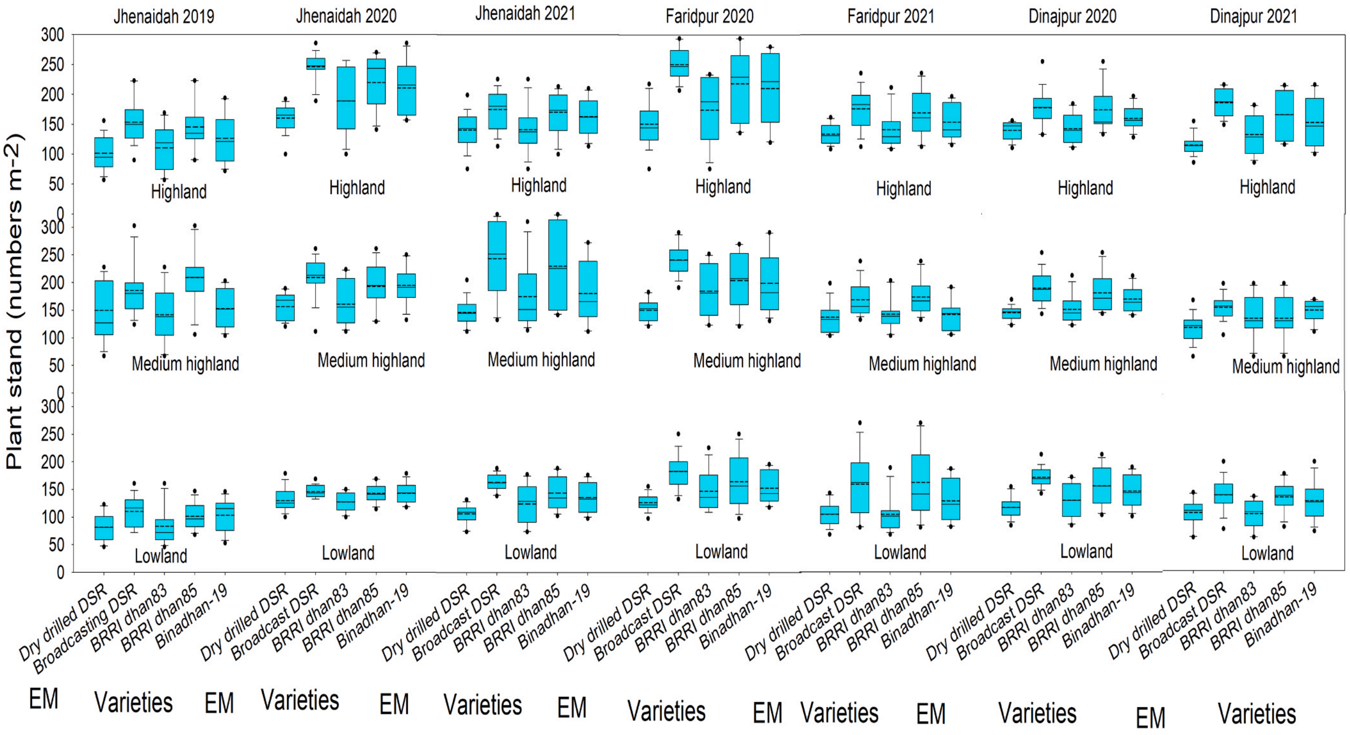

Fig. 2. Plant stand establishment (numbers m^{-2}) at 10 days after emergence as influenced by landscape position, rice establishment method (EM) and variety in 2019, 2020 and 2021. The horizontal dash and solid lines in the boxes represent the mean and median respectively; the boundaries of the boxes closest to and farthest from zero indicate the 25th 75th percentiles respectively. 'Whiskers' below and above the boxes indicate the 10th and 90th percentiles, while bullets are outliers.

Table 3

Grain and straw yields of *aus* rice as influenced by location, landscape position, establishment method, and variety.

	Grain yield (t ha^{-1})			Straw yield (t ha^{-1})		
	2019[a]	2020	2021	2019[a]	2020	2021
Location (L)						
Jhenaidah		5.23 a	4.82 b		5.30 a	4.89 b
Faridpur		5.21 a	5.12 a		5.48 a	5.81 a
Dinajpur		4.58 b	4.14c		5.07 b	4.89 b
Landscape position (LP)						
Highland	4.56 a	4.95 b	4.61 b	5.71 a	5.55 a	4.97 b
Medium highland	4.70 a	5.14 a	4.83 a	5.76 a	5.64 a	5.39 a
Lowland	4.38 b	4.93 b	4.64 b	5.05 b	5.32 b	5.22 ab
Establishment method (EM)						
Drill seeding	4.55	4.97 b	4.62 b	5.44	5.36 b	5.04 b
Broadcasting	4.47	4.90 b	4.58 b	5.41	5.38 b	5.03 b
Transplanting	4.62	5.14 a	4.88 a	5.67	5.78 a	5.51 a
Variety (V)						
BRRI dhan83	4.80 a	5.36 a	5.02 a	6.02 a	6.06 a	5.58 a
BRRI dhan85	4.43 b	5.10 b	4.72 b	5.41 b	5.63 b	5.25 a
Binadhan−19	4.41 b	4.56c	4.34c	5.10 b	4.82c	4.75 b
***F*-values**						
L		282.2 * **	577.7 * **		205.5 * **	18.8 * **
LP	3.49 * *	26.2 * **	29.7 * **	7.84 * **	13.6 * **	4.9 * *
EM	ns	4.9 * **	66.3 * **	ns	29.5 * **	5.1 * **
V	6.09 * **	338.7 * **	119.3 * **	10.8 * **	207.8 * **	11.8 * **
L × LP		22.1 * **	15.2 * **		24.4 * **	3.3 * *
L × EM		2.4 *	20.8 * **		7.8 * **	6.1 * **
L × V		17.1 * **	16.9 * **		18.5 * **	12.2 * **
LP × EM	6.09 * **	16.7 * **	20.5 * **	ns	3.5 * *	2.8 *
EM × V	ns	ns	ns	ns	ns	ns
LP × V	ns	ns	ns	ns	ns	ns
L × LP × EM		1.9 *	1.8 *		4.6 * **	2.3 *
L × LP × V		ns	ns		ns	ns
L × EM × V		ns	ns		ns	ns
LP × EM × V	ns	ns	ns	ns	ns	ns
L × LP × EM × V		ns	ns		ns	ns

NS refers to non-significance; * ** ** , and * indicate significance levels at 0.1, 1, and 5 %, respectively.

[a] This trial was conducted only at Jhenaidah. Different lowercase letters in the column indicate significant differences.

Table 4

Effect of landscape position and establishment method on grain yield (t ha^{-1}) of *aus* rice across varieties by location in 2020 and 2021.

		2020			2021		
Landscape position	Establishment method	Jhenaidah	Faridpur	Dinajpur	Jhenaidah	Faridpur	Dinajpur
Highland	Drill seeding	5.01 a	5.22	4.75	4.62	4.89 b	3.29
	Broadcasting	4.74 b	5.26	4.68	4.57	4.75 b	3.26
	Transplanting	5.10 a	5.30	4.58	4.44	5.40 a	3.45
Medium highland	Drill seeding	5.49 a	5.45 a	4.67 a	4.85	5.15 b	3.86 ab
	Broadcasting	5.26 b	5.43 b	4.49 b	4.71	4.92 b	3.70 b
	Transplanting	5.58 a	5.24 a	4.65 ab	4.67	5.59 a	3.98 a
Lowland	Drill seeding	5.1 b	4.79 b	4.31 b	4.57 b	4.11c	3.67 b
	Broadcasting	5.2 b	4.87 b	4.36 b	4.66 b	4.72 b	3.72 b
	Transplanting	5.6 a	5.45 a	4.70 a	5.01 a	5.72 a	4.37 a

Different lowercase letters in the column indicate significant differences.

Table 5

Panicle density, grains $panicle^{-1}$, percent sterility, and growth duration of *aus* rice as influenced by location, landscape position, establishment method, and variety in 2019, 2020 and 2021.

	Panicle density (numbers m^{-2})			Grain $panicle^{-1}$			% sterility			Growth duration (days)		
	2019[a]	2020	2021	2019[a]	2020	2021	2019[a]	2020	2021	2019[a]	2020	2021
Location (L)												
Jhenaidah		467 a	399 b		77 b	73c		17 b	27 b		107 a	109 a
Faridpur		378 b	436 a		73c	77 b		20 a	26c		105 b	107 b
Dinajpur		295c	243c		85 a	87 a		15 b	29 a		107 a	108 a
Landscape position (LP)												
Highland	422 ab	385 a	367 a	63c	76 b	77 b	23	17	27	111 ab	105 b	106 b
Medium highland	447 a	385 a	366 a	66 b	79 a	77 b	22	19	26	109 b	106 b	109 a
Lowland	403 b	371 b	344 b	69 a	79 a	83 a	22	16	28	113 a	109 a	109 a
Establishment method (EM)												
Drill seeding	417 b	389 a	359c	65 b	77 b	78 b	22	17 a	26 b	109 b	105 b	107 b
Broadcasting	442 a	392 a	373 a	63c	76c	76c	23	19 a	28 a	109 b	104c	106 b
Transplanting	414 b	359 b	347 b	69 a	82 a	83 a	22	16 b	27 ab	115 a	111 a	111 a
Variety (V)												
BRRI dhan83	418 b	375 b	353 b	74 a	83 a	87 a	24 a	19 a	30 a	114 a	109 a	111 a
BRRI dhan85	432 a	391 a	368 a	65 b	81 b	79 b	21 b	17 b	25c	111 b	107 b	108 b
BINA dhan−19	422 b	376 b	357 b	59c	71c	71c	22 b	16c	26 b	108c	103c	105c
F-values												
L		1351.4 * **	949.9 * **		266.8 * **	176.4 * **		33.9 * **	20.6 * **		24.3 * **	9.3 * **
LP	7.5 * **	12.5 * **	15.1 * **	14.5 * **	18.7 * **	35.2 * **	ns	ns	ns	10.8 * **	4.6 * *	73.7 * **
EM	3.7 * *	60.6 * **	15.4 * **	19.5 * **	74.1 * **	36.5 * **	ns	24.9 * **	6.6 * *	96.1 * **	291.1 * **	161.9 * **
V	2.2 * *	15.1 * **	7.9 * **	108.9 * **	294.1 * **	236.4 * **	8.1 * **	51.4 * **	70.7 * *	93.1 * **	158.1 * **	153.6 * **
L × LP		33.6 * **	12.3 * **		ns	ns		ns	ns		17.9 * **	10.9 * **
L × EM		10.7 * **	5.7 * *		8.5 * **	5.3 * *		7.4 * **	9.3 * **		9.1 * **	45.4 * **
L × V		7.53 * **	ns		63.1 * **	3.7 * *		17.9 * **	13.2 * **		9.1 * **	ns
LP × EM	ns	ns	ns	ns	4.9 * *	2.2 *	ns	ns	ns		ns	ns
EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns	3.4 * *	ns	ns
LP × V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
L × LP × EM		5.9 * **	ns		4.2 * *	2.6 *		ns	ns	ns	ns	8.2 * *
L × LP × V		ns	ns		ns	ns		ns	ns		ns	ns
L × EM × V		ns	ns		ns	ns		ns	ns		ns	ns
LP × EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
L × LP × EM × V		ns	ns		ns	ns		ns	ns		ns	ns

NS refers to non-significance; * ** ** , and * indicate significance levels at 0.1, 1, and 5 %, respectively.

[a] This trial was conducted only at Jhenaidah. Different lowercase letters in the column indicate significant differences.

density (447 m^{-2}) was recorded in mediumland followed by high and lowlands. Among the EM, the highest panicle density (442 m^{-2}) was recorded from broadcast DSR, and the lowest (414 panicles m^{-2}) from PTR. Across LP and EM, BRRI dhan85 produced the highest panicle density while the other two varieties produced similar panicle density (Table 5). Grains per panicle were also affected by LP, EM, and V but not their interactions (Table 5). Considering the EM, the order for the number of grains per panicle was PTR > drill seeding > broadcasting, and considering the variety it was BRRI dhan83 > BRRI dhan85 > Binadhan-19. Grain sterility was not affected by LP and EM but was affected by V (Table 5). Across LP and EM, the highest sterility (24 %) was found for BRRI dhan83 while the other two varieties had similar sterility percentages.

Growth duration differed significantly by LP, EM, V, and the interaction of LP × EM. but not by the interaction of others (Table 5). Across EM and V, crop growth duration was slightly longer (2–4 days) in the lowland than in the high or the mediumland. Both direct drilling and broadcasting DSR had similar growth duration but significantly lower (6 days less) than PTR.

Panicle density was affected by L, LP, EM, V in In 2020 and 2021 and the interactions of L × LP and L × EM, and by L × V and L × LP × EM in 2020 only (Table 5). Across LP, EM, and V, the highest panicle density was recorded in Jhenaidah in 2020 (467 panicles m^{-2}) and Faridpur in 2021 (436 panicles m^{-2}), while it was lowest in Dinajpur. Low and mediumlands had similar but significantly higher panicle density than highlands. In 2020, both DSR methods had similar but significantly higher panicle density than PTR but in 2021, the order was broadcasting > drill seeding > transplanting. The panicle density of all varieties didn't differ significantly in all years.

Grains per panicle in 2020 and 2021 were affected by L, LP, EM, V and the interactions of L × EM, L × V, LP × EM, and L × LP × EM (Table 5). In both years, the highest number of grains per panicle was recorded in Dinajpur. For LP, EM, and V, the number of grains per panicle in both years maintained a similar trend to 2019. Grain sterility was affected by L, EM, V, and the interaction of L × EM and L × V, but not by LP or other interactions (Table 5). Considering EM, the highest sterility was found for broadcasting, and considering variety, the highest sterility was recorded for BRRI dhan83. Growth duration in both years was affected by L, LP, EM, V, and L × LP and L × EM, and by L × V (only in 2020) and L × LP × EM (only in 2021) (Table 5).

3.4. Labor requirement, production cost, and economics

In 2019, the labor use differed significantly by LP and EM but not by V or other interactions (Table 6). In 2020 and 2021, it differed significantly by L, LP, EM, L × LP, L × EM, and LP × EM (only in 2020) (Table 6). Across LP, EM and V, labor use was highest in Dinajpur followed by Jhenaidah and Faridpur. It was highest for highland and similar for medium and lowland. Labor used was always significantly higher (15–47 %) for PTR than DSR. Drill seeding required significantly fewer person-days (10–15 %) than broadcast seeding.

Production costs followed a similar trend to labor use (Table 6). Production cost was 10–20 % higher for highland than for the medium or lowland. Across L, LP and V, production costs ranked PTR > drill seeding DSR > broadcast DSR. Production cost in DSR was 5–35 % lower than in PTR and was significantly lower (8–15 %) in drill DSR compared to broadcast DSR.

In 2019, gross income was affected only by LP and not by EM, V, or any of the interactions; however, in 2020 and 2021, it was affected by L, LP, EM, V, and L × LP, L × EM, L × V, LP × EM, and L × LP × EM (only in 2021) (Table 6). Gross income in 2020 was highest for Jhenaidah while in 2021, it was highest for Faridpur. In both years, it was lowest in Dinajpur. Among LP, the gross income followed the following trend in 2019 and 2020: mediumland > highland > lowland, while in 2021, it followed the following order: mediumland > lowland > highland. The gross income was not affected by EM in 2019 but was affected in 2020 and 2021. In both years, gross income was highest for PTR and was 5–9 % higher than for DSR methods. Both drill DSR and broadcast DSR had similar gross income.

The added net return differed significantly among years, districts and LP; therefore, data were plotted on box plots by year, district and LP. Except for a few cases, the added net return between drill seeding and broadcast seeding differed significantly, with the former mostly higher than the latter. The exceptions were for lowlands in Jhenaidah and Faridpur in 2020 and 2021 and for lowlands in Dinajpur in 2021 where the added net return of drill seeding and broadcast seeding was similar. Across L, LP and EM, the ANR in most cases greatly varied among the varieties (Fig. 3).

In high and mediumlands, except for Faridpur and Jhenaidah in 2021, the mean ANR values for DSR were positive, implying that DSR was more profitable than PTR. However, in lowlands, except for Jhenaidah in 2019 and 2021, and for drill seeding in Dinajpur in 2020, DSR had negative mean ANR values implying that it was less profitable than PTR. Overall, in high and mediumlands the DSR had positive mean ANR values over PTR, but in lowlands, the ANR values were in the opposite order.

Table 6
Labor, production cost, and gross income of *aus* rice influenced by location, landscape position, establishment method, and variety.

	Total labor used (person-day ha^{-1})			Total production cost (USD ha^{-1})			Gross income (USD ha^{-1})			Added net return (USD ha^{-1})		
	2019[a]	2020	2021	2019[a]	2020	2021	2019[a]	2020	2021	2019[a]	2020	2021
Location (L)												
Jhenaidah		47 b	79 a		399 a	640 a		2077 a	1857 b		−11.4 b	127.5 a
Faridpur		38c	67 b		379 b	583 b		2013 b	2032 a		14.1 b	−218.4c
Dinajpur		50 a	80 a		387 ab	557c		1788c	1540c		108.7 a	−165.5 b
Landscape position (LP)												
Highland	83 a	50 a	83 a	696 a	413 a	652 a	1744 ab	1947 b	1738c	118 ab	93.8 a	−44.1 a
Medium highland	63 b	43 b	73 b	566 b	380 b	578 b	1791 a	2008 a	1868 a	170 a	67.9 a	−21.2 a
Lowland	64 b	42 b	70 b	587 b	372 b	550c	1643 b	1922 b	1823 b	48 b	−50.5 b	−190.9 b
Establishment method (EM)												
Drill seeding	62c	34c	64c	511c	312c	541c	1743	1939 b	1756 b	169 a	73.3 a	−55.9 a
Broadcasting	69 b	39 b	71 b	620 b	374 b	604 b	1727	1917 b	1754 b	54 b	0.95 b	−144.9 b
Transplanting	81 a	64 a	91 a	717 a	479 a	635 a	1708	2021 a	1919 a			
Variety (V)												
BRRI dhan83	71	46	76	619	390	598	1744	1987 b	1848 a	151 a	32.4 b	−97.6
BRRI dhan85	71	45	75	618	387	592	1730	2061 a	1861 a	117 ab	−4.3 b	−85.2
BINA dhan−19	70	45	75	612	387	591	1703	1829c	1720 b	68c	83.2 a	−73.3
F-values												
L		98.4 * **	116.7 * **		5.8 * *	99.4		390.4 * **	379.3 * **		26.5 * **	138.8 * **
LP	72.1 * **	52.7 * **	113.6 * **	81.3 * **	28.2 * **	155.8	5.9 * *	33.3 * **	26.5 * **	3.5 *	39.2 * **	33.9 * **
EM	54.1 * **	671.9 * **	446.1 * **	178.6 * **	424.3 * **	20.1	ns	50.6 * **	54.9 * **	9.2 * *	25.9 * **	10.4 * **
V	ns	ns	ns	ns	ns	ns	ns	239.6 * **	37.1 * **	8.5 * *	12.7 * **	ns
L × LP		22.8 * **	14.9 * **		14.1 * **	ns		34.7 * **	9.7 * **		ns	3.6 * *
L × EM		35.3 * **	4.5 * *		7.6 * **	89.9		4.3 * **	23.7 * **		ns	ns
L × V		ns	ns		ns	ns		24.11 * **	11.9 * **		ns	ns
LP × EM	ns	3.3 * *	ns	ns	2.5 * *	ns	ns	18.8 * **	16.7 * **	ns	3.9 * *	ns
EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LP × V	ns	ns	ns	ns	ns	ns	4.7 * *	ns	ns	ns	ns	ns
L × LP × EM		ns	ns		ns	ns		ns	2.9 * *		ns	ns
L × LP × V		ns	ns		ns	ns		ns	ns		ns	ns
L × EM × V		ns	ns		ns	ns		ns	ns		ns	ns
LP × EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
L × LP × EM × V		ns	ns		ns	ns		ns	ns	ns	ns	ns

NS refers to non-significance; * ** ** , and * indicate significance levels at 0.1, 1, and 5 %, respectively.

[a] This trial was conducted only at Jhenaidah. Different lowercase letters in the column indicate significant differences.

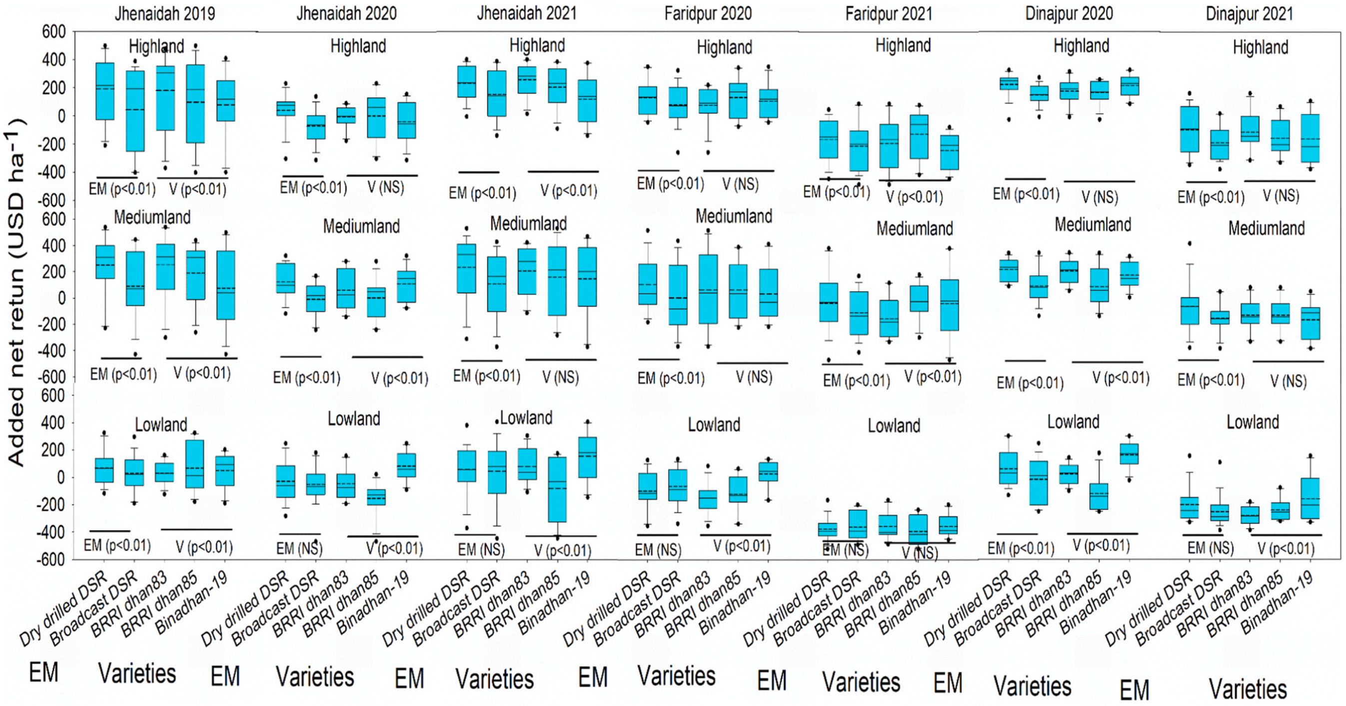

Fig. 3. Added net return in direct-seeded rice (drill seeding and broadcasting) as compared with the transplanted rice. The horizontal dash and solid lines in the boxes represent mean and median respectively; the boundaries of the boxes closest to and farthest from zero indicate the 25th 75th percentiles respectively. 'Whiskers' below and above the boxes indicate the 10th and 90th percentiles, while bullets are outliers. EM: establishment method. NS refers to non-significance; $p < 0.01$ refers significance at a 1 % probability level.

Table 7
Energy parameters of *aus* rice influenced by location, landscape position, establishment method, and variety.

	Net energy (Mj ha^{-1})			Specific energy (Mj kg^{-1})			Energy productivity (kg grain MJ^{-1})		
	2019[a]	2020	2021	2019[a]	2020	2021	2019[a]	2020	2021
Location (L)									
Jhenaidah		146473 a	111747 b		1.24c	1.94 b		0.38 a	0.22 b
Faridpur		133410 b	129556 a		1.41 a	1.90 b		0.34 b	0.24 a
Dinajpur		119217c	94580c		1.36 b	2.18 a		0.31c	0.15c
Landscape position (LP)									
Highland	117098 ab	132858 b	104947 b	2.41 a	1.42 a	2.26 a	0.18 b	0.33 b	0.18c
Medium highland	124545 a	136732 a	117270 a	1.76c	1.26c	1.80c	0.23 a	0.35 a	0.22 a
Lowland	108392 b	129509c	113266 a	2.01 b	1.33 b	1.95 b	0.20 b	0.33 b	0.20 b
Establishment method (EM)									
Drill seeding	140254	133914 a	111251 b	1.69c	1.07c	1.75 b	0.25 a	0.41 a	0.23 a
Broadcasting	138284	129112 b	106667 b	1.92 b	1.42 b	2.13 a	0.22 b	0.31 b	0.19 b
Transplanting	141747	136074 a	117955 a	2.57 a	1.51 a	2.14 a	0.15c	0.29c	0.19 b
Variety (V)									
BRRI dhan83	126965 a	145482 a	121582 a	1.88 b	1.22c	1.84c	0.22	0.36 a	0.22 a
BRRI dhan85	113629 b	136230 b	112790 b	2.00 b	1.29 b	1.95 b	0.20	0.34 b	0.20 b
Binadhan−19	109441 b	117388c	101511c	2.30 a	1.50 a	2.25 a	0.20	0.31c	0.19c
***F*-values**									
L		393.6 * **	106.9 * **		44.6 * **	100.2 * **		159.4 * **	701.0 * **
LP	8.9 * **	27.7 * **	15.3 * **	74.8 * **	41.4 * **	219.1 * **	22.2 * **	18.7 * **	90.9 * **
EM	3.3 *	26.4 * **	14.5 * **	144.6 * **	336.9 * **	194.1 * **	93.5 * **	649.5 * **	205.6 * **
V	11.4 * **	434.5 * **	35.4 * **	32.2 * **	129.6 * **	181.8 * **	ns	98.6 * **	69.8 * **
L × LP		35.1 * **	3.9 * *		2.4 * *	44.1 * **		4.5 * *	48.2 * **
L × EM		8.4 * **	11.43 * **		16.9 * **	3.8 * *		38.6 * **	19.6 * **
L × V		29.3 * **	5.3 * *		ns	ns		6.5 * *	9.5 * **
LP × EM	ns	10.4 * **	5.6 * *	3.4 * *	ns	ns	3.5 *	5.3 * *	9.6 * **
EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns
LP × V	ns	ns	ns	ns	ns	ns	ns	ns	ns
L × LP × EM		ns	3.1 * *		ns	5.5 * **		ns	11.8 * **
L × LP × V		ns	ns		ns	ns		ns	
L × EM × V		ns	ns		ns	ns		ns	ns
LP × EM × V	ns	ns	ns	ns	ns	ns	ns	ns	ns
L × LP × EM × V		ns	ns		ns	ns		ns	ns

NS refers to non-significance; * ** ** , and * indicate significance levels at 0.1, 1, and 5 %, respectively.

[a] This trial was conducted only at Jhenaidah. Different lowercase letters in the column indicate significant differences.

3.5. Energy inputs and outputs, energy use efficiency and energy productivity

In 2019, energy input differed significantly by LP and EM but not by variety and any of the interactions (Table S1). Within LP, energy input declined in the following order: highland > lowland > mediumland, whereas within EM, it declined in this order: transplanting > broadcasting > drill seeding.

In 2020 and 2021, energy input varied across L, LP (only in 2021), EM, L × LP, L × EM, LP × EM, and L × LP × EM (only in 2021) (Table S1). Within EM, transplanting required significantly higher energy input than drill seeding and broadcasting. In 2021, energy input was highest in highlands and was significantly higher than in both the medium and lowlands. The energy output was influenced by LP and EM in 2019 (Table S1); by L, LP, EM and V in 2020 and 2021; and by L × LP, L × EM, LP × EM in 2020, and by L × EM and LP × EM in 2021.

In 2019, energy output was similar for medium and highlands and was significantly higher than for lowlands (Table S1). It was the highest for BRRI dhan83 in all years. In 2020, the energy output was higher for Jhenaidah, in 2021 higher for Faridpur, and in both years, it was lowest for Dinajpur (Table S1). In both 2020 and 2021, energy output was highest for mediumland followed by lowland and highland. In both years, PTR produced the highest energy output. Both direct drilling and broadcasting DSR had similar but significantly lower energy output than PTR.

In 2019, net energy was influenced by EM but not the energy output. In 2020 and 2021, however, net energy had a similar trend to energy output (Table 7). Energy use efficiency (EUE) was affected by LP × EM in 2019, L × LP, L × EM, L × V (only in 2020), and by LP × EM and L × LP × EM in 2020 and 2021 (Table S1). In 2020, EUE was highest for Jhenaidah but in 2021 it was highest for Faridpur. In both years, EUE was the lowest for Dinajpur. EUE was highest for mediumland and was highest for drill seeding DSR. The EUE order was BRRI dhan83 > BRRI dhan85 > Binadhan-19.

The specific energy (SE) was highest for highland followed by lowland and then mediumland, and was highest for transplanting and lowest for drill seeding (Table 7). The SE of growing Binadhan-19 was higher than both BRRI dhan83 and BRRI dhan85. However, the SE of BRRI dhan83 and 85 were either similar (in 2019) or BRRI dhan85 had higher SE than BRRI dhan83 in 2020 and 2021.

Energy productivity (EP) was not affected by variety but was affected by LP and EM in 2019 and by all factors in 2020 and 2021 (Table 7). The EP was always lowest for Dinajpur. EP was highest for mediumland compared to other land types. EP for EM followed the order of drill seeding > broadcasting > transplanting and for variety: of BRRI dhan83 > BRRI dhan85 > Binadhan-19.

3.6. Global warming potential (GWP) and yield-scaled emissions (YSE)

GWP greatly varied across locations, with highest GWP for Dinajpur and lowest for Jhenaidah (Table 8). In all years, it was lowest for mediumland and highest for lowland. It was consistently higher by 58–66 % for PTR than DSR though there was no difference in GWP between drill DSR and broadcast DSR. GWP was highest for BRRI dhan83 and lowest for Binadhan-19.

Yield-scaled emission was similar for both high and lowlands in 2019 and 2020 but in 2021, it was significantly higher for highlands than the other two land types (Table 8). Similar to GWP, the yield-scaled emission of PTR was higher (55–64 %) than both DSR methods and was highest for BINA dhan-19 and lowest for BRRI dhan83.

Table 8

Global warming potential and yield scaled emissions of *aus* rice influenced by location, landscape position, establishment method, and variety.

	Global warming potential (Mt CO$_2$eq ha$^{-1)}$			Yield-scaled emissions (Kg CO$_2$eq Mt^{-1} grain)		
	2019[a]	2020	2021	2019[a]	2020	2021
Location (L)						
Jhenaidah		2550c	2872c		0.48c	0.62 b
Faridpur		2866 b	3103 b		0.55 b	0.61 b
Dinajpur		2904 a	3355 a		0.63 a	0.90 a
Landscape position (LP)						
Highland	2936 b	2760 b	3123 a	0.71 a	0.56 a	0.76 a
Medium highland	2876c	2748 b	3069 b	0.63 b	0.54 b	0.68 b
Lowland	3088 a	2811 a	3137 a	0.67 ab	0.57 a	0.69 b
Establishment method (EM)						
Drill seeding	1940 b	1680 b	2071 b	0.43 b	0.35 b	0.50 b
Broadcasting	2028 b	1759 b	2112 b	0.45 b	0.36 b	0.51 b
Transplanting	4982 a	4881 a	5147 a	1.14 a	0.96 a	1.13 a
Variety (V)						
BRRI dhan83	3064 a	2853 a	3192 a	0.65 b	0.53 b	0.68c
BRRI dhan85	2974 b	2771 b	3097 b	0.68 a	0.54 b	0.70 b
Binadhan−19	2913c	2696c	3041 c	0.69 a	0.59 a	0.74 a
***F*-values**						
L		1120.2 * **	1112.7 * **	5.3 * *	778.1 * **	1010.7 * **
LP	60.4 * **	33.4 * **	24.6 * **	598.9 * **	29.2 * **	72.8 * **
EM	15433.3 * **	98848.3 * **	59310.9 * **	9.3 * *	17295.5 * **	4634.1 * **
V	29.8 * **	183.4 * **	111.1 * **		144.6 * **	33.2 * **
L × LP		59.8 * **	93.8 * **		26.6 * **	50.5 * **
L × EM		285.8 * **	115.6 * **		171.4 * **	79.1 * **
L × V		ns	10.9 * **		9.2 * **	ns
LP × EM	ns	18.9 * **	47.3 * **	ns	13.2 * **	8.9 * **
EM × V	ns	20.8 * **	17.9 * **	ns	9.6 * **	6.2 * **
LP × V	ns	ns	ns	ns	ns	ns
L × LP × EM		16.7 * **	23.2		3.6 * *	ns
L × LP × V		ns	ns		ns	ns
L × EM × V		ns	6.2 * **		ns	ns
LP × EM × V	ns	ns	ns	ns	ns	ns
L × LP × EM × V		ns	ns		ns	ns

NS refers to non-significance; * **, ** , and * indicate significance levels at 0.1, 1, and 5 %, respectively.

[a] This trial was conducted only at Jhenaida. Different lowercase letters in the column indicate significant differences.

3.7. *Multi-criteria assessment of crop establishment methods*

The holistic multi-criteria assessment of grain yield, crop duration, labor use, production cost, energetics, GWP, and YSE comparing the three establishment methods in all three landscape positions using the radial or spider diagrams showed both drill DSR and broadcast DSR methods better than PTR. This was reflected by lower production cost, lower labor use, lower crop duration, lower SE, and lower GWP and yield-scaled emissions and higher EUE in DSR compared to PTR. (Fig. 4). On the other hand, PTR performed better than DSR in terms of grain yield in lowlands and slightly higher or similar yield in medium and highlands.

4. Discussion

4.1. *Tradeoffs on productivity and resource use efficiency*

Across years, locations, landscape positions, and varieties the grain and straw yields of DSR (both drill seeding and broadcasting) in the current study were slightly lower (2–8 % for grain and 4–10 % for straw) than PTR. Our results agree with those of Xu et al. (2019) who reported that the overall yield of DSR was 12 % lower than PTR and the yield reduction of DSR relative to PTR was highly variable, ranging from −2 % to −42 %, and yield varying on climatic conditions, soil type, and management practices.

Our results also agree with Alam et al. (2018) who reported a 5 % lower yield in *aman* season DSR compared to PTR in a well-managed on-station field trial in Bangladesh. In their study, they used all recommended and need-based inputs for both establishment methods and although the DSR yield was slightly lower than of PTR, net profit and other benefits were higher for DSR. DSR required 30–50 % less irrigation water and 9 % lower production cost compared to PTR, with also the yield advantage in the subsequent crop following DSR due to the improvement of soil chemical and physical properties. In contrast to Alam et al.'s study, our study was conducted across several locations in farmers' fields with different landscape positions in the *aus* season. In our study, similar grain yield of drill seeding DSR and PTR in both high and mediumlands and lower yield of DSR in lowlands indicates no yield advantage from DSR compared to PTR in the given soil and landscape situations. In line with our results, a yield decrease in DSR compared to PTR was recorded in many previous studies (Farooq et al., 2006; Jat et al., 2009; Saharawat et al., 2010; Gathala et al., 2011; Kumar et al., 2015) and similar yields in DSR and PTR in other studies (Bhushan et al., 2007; Singh et al., 2009; Yadav et al., 2011; Liu et al., 2015; Devkota et al., 2019;) in South Asia. However, in contrast to our studies, some studies from Japan (Harada et al., 2007; Kato et al., 2009) and China (Xu et al., 2022a) recorded higher yields in DSR than PTR.

Most of the previous studies reported high weed incidence as the major yield-limiting factor of DSR. Weed competition against the crop during seedling establishment and critical crop growth periods is often responsible for lower yield (Kumar and Ladha, 2011; Ahmed et al., 2014, 2021b; Awan et al., 2015; Chauhan et al., 2015). In our study, we controlled weeds well in DSR by the application of pre-emergence herbicide fb post-emergence herbicide, and need-based manual hand weeding. Even then, there was some weed competition between the time of pre-emergence and post-emergence herbicide application. Such weed competition was comparatively lower for PTR. Along with weeds, other yield-limiting factors in DSR, as reported in the previous studies, include: lack of uniform seeding to maintain optimum plant population, seed and seedling damage by birds and rats, and poor crop establishment at the early stage due to poor seed germination and emergence, micronutrient deficiency, root nematodes, and blast disease (Gao et al., 2006; Choudhary et al., 2007; Pal et al., 2008; Kumar and Ladha, 2011; Yadav et al., 2011; Ahmed et al., 2014, 2016; Chaudhary et al., 2022).

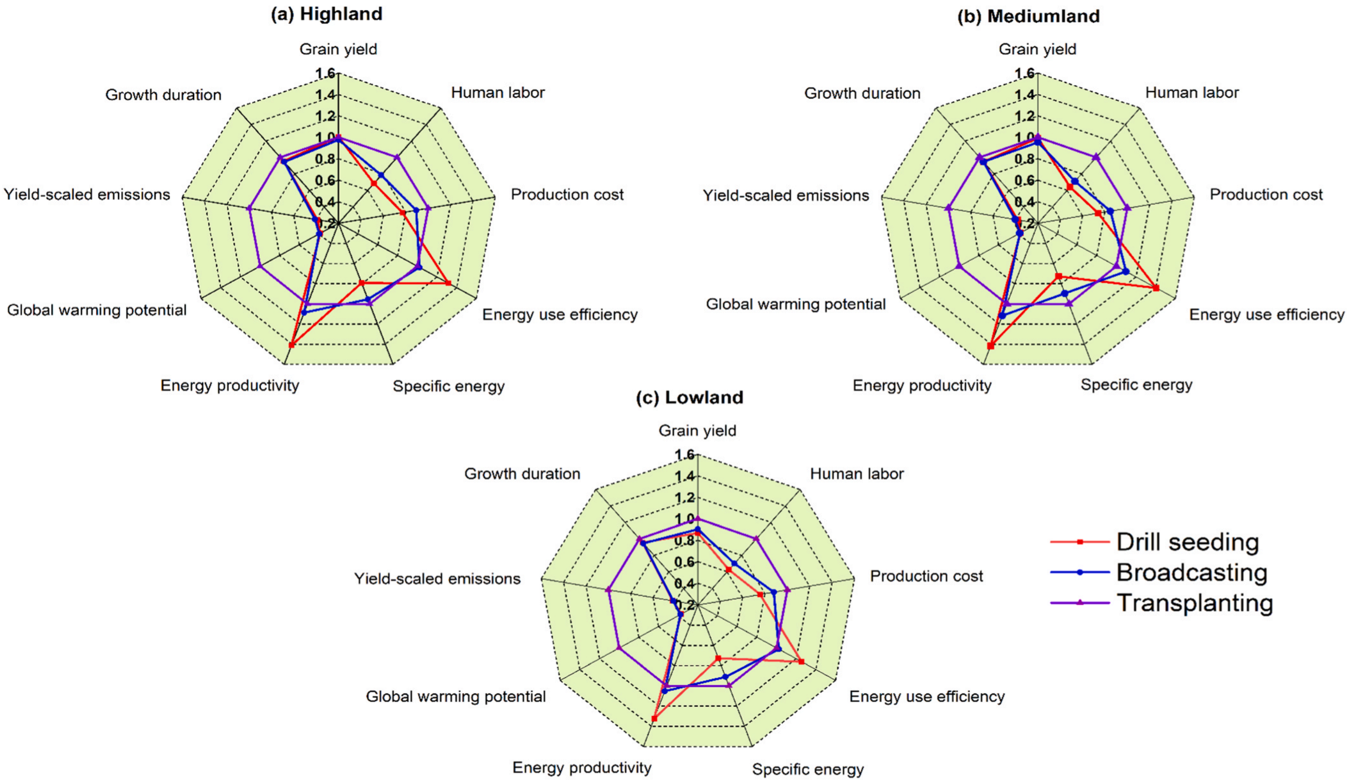

Fig. 4. Radar diagrams representing multi-criteria assessment showing relative values (percent change relative to transplanting) for grain yield (t ha^{-1}), manual labor requirements (person-days ha^{-1}), total production cost (USD ha^{-1}), energy use efficiency, specific energy (Mj kg^{-1}), energy productivity (Kg ha^{-1} grain yield/ Mj ha^{-1} input energy), global warming potential (Mt CO2eq ha^{-1}), yield-scaled emissions (Kg CO$_2$eq Mt^{-1} grain), and growth duration for drill seeded, broadcasted and transplanted rice in (A) highland, (B) mediumland, (C) lowland. Data presented show the average of years, locations and varieties.

While we did not observe any nematodes and blast disease but we noted reduced seed germination and emergence, and seed and seedling damage by birds. The higher variability in plant density at 10 days after emergence indicates that seeds were not always uniformly distributed in DSR plots which might be due to different soil moisture conditions during or after sowing, soil type, planting machinery, depth of seeding and seedling damage by birds and rats. The initial plant density was always higher (average 30 %) for broadcasting DSR than drill seeding DSR, mainly due to the use of a 44 % higher seed rate in broadcasting DSR (Fig. 2). The seed rate for drill seeding DSR was determined based on the previous study by Ahmed et al. (2014). For broadcast seeding, however, the average seed rate used by local farmers as their common practice was considered because currently there is no recommended seed rate for broadcasting DSR in Bangladesh. The results of our study show that across years, locations, and varieties, the initial plant density was similar for high and mediumlands but the lowland had around 20 % lower plant density than the other two land types. The lower plant density in the lowland was probably due to the compactness of the upper soil layer resulting from soil drying after sowing or irrigation. In addition, the soil of the lowland was a little harder than the other two land types. Plant density differed among varieties due to different grain sizes. The seed weight of different varieties was different due to the differences in seed size, with the order of 1000 seed weight as Binadhan-19 < BRRI dhan85 < BRRI dhan83.

The initial plant population is crucial for achieving optimum yield in DSR because the final yield depends on panicle numbers per unit area which are mostly achieved by the optimum plant stand. Ahmed et al. (2014) reported that a plant density of 106 to 170 plants m^{-2} for inbreds was good enough for the optimum yield of DSR. In our study, in high and mediumlands, the average initial plant density was within the range reported by Ahmed et al. but was lower in some cases in lowlands, especially for the drill seeding DSR. In dry seeding, dry seeds are sown into dry soil, and seed germination and early seedling growth are sometimes limited by soil moisture conditions (Guan et al., 2009; Ismail et al., 2009).

The initial higher plant density in broadcasting DSR resulted in a higher number of panicles though the number of grains $panicle^{-1}$ with this establishment method was lower than the other two methods. The PTR had always lower panicle density but higher grains $panicle^{-1}$ than the other two establishment methods. These results are in agreement with Ahmed et al. (2016), (2021a) and Gravois and Helms (1996), who reported that as the rice seeding rate increases, panicle density also increases but grains per panicle decreases.

The results of the current study indicate that the lower yield in DSR compared to PTR was mainly due to fewer grains per panicle (Table 5). Although there was a compensation mechanism between the panicle density and grains $panicle^{-1}$ (Li et al., 2019), the increase in panicle density was not large enough to compensate for the decrease in the number of grains per panicle in DSR (Ahmed et al., 2014, 2021a; Liu et al., 2015).

Although higher panicle density was recorded in the broadcasting DSR, a similar or lower yield to drill seeding DSR was mainly due to the lower number of grains $panicle^{-1}$ and higher grain sterility percentage (Table 5). The gross income was always higher in PTR than in DSR, which was mainly due to the grain and straw yield advantage over DSR. Although the gross income was higher from PTR than DSR, the added net return (net profit) was not always higher because of the higher production cost of PTR than DSR (Fig. 3; Table 6). We used the added net return instead of net profit because, for the economic analysis, we considered only those costs that were variable among the treatments. Since the fertilizers and harvesting costs were similar across all treatments, we didn't consider them in the economic analysis.

Positive added net return in DSR from 60 %, 65 %, and 35 % of farmers' fields in the highland, mediumland, and lowland, respectively, indicate that DSR was more profitable in the highland and mediumland and comparatively less profitable in the lowland. In high and mediumlands, the mean ANR was positive due to the positive ANR obtained from a higher number of farmers' fields. On the other hand, the mean ANR was negative for the lowland due to negative ANR from the higher number of farmers' fields. In the lowland, the negative ANR in DSR was mainly due to a 7–28 % lower yield than PTR but comparatively lower production cost differences (16 % lower cost). On the other hand, the yield difference between DSR and PTR was −3 to 7 % and −4 to 11 %, and the average production cost difference was 18 % and 20 % in highland and mediumland, respectively.

The higher labor requirement and higher production cost in PTR than DSR were mainly due to extra operations such as seed bed and seedling preparation, land preparation by repeated puddling followed by leveling, and seedling transplanting required for PTR. These operations in PTR required a cost of around USD 200–300 ha^{-1} but for the DSR the cost required for up to seeding was only USD 60–80 ha^{-1} (data not presented). The irrigation cost was up to 35 % lower for DSR than PTR. On the other hand, due to higher weed pressure, the weeding cost was always higher in DSR (around USD 220 ha^{-1}) than in PTR (around USD 120 ha^{-1}). Similar to our findings, lower production costs for DSR compared to PTR have also been reported in many previous studies (Liu et al., 2015; Tao et al., 2016; Chakraborty et al., 2017; Alam et al., 2018; Devkota et al., 2020).

4.2. *Tradeoffs on energy use, global warming potential, and GHG emissions*

Agriculture and energy have a very close relationship and they can both produce and consume energy (Alam et al., 2005). Analysis of energy in agricultural production systems is a promising approach to studying and investigating trends in energy inputs, outputs, and EUE (Khan et al., 2007; Pokhrel and Soni, 2017; Wu et al., 2017; Yuan and Peng, 2017a; Krupnik et al., 2022; Magar et al., 2022; Timsina et al., 2022). The efficient use of energy in agriculture helps to reduce production costs, protect natural resources, minimize negative environmental impacts, and promote sustainable production systems (Pervanchon et al., 2002; Timsina et al., 2022). In addition, GWP and GHG emissions in agriculture greatly depend on the energy inputs (Pittelkow et al., 2014). In our study, the energy input in drill-seeded DSR was 20–35 % lower than in PTR which was mainly due to the transplanting operation requiring more diesel fuel for land preparation in the nursery bed and main field and irrigation. Baruah and Dutta (2007) reported that more than 50 % of energy consumption in puddled rice production was related to tillage and land preparation operations. In the current study, the energy input for land preparation in PTR was 50–75 % higher than in drill-seeded DSR. In addition, due to the higher total labor requirement in PTR than in DSR, the energy input from the labor was also higher in PTR. In agreement with our results, many previous studies also reported lower total energy input in DSR compared to PTR (Islam et al., 2013; Eskandari and Attar, 2015; Kumar et al., 2018; Liu et al., 2015; Devkota et al., 2020).

Although total energy output was slightly higher in PTR due to slightly higher grain and straw yields, net energy was not always higher in PTR due to higher energy input. EUE and EP were 15–40 % higher in DSR compared to PTR due to lower energy input in the former compared to the latter. Higher EUE and higher EP in DSR compared to PTR were also reported in previous studies (Barut et al., 2011; Quilty et al., 2014; Eskandari and Attar, 2015; Kazemi et al., 2015; Pratibha et al., 2015). The SE was always higher in PTR than in DSR indicating that the energy used to produce one kg of rice grain was higher in the former than in the latter.

Intensive energy inputs from machinery, diesel oil, fertilizer, and pesticides in agriculture are responsible for GHG emissions (Yuan et al., 2019), which in turn threaten the sustainability of agriculture by contributing to global warming (Maraseni et al., 2015; Chen, 2016). Therefore, reducing energy inputs in agricultural production systems and enhancing EUE is crucial to minimizing environmental impact

(Mohammadi et al., 2014). Flooded rice fields are a major anthropogenic source of CH_4 in the atmosphere and contribute approximately 10–20 % to global CH_4 emissions (Reiner and Milkha, 2000; Carlson et al., 2017; Zhang et al., 2019; Chen et al., 2020;).

A recent assessment from the United Nations Environment Programme (UNEP) and the Climate and Clean Air Coalition found that cutting farming-related CH_4 emissions would be key to battling against climate change (IPCC, 2022). Therefore, in Asia, rice is an essential target for mitigating GHG emissions. Many previous studies reported lower CH_4 emissions from DSR fields compared to PTR resulting in lower GWP (Padre et al., 2016; Tao et al., 2016; Chaudhary et al., 2017; Susilawati et al., 2019; Liu et al., 2022). In our multilocation and multiyear study, we found 58–66 % lower GWP from DSR fields than from the PTR fields, implying that if flooded puddled rice could be replaced by DSR, mitigation of a significant amount of CH_4 would be possible. Thus, our results suggest that DSR is a potential climate-smart alternative to PTR production.

4.3. *Effect of location, landscape position, and variety on rice establishment methods*

Inour study, yield, resource use efficiency, profitability, energy productivity, and GWP greatly varied across the locations mainly due to climate, soil, and operation cost differences. Yield, added net return, and

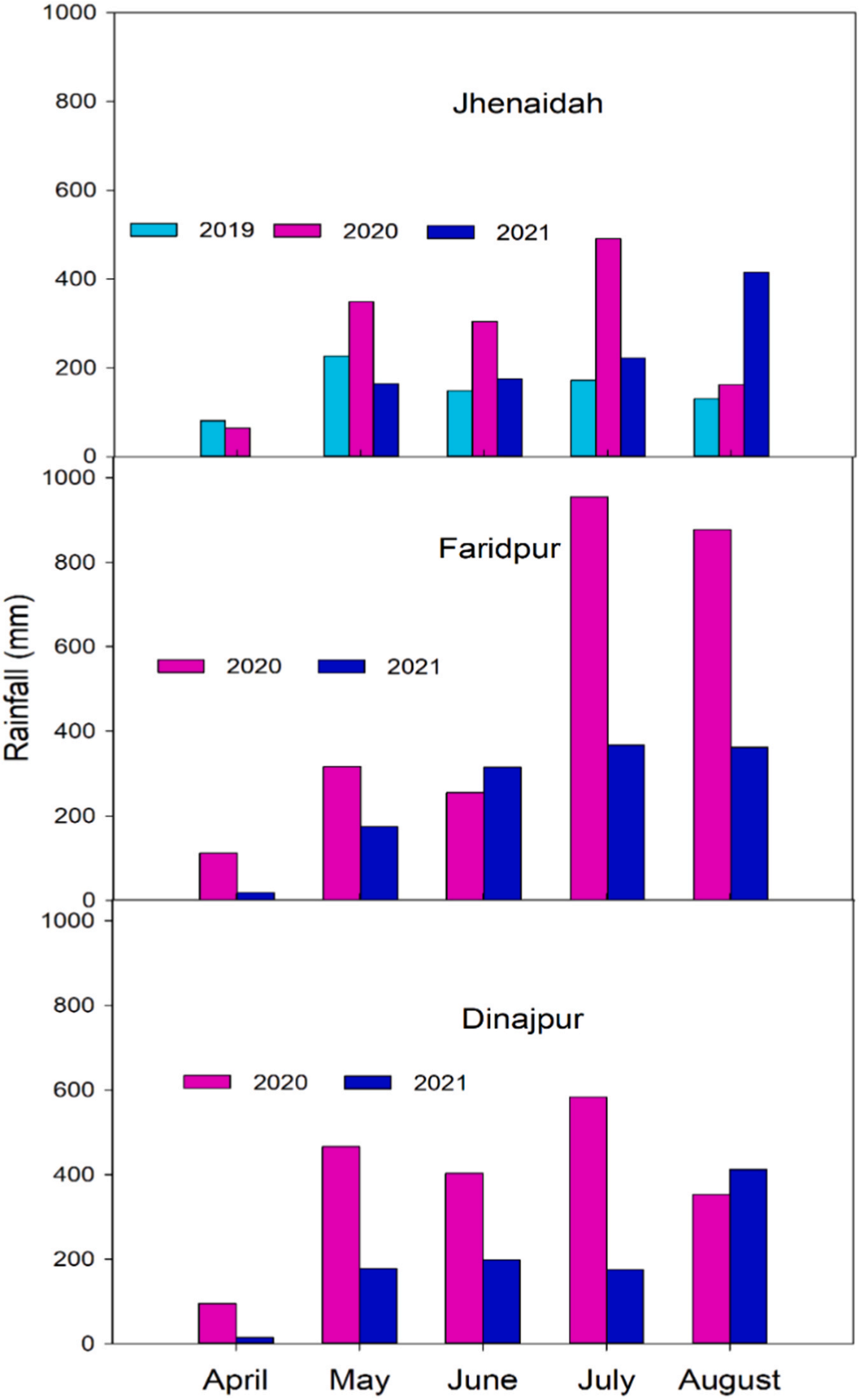

Fig. 5. Monthly cumulative rainfall during the cropping seasons.

energy productivity in 2020 were relatively higher than in the other two seasons mainly due to the crop receiving relatively more rainfall (Fig. 5). With frequent and higher rainfall during the season, the nutrient availability was probably higher, and weed infestation and irrigation water requirements were lower resulting in lower total production costs and labor requirements (Table 6). Variations in rainfall across different locations and seasons had a significant impact on irrigation costs, weed management expenses, crop growth, and crop yield; all of which ultimately affect production and economic outcomes. Dou et al. (2016) reported that the soil texture has an important role in affecting both water productivity and nutrient supply resulting in the growth and yield differences of rice. In the lowland, we found always lower yield in DSR than in PTR, which was mainly due to high moisture holding capacity. In addition, the initial plant stand was also lower in the lowland for DSR compared to the highland and medium highland. The total labor requirement was higher in Dinajpur which was mainly due to high weed infestation and higher labor used for manual weeding. The labor wage rate was however lower in Dinajpur compared to the other two locations, resulting in comparatively lower production costs. The higher production cost in the highland was mainly due to higher irrigation and weed management costs. The higher gross income from the medium highland was due to slightly lower production costs but slightly higher yield and income than the other two landscape positions. The negative added net return in the lowland in DSR was due to the high yield difference between DSR and PTR.

4.4. *Effect of line seeding DSR vs broadcasting DSR and multi-criteria assessment*

Although the yield of both DSR establishment methods was almost similar, the labor requirement and production cost were higher for broadcasting DSR than PTR, the latter mainly due to higher land preparation cost and higher labor requirement required for the manual hand weeding. Manual weeding was challenging for broadcasting and required more time than line seeding. Higher labor and higher energy requirements for the land preparation are responsible for the higher SE and lower EP in broadcasting DSR than the line seeding DSR (Table 7). In addition, in broadcast DSR we found some sheath rot disease in some cases which was absent in line seeding.

The multi-criteria assessment revealed that DSR results in improved energetic performance while entailing reductions in labor use, and production costs. DSR also tended to lower yield-scaled GHG emissions compared to PTR. Nevertheless, there is an increasing interest in DSR in many countries as it has the potential to reduce production costs by saving labor, tillage intensity, and irrigation water (Alam et al., 2018; Ahmed et al., 2021a) and reduce GHG emissions, particularly the CH4 emission. Despite the potential advantages of DSR and as a potential climate-smart technology and an alternative to PTR, it has not yet been adopted on a large scale in Bangladesh or any other rice-growing countries in Asia due to the absence of systematic technology assessment across production ecology gradients and lack of awareness at the policy level as well as due to important risks associated with it (Bhatt and Singh, 2021; CSISA, 2016; Zhang and Hu, 2022). In addition, issues with weed management, low availability of appropriate seed drills, and basic awareness of benefits are also the constraints of DSR adoption. To change this scenario, more efforts are required to coordinate the efforts of the public and private sectors to systematically address these factors.

4.5. *Implementation of DSR on environment and production systems*

Implementing DSR as a shift from traditional PTR presents significant environmental benefits and enhances production systems. DSR reduces water usage -by eliminating the need for flooded fields during the early growth stages, thus conserving invaluable water resources, particularly in regions where water scarcity is a pressing issue. This approach not only enhances efficient water management but also reduces methane emissions by limiting anaerobic conditions linked to PTR. Additionally, DSR fosters improved soil health through reduced soil disturbance, leading to enhanced soil structure and increased organic matter over time. This practice allows beneficial microorganisms to flourish, promoting nutrient cycling and facilitating better crop growth (Chaudhary et al., 2022). The shift towards DSR also encourages the adoption of conservation agriculture principles, such as minimum tillage, which further enhances soil carbon sequestration (Devkota et al., 2019). Tater and Vashisht (2024) reported from a long-term study conducted between 2010 and 2020. They found that compared to the traditional PTR method, DSR demonstrated a significant decrease in physical parameters such as bulk density and soil penetration resistance. Conversely, DSR exhibited a notable increase in plant available water content, soil infiltration, and hydraulic conductivity. Additionally, the amount of organic carbon in the soil increased by 5–13 % in DSR compared to PTR. While many Southeast Asian countries, such as Sri Lanka, Vietnam, Malaysia, and Cambodia, have successfully adopted DSR methods, South Asia's adoption rate remains very limited (Kaur et al., 2024).

As we mentioned earlier, the PTR is the dominant rice establishment method in Bangladesh, and considering the growing season and planting windows *aus* is the best fit for DSR but current areas of aus production are around 10 % of the country's rice production areas. *Aman* and *boro* are the major rice growing seasons and if it is possible to shift certain portions to DSR in both seasons it would be a great contribution to resource use efficiency and climate change mitigation. The current planting windows of *aman* and *boro* are not suitable for the DSR (Ahmed et al., 2014, 2016) but changing the current windows might be fit for the DSR but other associated challenges are to fit them in the cropping systems. Therefore, Bangladesh needs more research on the best fit of *aman* and *boro* DSR in the cropping systems.

Weedy rice in DSR is a significant production issue reported in countries that have relied on this method for an extended period (Juliano et al., 2020). In Bangladesh, where the predominant method is PTR, the introduction of DSR could lead to the emergence of weedy rice problems, as observed in other countries with a long history of DSR. Weedy rice, which competes directly with cultivated rice for resources, can severely reduce yields and complicate weed management strategies (Ziska et al., 2014). Therefore, it is crucial to implement integrated weed management practices for DSR adoption.

DSR can help reduce methane emissions, but aerobic soil conditions in DSR, especially in dry-DSR, contribute to increased nitrous oxide N_2O emissions. In the prevailing anaerobic conditions of PTR, denitrification is the main mechanism for emissions, while DSR nitrification serves as the primary mechanism. Pathak et al. (2013) quantified the N_2O emissions from the DSR and PTR fields in Punjab, India. They reported that emissions from DSR fields were slightly higher than those from PTR fields. However, the contribution of N_2O to GHG emission was much lower than that of methane (CH_4).

5. Conclusion

Our study aimed to identify the landscape positions and varieties suitable for DSR and compare the performance of DSR with dominant practice PTR in terms of yield, labor use, energy, GWP, and YSE. The results of this study revealed that the DSR had a similar or slightly lower yield than PTR but EUE and EP were higher in DSR due to lower energy input. The lower SE, GWP and yield-scaled emissions in DSR than in PTR demonstrated that DSR is a clean production technology and, if adopted, it could be an effective way to mitigate GHG emissions from agriculture in Asia. Moreover, lower production costs and higher net returns obtained from the predominant farmers' fields indicate that DSR is more economically viable than PTR. DSR promotes sustainability, enhances resource use efficiency, and contributes to reducing the environmental impacts associated with traditional rice production systems; therefore, it can be considered a climate-smart production system. Cultivars currently used in PTR plots performed similarly in DSR plots under well management but cultivars with early vigor trait and weed competitiveness would be required to reduce both weed management cost and agrochemical use. This study demonstrated that the medium highland was more suitable than the lowland or highland in terms of good crop establishment, lowering weed pressure, and obtaining higher input use efficiency and higher added net return, suggesting that the selection of appropriate landscape position should be an important consideration for the success of DSR. However, for the widespread adoption of DSR in Bangladesh and South Asia as a whole, appropriate technological, social, and policy-level interventions would be necessary. Our current research is based on a three-year multi-location study that primarily focuses on the comparison of DSR and PTR based on some immediate outcomes. While these results offer valuable insights into the current growing season's performance, a major challenge for DSR in Bangladesh is to fit them into the existing cropping systems, therefore we recommend conducting long-term studies and analyses to gain a more comprehensive understanding of the long-term impacts of DSR on cropping systems and ecosystem balances.

CRediT authorship contribution statement

Amina Khatun: Writing – review & editing, Supervision, Resources, Data curation. **Khaled Hossain:** Formal analysis. **Asad Zaman:** Validation, Investigation, Data curation. **Mahbubur Dewan:** Investigation, Data curation. **Timothy J. Krupnik:** Writing – review & editing, Visualization, Validation, Project administration, Funding acquisition, Conceptualization, Methodology. **Sudhanshu Singh:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Jagadish Timsina:** Writing – review & editing, Visualization, Validation. **Sharif Ahmed:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Virender Kumar:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was carried out under the project Cereal Systems Initiative for South Asia (https://csisa.org) funded by the United States Agency for International Development (USAID) and the Bill and Melinda Gates Foundation (BMGF). Finalization of this paper was made possible through the CGIAR Regional Integrated Initiative Transforming Agrifood Systems in South Asia (TAFSSA; https://www.cgiar.org/initiative/20-transforming-agrifood-systems-in-south-asia-tafssa/). The authors would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders/. The contents do not necessarily reflect the views of USAID, BMGF, or CGIAR. We gratefully acknowledge all farmers, and field technicians who were directly involved in this study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109739.

Data availability

Data will be made available on request.

References

Acaroğlu, M., Aksoy, A.Ş., 2005. The cultivation and energy balance of Miscanthus × giganteus production in Turkey. Biomass Bioenergy 29 (1), 42–48. https://doi.org/10.1016/j.biombioe.2005.01.002.

Ahmed et al., 2018. Fertilizer Recommendation Guide. 2018. Bangladesh Agricultural Research Council (BARC). Farmgate, Dhaka 1215. 223p. ⟨https://moa.portal.gov.bd/sites/default/files/files/moa.portal.gov.bd/page/9d1b92d4_1793_43af_9425_0ed49f27b8d0/FRG-2018%20%28English%29.pdf⟩.

Ahmed, S., Alam, M.J., Hossain, A., Islam, A.K.M.M., Awan, T.H., Soufan, W., Qahtan, A.A., Okla, M.K., El Sabagh, A., 2021a. Interactive effect of weeding regimes, rice cultivars, and seeding rates influence the rice-weed competition under dry direct-seeded condition. Sustainability 13, 317. https://doi.org/10.3390/su13010317.

Ahmed, S., Humphreys, E., Salim, M., Chauhan, B.S., 2014. Optimizing sowing management for short duration dry seeded *aman* rice on the High Ganges River Floodplain of Bangladesh. Field Crops Res. 169, 77–88 https://doi.org/10.1016/j.fcr.2014.09.009.

Ahmed, S., Humphreys, E., Salim, M., Chauhan, B.S., 2016. Growth, yield and nitrogen use efficiency of dry-seeded rice as influenced by nitrogen and seed rates in Bangladesh. Field Crops Res. 186, 18–31 https://doi.org/10.1016/j.fcr.2015.11.001.

Ahmed, S., Kumar, V., Alam, M., Dewan, M.R., Bhuiyan, K.A., Miajy, A.A., Saha, A., Singh, S., Timsina, J., Krupnik, T.J., 2021b. Integrated weed management in transplanted rice: options for addressing labor constraints and improving farmers' income in Bangladesh. Weed Technol. 35 (5), 697–709. https://doi.org/10.1017/wet.2021.50.

Alam, M.J., Ahmed, S., Islam, M.K., Islam, R., Islam, M., 2019. Effect of cropping system and rice residue retention on crop productivity and soil physical properties in rice-based cropping system of Bangladesh. Agriculturists 17 (1-2), 14–30. https://doi.org/10.3329/agric.v17i1-2.44693.

Alam, M.S., Alam, M.R., Islam, K.K., 2005. Energy flow in agriculture: Bangladesh. Am. J. Environ. Sci., 213220 https://doi.org/10.3844/ajessp.2005.213.220.

Alam, M.J., Humphreys, E., Sarkar, M.A.R., Yadav, S., 2018. Comparison of dry seeded and puddled transplanted rainy season rice on the High Ganges River Floodplain of Bangladesh. Eur. J. Agron. 96, 120–130. https://doi.org/10.1016/j.eja.2018.03.006.

Anonymous, 2022. Bangladesh Institute of Nuclear Agriculture (BINA). ⟨https://bina.gov.bd/site/page/3149b016-dfcb-436a-80d3-d3d8036274ea⟩/-. Accessed on March 12, 2022.

Awan, T.H., Cruz, P.C.S., Chauhan, B.S., 2015. Agronomic indices, growth, yield-contributing traits, and yield of dry-seeded rice under varying herbicides. Field Crops Res. 177, 15–25. https://doi.org/10.1016/j.fcr.2015.03.001.

Bari, L., Ahmed, S., 2018. Performance of Aus rice in different tillage systems and crop establishment method in Southwest Bangladesh. J. Exp. Sci. 9, 05–09. https://doi.org/10.25081/jes.2018.v9.3577.

Baruah, D.C., Dutta, P.K., 2007. An investigation into the energy use in relation to yield of rice (*Oryza sativa*) in Assam, India. Agric. Ecosyst. Environ. 120 (2-4), 185–191. https://doi.org/10.1016/j.agee.2006.09.003.

Barut, Z.B., Ertekin, C., Karaaga, H.A., 2011. Tillage effects on energy use for corn silage in Mediterranean Coastal of Turkey. Energy 36, 5466–5475. https://doi.org/10.1016/j.energy.2011.07.035.

BBS. 2022. Statistical yearbook Bangladesh. Bangladesh Bureau of Statistics, Statistics and Information Division, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh. Pp. 556. ⟨https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b2db8758_8497_412c_a9ec_6bb299f8b3ab/2023-06-26-09-19-2edf60824b00a7114d8a51ef5d8ddbce.pdf⟩.

Bhatt, R., Singh, P., 2021. Adoption status of crop production practices in direct seeded rice: a case study of Kapurthala district of Punjab (India). Indian J. Exten. Educ. 57 (3), 24–27. https://doi.org/10.48165/IJEE.2021.57306.

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y.S., 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. https://doi.org/10.2134/agronj2006.0227.

Borna, S.N., Siddique, I.A., Mahmud, A.A., Khatun, R., Hossain, M., Islam, S., Meharg, A.A., Islam, M.R., 2022. Influence of rice establishment methods on water productivity, methane emissions and rice grain heavy metals content from irrigated rice paddies in Bangladesh. Eur. J. Agric. Food Sci. 44, 8515–8521. https://doi.org/10.24018/ejfood.2022.4.5.586.

BRRI. 2020. Modern Rice Cultivation. Bangladesh Rice Research Institute. 23rd Editions. P. 103. ⟨https://knowledgebank-brri.org/wp-content/uploads/2020/06/ADC.pdf⟩.

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., et al., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Change 7 (1), 63–68. https://doi.org/10.1038/nclimate3158.

Chakraborty, D., Ladha, J.K., Rana, D.S., Jat, M.L., Gathala, M.K., Yadav, S., Rao, A.N., Ramesha, M., Raman, A., 2017. A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci. Rep. 7 (1), 9342. https://doi.org/10.1038/s41598-017-09742-9.

Chaudhary, V.P., Singh, K.K., Pratibha, G., Bhattacharyya, R., Shamim, M., Srinivas, I., Patel, A., 2017. Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation. Energy 130, 307–317. https://doi.org/10.1016/j.energy.2017.04.131.

Chaudhary, A., Venkatramanan, V., Mishra, A.K., Sharma, S., 2022. Agronomic and environmental determinants of direct seeded rice in South Asia. Circ. Econ. Sustain. https://doi.org/10.1007/s43615-022-00173-x.

Chauhan, B.S., Ahmed, S., Awan, T.H., Jabran, K., Manalil, S., 2015. Integrated weed management approach to improve weed control efficiencies for sustainable rice production in dry-seeded systems. Crop Prot. 71, 19–24. https://doi.org/10.1016/j.cropro.2015.01.012.

Chen, X., 2016. Economic potential of biomass supply from crop residues in China. Appl. Energy 166, 141. https://doi.org/10.1016/j.apenergy.2016.01.034.

Chen, C., van Groenigen, K.J., Yang, H., Hungate, B.A., Yang, B., Tian, Y., Chen, J., Dong, W., Huang, S., Deng, A., Jiang, Y., 2020. Global warming and shifts in cropping systems together reduce China's rice production. Glob. Food Secur. 24, 100359. https://doi.org/10.1016/j.gfs.2020.100359.

Choudhary, B.U., Bouman, B.A.M., Singh, A.K., 2007. Yield and water productivity of rice-wheat on raised beds at New Delhi, India. Field Crops Res. 100, 229–239. https://doi.org/10.1016/j.fcr.2006.07.009.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Asis, C.A., Wassmann, R., 2000. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycl. Agroecosyst. 58, 37–53. https://doi.org/10.1023/A:1009826131741.

CSISA. 2016. Accelerating Adoption of Direct Seeded Rice in Bangladesh and Nepal. Devkota, K.P., Sudhir-Yadav, Khanda C.M., Beebout, S.J., Mohapatra, B.K., Singleton, G. R., Puskur, R., 2020. Assessing alternative crop establishment methods with a sustainability lens in rice production systems of eastern India. J. Clean. Prod. 118835 ⟨https://doi.org/10.1016/j.jclepro.2019.118835⟩.

Da Silva, J.M., Silva, L.L., 2008. Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. Biosyst. Eng. 101 (2), 183–190. https://doi.org/10.1016/j.biosystemseng.2008.07.003.

Devkota, M., Devkota, K.P., Acharya, S., McDonald, A.J., 2019. Increasing profitability, yields and yield stability through sustainable crop establishment practices in the rice-wheat systems of Nepal. Agric. Syst. 173, 414–423. https://doi.org/10.1016/j.agsy.2019.03.022.

Devkota, K.P., Yadav, S., Khanda, C.M., Beebout, S.J., Mohapatra, B.K., Singleton, G.R., Puskur, R., 2020. Assessing alternative crop establishment methods with a sustainability lens in rice production systems of Eastern India. J. Clean. Prod. 244, 118835 https://doi.org/10.1016/j.jclepro.2019.118835.

Dou, F., Soriano, J., Tabien, R.E., Chen, K., 2016. Soil texture and cultivar effects on rice (Oryza sativa, L.) grain yield, yield components and water productivity in three water regimes. PLoS One 11. https://doi.org/10.1371/journal.pone.0150549.

Ecoinvent Center., 2007. Ecoinvent Data V2.0. Ecoinvent Report No. 1-25," in Swiss Centre of Life Cycle Inventories (Dubendorf, Switzerland: Swiss Centre for Life Cycle Inventories, Dübendorf).

Esengun, K., Gunduz, O., Erdal, G., 2007. Input–output energy analysis in dry apricot production of Turkey. Energy Convers. Manag. 48 (2), 592–598. https://doi.org/10.1016/j.enconman.2006.06.006.

Eskandari, H., Attar, S., 2015. Energy comparison of two rice cultivation systems. Renew. Sustain. Energy Rev. 42, 666–671. https://doi.org/10.1007/s10479-015-1938-x.

FAO. 2022. FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. Rome, Italiy. Accessed on 24 December 2022.

Farooq, M., Tabassum, R., Afzal, I., 2006. Enhancing the performance of direct seeded fine rice by seed priming. Plant Prod. Sci. 9, 446–456. https://doi.org/10.1626/pps.9.446.

Feliciano, D., Nayak, D.R., Vetter, S.H., Hillier, J., 2017. CCAFS-MOT - a tool for farmers, extension services and policy-advisors to identify mitigation options for agriculture. Agric. Syst. 154, 100–111. https://doi.org/10.1016/j.agsy.2017.03.006.

Fukagawa, N.K., Ziska, L.H., 2019. Rice: importance for global nutrition. J. Nutr. Sci. Vitaminol. https://doi.org/10.3177/jnsv.65.S2.

Gao, X., Zou, C., Fan, X., Zhang, F., Hoffland, E., 2006. From flooded to aerobic conditions in rice cultivation: consequences for zinc uptake. Plant Soil 280, 41–47. https://doi.org/10.1007/s11104-004-7652-0.

Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Kumar, V., Sharma, P.K., 2011. Effect of tillage and crop establishment methods on physical properties of medium-textured soil under a seven-year rice–wheat rotation. Soil Sci. Soc. Am. J. 75, 1851–1862. https://doi.org/10.2136/sssaj2010.0362.

Gravois, K.A., Helms, R.S., 1996. Seeding rate effects on rough rice yield, head rice, and total milled rice. Agron. J. 82–84. https://doi.org/10.2134/agronj1996.00021962008800010017x.

Guan, B., Zhou, D., Zhang, H., Tian, Y., Japhet, W., Wang, P., 2009. Germination responses of Medicago ruthenica seeds to salinity, alkalinity, and temperature. J. Arid Environ. 73 (1), 135–138. https://doi.org/10.1016/j.jaridenv.2008.08.009.

Gundogmus, E., 2006. Energy use on organic farming: a comparative analysis on organic versus conventional apricot production on small holding in Turkey. Energy Convers. Manag. 47, 3351–3359. https://doi.org/10.1016/j.enconman.2006.01.001.

Hao, X., Thelen, K., Gao, J., 2010. Effects of soil and topographic properties on spatial variability of corn grain ethanol yield. Agron. J. 102 (3), 998–1006. https://doi.org/10.2134/agronj2009.0481.

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. https://doi.org/10.1111/j.1747-0765.2007.00174.x.

Hussain, S., Hussain, S., Aslam, Z., Rafiq, M., Abbas, A., Saqib, M., Rauf, A., Hano, C., El-Esawi, M.A., 2021. Impact of different water management regimes on the growth, productivity, and resource use efficiency of dry direct seeded rice in central Punjab-Pakistan. Agronomy 11 (6), 1151 https://doi.org/s10.3390/agronomy11061151.

IPCC, 2019. Summary for Policymakers. In: Shukla, P.R., Skea, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J.P., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. In press.

IPCC. 2013. Climate Change: The Physical Science Basis. Working Group I Contribution to the FiCTh Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 8: Anthropogenic and Natural Radiative Forcing. Intergovern. Panel. Climate Change. ⟨https://www.ipcc.ch/report/ar5/wg1/⟩.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. ⟨https://www.ipcc.ch/report/ar5/syr/⟩.

IPCC. 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp.

Islam, A.K.M.S., Hossain, M.M., Saleque, M.A., Rabbani, M.A., Sarker, R.I., 2013. Energy consumption in unpuddled transplanting of wet season rice cultivation in north west region of Bangladesh. Progr. Agric. 24 (1-2), 229–237.

Ismail, A.M., Ella, E.S., Vergara, G.V., Mackill, D.J., 2009. Mechanisms associated with tolerance to flooding during germination and early seedling growth in rice (Oryza sativa L). Ann. Bot. 103, 197–209. https://doi.org/10.1093/aob/mcn211.

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, V., Sharma, S.K., Kumar, V., Gupta, R., 2009. Evaluation of precision land leveling and double zero till systems in the rice-wheat rotation: water use, productivity, profitability and soil physical properties. Soil Till. Res. 105, 112–121. https://doi.org/10.1016/j.still.2009.06.003.

Joshi, E., Dinesh, K., Lal, B., Nepalia, V., Gautam, P., Vyas, A.K., 2013. Management of direct-seeded rice for enhanced resource–use efficiency. Plant Knowl. J. 2 (3), 119–134. ⟨https://search.informit.org/doi/10.3316/informit.766917019565468⟩.

Juliano, L.M., Donayre, D.K.M., Martin, E.C., Beltran, J.C., 2020. Weedy rice: An expanding problem in direct-seeded rice in the Philippines. Weed Biol. Manag. 20 (2), 27–37. https://doi.org/10.1111/wbm.12196.

Kato, Y., Okami, M., Katsura, K., 2009. Yield potential and water use efficiency of aerobic rice (*Oryza sativa L.*) in Japan. Field Crops Res. 113, 328–334. https://doi.org/10.1016/j.fcr.2009.06.010.

Kaur, S., Ahmed, S., Awan, T.H., Ali, H.H., Singh, R., Mahajan, G., Chauhan, B.S., 2024. Adoption pattern of direct-seeded rice systems in three south Asian countries during COVID-19 and thereafter. Crops 4 (3), 324–332. https://doi.org/10.3390/crops4030023.

Kazemi, H., Kamkar, B., Lakzaei, S., Badsar, M., Shahbyki, M., 2015. Energy flow analysis for rice production in different geographical regions of Iran. Energy 84, 390–396. https://doi.org/10.1016/j.energy.2015.03.005.

Khan, M.R.U., Fazal, A., Saleh, M., 2015. Model-based estimation of methane emission from rice fields in Bangladesh. J. Agric. Eng. Biotechnol. 3 (4), 125–137. https://doi.org/10.18005/JAEB0304001.

Khan, M.A., Khan, S., Mushtaq, S., 2007. Energy and economic efficiency of wheat production using different irrigation supply methods. Soil Environ. 26, 121–129.

Ko, J.Y., Kang, H.W., 2000. The effects of cultural practices on methane emission from rice fields. Nutr. Cycl. Agroecosyst. 58, 311–314. https://doi.org/10.1007/978-94-010-0898-3_24.

Krupnik, T.J., Hossain, M.K., Timsina, J., Gathala, M.K., Sapkota, T.B., Yasmin, S., et al., 2022. Adapted conservation agriculture practices can increase energy productivity and lower yield-scaled greenhouse gas emissions in coastal Bangladesh. Front. Agron. 4, 829737. https://doi.org/10.3389/fagro.2022.829737.

Krupnik, T.J., Santos Valle, S., Hossain, I., Gathala, M.K., Justice, S., Gathala, M.K., McDonald, A.J., 2013. Made in Bangladesh: Scale-appropriate Machinery for Agricultural Resource Conservation. International Maize and Wheat Improvement Center, Mexico. ⟨https://repository.cimmyt.org/entities/publication/9df80f83-eca3-4ebd-9974-22b1b3c32b8f⟩.

Kumar, V., Jat, H.S., Sharma, P.C., Gathala, M.K., Malik, R.K., Kamboj, B.R., Yadav, A.K., Ladha, J.K., Raman, Anitha, Sharma, D.K., McDonald, A., 2018. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric. Ecosyst. Environ. 252, 132–147. https://doi.org/10.1016/j.agee.2017.10.006.

Kumar, A., Kumar, S., Dahiya, K., Kumar, S., Kumar, M., 2015. Productivity and economics of direct seeded rice (*Oryza sativa* L.). J. Appl. Nat. Sci. 7 (1), 410–416. https://doi.org/10.31018/jans.v7i1.625.

Kumar, V., Ladha, J.K., 2011. Direct seeding of rice: recent developments and future research needs. Adv. Agron. 111, 297–413 https://doi.org/10.1016/B978-0-12-494-387689-8.00001-1.

Kumar, V., Saharawat, Y.S., Gathala, M.K., Jat, A.S., Singh, S.K., Chaudhary, N., et al., 2013. Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. Field Crops Res. 142, 1–8. https://doi.org/10.1016/j.fcr.2012.11.013.

Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30, 981–990. https://doi.org/10.1016/j.envint.2004.03.005.

Li, R., Li, M., Ashraf, U., Liu, S., Zhang, J., 2019. Exploring the relationships between yield and yield-related traits for rice varieties released in China from 1978 to 2017. Front. Plant Sci. 10, 543. https://doi.org/10.3389/fpls.2019.00543.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D.P., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Torquebiau, E., 2014. Climate-smart agriculture for food security. Nat. Clim. Change 4 (12), 1068–1072. https://doi.org/10.1038/nclimate2437.

Liu, H., Hussain, S., Zheng, M., Peng, S., Huang, J., Cui, K., et al., 2015. Dry seeded rice as an alternative to transplanted-flooded rice in central China. Agron. Sustain. Dev. 35, 285–294. https://doi.org/10.1007/s13593-014-0239-0.

Liu, Y., Liu, W., Geng, X., Liu, B., Fu, X., Guo, L., et al., 2022. Direct-seeded rice reduces methane emissions by improving root physiological characteristics through affecting the water status of paddy fields. Rhizosphere 24 (100628), 2198–2452. https://doi.org/10.1016/j.rhisph.2022.100628.

Lobell, D., Sibley, A., Ortiz-Monasterio, J.I., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Chang. 2, 186–189. https://doi.org/10.1038/nclimate1356.

Ly, P., Jensen, L.S., Bruun, T.B., de Neergaard, A., 2012. The system of rice intensification: adapted practices, reported outcomes and their relevance in Cambodia. Agric. Syst. 113 (0), 16–27. https://doi.org/10.1016/j.njas.2016.05.003.

Magar, S.T., Timsina, J., Devkota, K.P., Weili, L., 2022. Energy and greenhouse gas footprint analysis of conventional and reduced tillage practices in rainfed and irrigated rice–wheat systems. Paddy Water Environ. https://doi.org/10.1007/s10333-022-00902-w.

Magar, S.T., Timsina, J., Devkota, K.P., Weili, L., Neeranjan, R., 2022. Conservation agriculture for increasing productivity, profitability and water productivity in rice-wheat system of the Eastern Gangetic Plain. Environ. Chall. 7, 100468. https://doi.org/10.1016/j.envc.2022.100468.

Maraseni, T., Chen, G., Banhazi, T., Bundschuh, J., Yusaf, T., 2015. An assessment of direct on-farm energy use for high value grain crops grown under different farming practices in Australia. Energies 8 (11), 13033–13046. https://doi.org/10.3390/en81112353.

Mohammadi, A., Rafiee, S., Jafari, A., Keyhani, A., Mousavi-Avval, S.H., Nonhebel, S., 2014. Energy use efficiency and greenhouse gas emissions of farming systems in north Iran. Renew. Sustain. Energy Rev. 724–733. https://doi.org/10.1016/j.rser.2013.11.012.

Mohidem, N.A., Hashim, N., Shamsudin, R., Che Man, H., 2022. Rice for food security: revisiting its production, diversity, rice milling process and nutrient content. Agriculture 12 (6), 741. https://doi.org/10.3390/agriculture12060741.

Nassiri, S.M., Singh, S., 2009. Study on energy use efficiency for paddy crop using data envelopment analysis (DEA) technique. Appl. Energy 86, 1320–1325. https://doi.org/10.1016/j.apenergy.2008.10.007.

Ogle, S., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochem 72, 87–121. https://doi.org/10.1007/s10533-004-0360-2.

Padre, A.T., Rai, M., Kumar, V., Gathala, M., Sharma, P.C., Sharma, S., Nagar, R.K., Deshwal, S., Singh, L.K., Jat, H.S., Sharma, D.K., Wassmann, R., Ladha, J.K., 2016. Quantifying changes to the global warming potential of rice wheat systems with the adoption of conservation agriculture in northwestern India. Agric. Ecosyst. Environ. 219, 1–13. https://doi.org/10.1016/j.agee.2015.12.020.

Pal, S., Datta, S.P., Rattan, R.K., Singh, A.K., 2008. Diagnosis and amelioration of iron deficiency under aerobic rice. J. Plant Nutr. 31, 919–940. https://doi.org/10.1080/01904160802043262.

Pathak, H., Sankhyan, S., Dubey, D.S., 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. https://doi.org/10.1007/s10333-012-0352-0.

Pervanchon, F., Bockstaller, C., Girardin, P., 2002. Assessment of energy use in arable farming systems by means of an agro-ecological indicator: the energy indicator. Agric. Syst. 72 (2), 149–172. https://doi.org/10.1016/s0308-521x(01)00073-7.

Pittelkow, C.M., Adviento-Borbe, M.A., van Kessel, C., Hill, J.E., Linquist, B.A., 2014. Optimizing rice yields while minimizing yield-scaled global warming potential. Glob. Chang. Biol. 20, 1382–1393. https://doi.org/10.1111/gcb.12413.

Pokhrel, A., Soni, P., 2017. Performance analysis of different rice-based cropping systems in tropical region of Nepal. J. Environ. Manag. 15, 70–79. https://doi.org/10.1016/j.jenvman.2017.03.035.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D. B., Travasso, M.I., 2014. Food Security and Food Production Systems. In: Field, et al. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA, pp. 485–533.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. https://doi.org/10.1016/j.agee.2016.01.005.

Prasanna, V., 2014. Impact of monsoon rainfall on the total foodgrain yield over India. J. Earth Syst. Sci. 123 (5), 1129–1145. https://doi.org/10.1007/s12040-014-0444-x.

Pratibha, G., Srinivas, I., Rao, K.V., Raju, B.M.K., Thyagaraj, C.R., Korwar, G.R., Venkateswarlu, B., Shanker, A.K., Choudhary, D.K., Srinivasrao, K., Srinivasarao, Ch, 2015. Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea castor systems. Eur. J. Agron. 66, 30–40. https://doi.org/10.1016/j.eja.2015.02.001.

Quilty, J.R., McKinley, J., Pede, V.O., Buresh, R.J., Correa Jr, T.Q., Sandro, J.M., 2014. Energy efficiency of rice production in farmers' fields and intensively cropped research fields in the Philippines. Field Crops Res. 168, 8–18. https://doi.org/10.1016/j.fcr.2014.08.001.

R Core Team., 2020. "R: A Language and Environment for Statistical Computing," in R Foundation for Statistical Computing (Vienna, Austria). Available at: ⟨www.R-project.org⟩.

Rahman, S., Rahman, S., 2013. Energy productivity and efficiency of maize accounting for the choice of season and environmental factors: an empirical analysis from Bangladesh. Energy 49, 339–346. https://doi.org/10.1016/j.energy.2012.10.042.

Ran, Y., Chen, H., Ruan, D., Liu, H., Wang, S., Tang, X., Wu, W., 2018. Identification of factors affecting rice yield gap in southwest China: an experimental study. PloS One 13 (11), e0206479. https://doi.org/10.1371/journal.pone.0206479.

Saharawat, Y.S., Singh, B., Malik, R.K., Ladha, J.K., Gathala, M., Jat, M.L., 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. https://doi.org/10.1016/j.fcr.2010.01.003.

Sapkota, T.B., Khanam, F., Mathivanan, G.P., Vetter, S., Hussain, G., Pilat, A.-L., Shahrin, S., Hossain, K., Sarker, N.R., Krupnik, T.J., 2021. Quantifying opportunities for greenhouse gas emissions mitigation using big data from smallholder crop and livestock farmers across Bangladesh. Sci. Total Environ., 147344 https://doi.org/10.1016/j.scitotenv.2021.147344.

Shahbandeh, M. 2022. World Rice Acreage from 2010 to 2020. Available at ⟨https://www.statista.com/statistics/271969/world-rice-acreage-since-2008⟩ (Accessed on 24 December 2022).

Shahin, S., Jafari, A., Mobli, H., Rafiee, S., Karini, M., 2008. Effect of farm size on energy ratio on wheat production: a case study from Arbadil Province of Iran. Am. Euras. J. Agric. Environ. Sci. 3, 604–608.

Singh, J.M., 2002. On Farm Energy Use Pattern in Different Cropping Systems in Haryana, India. Master of Science. International Institute of Management University of Flensburg, Germany.

Singh, S.K., Bharadwaj, V., Thakur, T.C., Pachauri, S.P., Singh, P.P., Mishra, A.K., 2009. Influence of crop establishment methods on methane emission from rice fields. Curr. Sci. 97, 84–89.

Singh, G., Mishra, D., Singh, K., Parmar, R., 2013. Effect of rainwater harvesting on plant growth, soil water dynamics and herbaceous biomass during rehabilitation of degraded hills in Rajasthan, India. For. Ecol. Manag. 310, 612–622. https://doi.org/10.1016/j.foreco.2013.09.002.

Singh, S., Mittal, J.P., 1992. Energy in Production Agriculture. New Delhi. India.: Mittal. Publ. New Delhi. India. p, 158.

Singh, Y., Singh, G., Johnson, D., Mortimer, M., 2005. Changing from transplanted rice to direct seeding in the rice-wheat cropping system in India. In: Rice is Life: Scientific Perspectives for the 21st Century. Tsukuba, Japan: Proceedings of the World Rice Research Conference, 198-201.

Smartt, A.D., Brye, K.R., Rogers, C.W., Norman, R.J., Gbur, E.E., Hardke, J.T., et al., 2016. Previous crop and cultivar effects on methane emissions from drill-seeded, delayed-flood rice grown on a clay soil. Appl. Environ. Soil Sci. https://doi.org/10.1155/2016/9542361.

Smith, P., Powlson, D., Glendining, M., Smith, J.O., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Glob. Change Biol. 3, 67–79. https://doi.org/10.1046/j.1365-2486.1997.00055.x.

Stehfest, E., Bouwman, L., 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74, 207–228. https://doi.org/10.1007/s10705-006-9000-7.

Susilawati, H.L., Setyanto, P., Kartikawati, R., Sutriadi, M.T., 2019. The opportunity of direct seeding to mitigate greenhouse gas emission from paddy rice field," in IOP Conference Series: Earth and Environmental Science, 393 (Bristol: IOP Publishing), 012042. https://doi.org/10.1088/1755-1315/393/1/012042.

Tao, Y., Chen, Q., Peng, S., Wang, W., Nie, L., 2016. Lower global warming potential and higher yield of wet direct-seeded rice in Central China. Agron. Sustain. Dev. 36, 1–9. https://doi.org/10.1007/s13593-016-0361-2.

Tater, A., Vashisht, B.B., 2024. Long-term effect of crop establishment methods and tillage practices on soil physical properties in rice-wheat system. Commun. Soil. Sci. Plant. Anal. 55 (11), 1613–1628. https://doi.org/10.1080/00103624.2024.2323073.

Timsina, J., Dutta, S., Devkota, K.P., Chakraborty, S., Neupane, R.K., Bista, S., Amgain, L. P., Majumdar, K., 2022. Assessment of nutrient management in major cereals: yield prediction, energy-use efficiency and greenhouse gas emission. Curr. Res. Environ. Sustain. 4, 100147. https://doi.org/10.1016/j.crsust.2022.100147.

Turhan, S., Ozbag, B.C., Rehber, E., 2008. A comparison of energy use in organic and conventional tomato production. J. Food Agric. Environ. 6, 318–321. ⟨https://worldveg.tind.io/record/37731⟩.

Uddin, M.J., Hooda, P.S., Mohiuddin, A.S.M., Smith, M., Waller, M., 2019. Land inundation and cropping intensity influences on organic carbon in the agricultural soils of Bangladesh. Catena 178. https://doi.org/10.1016/j.catena.2019.03.002.

Wang, H., Yang, Y., Zhang, X., Tian, G., 2015. Carbon footprint analysis for mechanization of maize production based on life cycle assessment: a case study in Jilin Province, China. Sustainability 7 (11), 15772–15784. https://doi.org/10.3390/su71115772.

Wang, J., Zhang, X., Xiong, Z., Khalil, M.A.K., Zhao, X., Xie, Y., Xing, G., 2012. Methane emissions from a rice agroecosystem in South China: effects of water regime, straw incorporation and nitrogen fertilizer. Nutr. Cycl. Agroecosyst. 93 (1), 103–112. https://doi.org/10.1007/s10705-012-9503-3.

Wassmann, R., Aulakh, M.S., 2000. The role of plants in regulating mechanisms of methane emissions. Biol. Fert. Soils 31, 20–29. https://doi.org/10.1007/s003740050619.

Wu, J., Xiong, B.B., An, Q.X., Sun, J.S., Wu, H.Q., 2017. Total-factor energy efficiency evaluation of Chinese industry by using two-stage DEA model with shared inputs. Ann. Oper. Res 255, 257–276. https://doi.org/10.1007/s10479-015-1938-x.

Xu, P., Han, Z., Wu, J., Li, Z., Wang, J., Zou, J., 2022b. Emissions of greenhouse gases and NO from rice fields and a peach orchard as affected by N input and land-use conversion. Agronomy 12, 1850. https://doi.org/10.3390/agronomy12081850.

Xu, L., Li, X., Wang, X., Xiong, D., Wang, F., 2019. Comparing the grain yields of direct-seeded and transplanted rice: a meta-analysis. Agronomy 9, 767. https://doi.org/10.3390/agronomy9110767.

Xu, L., Yuan, S., Wang, X., Chen, Z., Li, X., Cao, J., Wang, F., Huang, J., Peng, S., 2022a. Comparison of yield performance between direct-seeded and transplanted double-season rice using ultrashort-duration varieties in central China. Crop J. 10 (2), 515–523. https://doi.org/10.1016/j.cj.2021.07.003.

Yadav, S.N., Chandra, R., Khura, T.K., Chuhan, N.S., 2013. Energy input– output analysis and mechanization status for cultivation of rice and maize crops in Sikkim. Agric. Eng. Int. CIGR J. 15, 108–116.

Yadav, S., Gill, G., Humphreys, E., Kukal, S.S., Walia, U.S., 2011. Effect of water management on dry seeded and puddled transplanted rice. Part 1: crop performance. Field Crops Res. 120 (1), 112–122. https://doi.org/10.1016/j.fcr.2010.09.002.

Yan, X., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Glob. Change Biol. 11, 1131–1141. https://doi.org/10.1111/j.1365-2486.2005.00976.x.

Yang, S., Peng, S., Xu, J., Luo, Y., Li, D., 2012. Methane and nitrous oxide emissions from paddy field as affected by water-saving irrigation. Phys. Chem. Earth Part A/ B/C. 53 30–37. https://doi.org/10.1016/j.pce.2011.08.020.

Yuan, S., Cassman, K.G., Huang, J., Peng, S., Grassini, P., 2019. Can ratoon cropping improve resource use efficiencies and profitability of rice in central China? Field Crops Res 234, 66–72. https://doi.org/10.1016/j.fcr.2019.02.004.

Yuan, S., Peng, S., 2017a. Input-output energy analysis of rice production in different crop management practices in central China. Energy 141, 1124–1132. https://doi.org/10.1016/j.energy.2017.10.007.

Yuan, S., Peng, S., 2017b. Trends in the economic return on energy use and energy use efficiency in China's crop production. Renew. Sustain. Energy Rev. 70, 836–844. https://doi.org/10.1016/j.rser.2016.11.264.

Zhang, C., Hu, R., 2022. Adoption of direct seeding, yield and fertilizer use in rice production: empirical evidence from China. Agriculture 12, 1439. https://doi.org/10.3390/agriculture12091439.

Zhang, H., Liu, H., Hou, D., Zhou, Y., Liu, M., Wang, Z., Liu, L., Gu, J., Yang, J., 2019. The effect of integrative crop management on root growth and methane emission of paddy rice. Crop J. 7 (4), 444–457. https://doi.org/10.1016/j.cj.2018.12.011.

Zheng, H., Ma, W., He, Q., 2024. Climate-smart agricultural practices for enhanced farm productivity, income, resilience, and greenhouse gas mitigation: a comprehensive review. Mitig. Adapt. Strateg. Glob. Change 29, 28. https://doi.org/10.1007/s11027-024-10124-6.

Ziska, L.H., Gealy, D.R., Burgos, N., Caicedo, A.L., Gressel, J., Lawton-Rauh, A.L., Avila, L.A., Theisen, G., Norsworthy, J., Ferrero, A., Vidotto, F., Johnson, D.E., Ferreira, F.G., Marchesan, E., Menezes, V., Cohn, M.A., Linscombe, S., Carmona, L., Tang, R., Merotto, A., 2014. Weedy (red) rice: an emerging constraint to global rice production. Adv. Agron. 181–228. https://doi.org/10.1016/bs.agron.2014.09.003.