

Increase energy use efficiency and economic benefit with reduced environmental footprint in rice production of central China

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Research Article

Keywords: Economic analysis, energy use efficiency, energy input, environmental impact, rice cropping system

Posted Date: February 25th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-232717/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on September 2nd, 2021. See the published version at <https://doi.org/10.1007/s11356-021-16217-y>.

1 **Increase energy use efficiency and economic benefit with reduced environmental**
2 **footprint in rice production of central China**

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17 Journal for submission: Environmental Science and Pollution Research

18

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Abstract

Identifying an energy-efficient system with low energy use, low global warming potential (GWP), and high profitability is essential for ensuring the sustainability of the agro-environment. Given the global importance of China's rice production, this study determines energy, environmental, and economic performances of transplanted (TPR) and direct-seeded rice system (DSR) in central China. The results showed that total energy inputs for TPR and DSR were 31.5 and 22.8 GJ ha⁻¹ across two growing seasons, respectively. Higher energy input for TPR primarily resulted from extra energy use of the nursery beds and transplanting. Higher energy output of DSR (202.5 GJ ha⁻¹) over that of TPR (187.7 GJ ha⁻¹) was due to a slightly higher yield from DSR. Therefore, DSR exhibited significantly higher energy use efficiency than that of TPR. Lower specific energy for DSR (2.78 MJ kg⁻¹) relative to TPR (4.02 MJ kg⁻¹) indicated that the energy used to produce per unit of rice grain could be reduced by 30.8% by adopting DSR. On average, GWP of DSR was reduced by 5.6% compared with TPR. Moreover, DSR had a 55.8% higher gross return and a 25.7% lower production cost than those of TPR. Overall, compared with TPR, DSR has the potential to increase gross economic return and energy output with reduced energy input and emissions. Therefore, this study suggests that DSR is an environmentally-sound and economically-viable production system. As such, DSR is noted as an energy-efficient and climate-smart production system that could be used by policymakers and farmers to achieve not only improvements in the environment but also financial benefits.

Keywords: Economic analysis; energy use efficiency; energy input; environmental impact; rice cropping system

1. Introduction

The agriculture sector has been extensively shown to face a great challenge in producing sufficient food for growing population under the pressures of decreased cropland area, climate change, and the need to protect environment (Gordon et al. 2005; Chen et al. 2020). Notably, energy input, environmental impact, crop productivity, and economic benefit are closely linked in agriculture (Mohammadi et al. 2017; Rautaray et al. 2020). Energy input is critical to agriculture, and it has increased substantially throughout the years in response to growing food demand (Yuan and Peng, 2017a). However, increased agricultural inputs not only cause high financial burdens but affect the economic return to farmers (Pokhrel and Soni 2017; Wu et al. 2017). Agricultural production is a critical source of greenhouse gas (GHG) emissions, accounting for 14-17% of global anthropogenic emissions (Maraseni and Qu 2016; Meena et al. 2017). Intensive energy input in forms of irrigation water, fertilizer, machinery, diesel oil, and pesticides have dramatically increased 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 expenditure and enhancing energy use efficiency (EUE) are crucial to increasing production and minimizing environmental impact (Mohammadi et al. 2014). These concerns are particularly strong for rice production in China.

Rice is one of the most important staple crops in the world; more than half of the global population depends on rice for food (Godfray et al. 2010). China is the largest rice producer and consumer worldwide, accounting for approximately 28% of total global rice production (FAOSTAT 2020). It is forecasted that approximately 60% more rice than the current level will be needed by the year 2025 (Normile 2008). However, there is a growing concern regarding this increase, as rice cultivation is a significant

contributor to climate change because it aggravates global warming potential (GWP) (Groenigen et al. 2013; Thanawong et al. 2014). Therefore, identifying a sustainable rice cultivation system with high crop productivity and reduced energy input and GHG emissions is fundamental for ensuring food and ecological security (Pokhrel and Soni 2017; Coltro et al. 2017; Pittelkow et al. 2014; Maraseni et al. 2018).

Rice is generally grown in transplanted (TPR) or direct-seeded system (DSR). As reported previously, TPR is the dominant rice cropping system in China (Peng et al. 2009). Compared with DSR, TPR requires more inputs, particularly at the time of land preparation and transplanting (Bouman 2009; Farooq et al. 2011), which not only leads to high energy use, and thereby more environmental issues but also reduces economic benefits for farmers (Yuan et al. 2017). Given the advantage of reducing labor inputs (Kumar and Ladha 2011; Pathak et al. 2013), increasing attention has been paid to DSR. It was reported that DSR had a lower energy input and higher EUE than TPR according to data collected from local rice farmers in Iran (Eskandari and Attar 2015). Additionally, GWP of DSR was approximately 68% lower than that of TPR (Tao et al. 2016). A meta-analysis revealed that DSR was an alternative method with yield advantages and higher economic return relative to TPR (Chakraborty et al. 2017). Moreover, it was noted that grain yield of DSR was similar to or higher than TPR with optimized crop management practices (Xu et al. 2019), while reducing emissions (Wang et al. 2017).

However, little information has been paid on the complex linkages among energy use, productivity, emissions, and financial return for DSR and TPR in China. Clearly, an environmentally- and economically-viable cultivation system is needed, and this system must be assessed based on knowledge of their energy, GWP, and profitability. Exploring this interaction can not only fill this knowledge gap in the literature but also

94 provide scientific information for policymakers to promote an energy-efficient system.
95 As such, this study was conducted with the following specific objectives: (i) assessing
96 the energy input and its use efficiency in DSR and TPR, (ii) identifying the
97 environmental and financial performances of DSR and TPR, and (iii) estimating the
98 eco-efficiency difference between DSR and TPR.
99

2. Materials and methods

2.1. Site description

This experiment was conducted in Wuxue County, Hubei Province, China. The site is located at 29°51' N and 115°33' E at an altitude of 23 m ASL (meters above sea level). Hubei Province is located in central China in the basin of the Yangtze River and represents a typical agricultural region in central China. The total arable land in Hubei is 3.4 Mha, of which 2.0 Mha is cultivated with rice crops (Statistical Bureau of Hubei Province 2017). The research field is located in a subtropical monsoon climate region, where summers are hot and rainy and winters are cool and dry. During the last decade, the mean annual rainfall, mean daily solar radiation, and mean annual temperature were 1310 mm, 12.5 MJ m⁻², and 18.1°C, respectively. The monthly distributions of precipitation, solar radiation, and minimum and maximum temperatures in 2014 are depicted in Fig. 1. The soil (0-20 cm) of the experimental site had a clay loam texture with pH of 5.35, organic matter of 22.4 g kg⁻¹, total N of 2.09 g kg⁻¹, available P of 22.2 mg kg⁻¹ and available K of 108.7 mg kg⁻¹.

2.2. Crop management

In this area, rice is grown under both DSR and TPR. To attain overviews of the EUE, GWP, and financial benefit involved in rice production, a replicated field experiment was conducted to study the impact of rice cultivation system on the energy, environmental, and economic performance. The experiment was performed during the early (April to July) and late (July to November) rice-growing seasons in 2014. Six rice varieties that are commonly grown in central China were used during each growing season.

For TPR, pregerminated rice seeds were sown in a nursery, and 30-day-old and 20-day-old rice seedlings were transplanted into well-prepared paddy soil on May 3

and July 29 during the early and late rice-growing seasons, respectively. Three seedlings per hill were transplanted at a hill spacing of 20.0×20.0 cm for both seasons. For DSR, pregerminated seeds were manually and uniformly broadcasted into standing water using the recommended seeding rate of 90 kg ha⁻¹ on April 13 for early-growing season and on July 15 for late-growing season. Chemical fertilizers were applied in accordance with the recommended fertilizer dose for rice production in this area. In this study, 176 kg ha⁻¹ N, 72 kg ha⁻¹ P₂O₅, and 113 kg ha⁻¹ K₂O were applied to the two systems during both growing seasons. Approximately 48% of N, all of P₂O₅, and 40% of K₂O were applied as basal fertilizer. The remaining N was top-dressed in two split doses during middle tillering and panicle initiation stages, and the remaining 60% of K₂O was top-dressed at panicle initiation.

2.3. Energy analysis

The energy analysis presented in this study compared energy input, output, and EUE between DSR and TPR. Energy input was estimated using direct and indirect energy inputs. Direct energy inputs include energy from diesel, water, and labor used in crop production. Indirect energy inputs consist of seed energy and energy used in the production of machinery, fertilizers, and pesticides (Yuan and Peng 2017b). Energy inputs are also classified as renewable and nonrenewable forms. Renewable energy includes labor, seed, and water for irrigation, while nonrenewable energy consists of machinery, fuel, fertilizers, and pesticides (Kazemi et al. 2015).

Energy equivalents shown in **Table S1** were used to estimate input and output energy. All of the inputs used in rice production, including fertilizers, seeds, pesticides, diesel, labor, water, and machinery, were determined and quantified. The grain and straw yield were considered as components of output energy. Energy input and output were calculated by multiplying inputs and outputs with the corresponding energy

equivalents and summation of all corresponding components. Net energy (NE), EUE, specific energy (SE), energy productivity (EP), and energy profitability (EPB) were calculated as follows (Pokhrel and Soni 2017; Lal et al. 2015):

$$\text{Net energy (NE)} = \text{Energy output (GJ ha}^{-1}\text{)} - \text{Energy input (GJ ha}^{-1}\text{)} \quad (1)$$

$$\text{Energy use efficiency (EUE)} = \frac{\text{Energy output (GJ ha}^{-1}\text{)}}{\text{Energy input (GJ ha}^{-1}\text{)}} \quad (2)$$

$$\text{Specific energy (SE)} = \frac{\text{Energy input (MJ ha}^{-1}\text{)}}{\text{Rice yield (kg ha}^{-1}\text{)}} \quad (3)$$

$$\text{Energy productivity (EP)} = \frac{\text{Rice yield (kg ha}^{-1}\text{)}}{\text{Energy input (GJ ha}^{-1}\text{)}} \quad (4)$$

$$\text{Energy profitability (EPB)} = \frac{\text{Net energy (GJ ha}^{-1}\text{)}}{\text{Energy input (GJ ha}^{-1}\text{)}} \quad (5)$$

2.4. Environmental analysis

The environmental impact was assessed by determining GWP. Thus, the total amount of GHG emissions in relation to CO₂-eq was calculated from CO₂, N₂O, and CH₄ released directly and indirectly during rice production. There are three major sources of GHG emissions in rice production: (i) GHGs emissions from production, packaging, and transportation of agricultural inputs, (ii) N₂O emissions due to nitrogen (N) application, and (iii) CH₄ emission from rice paddy field (Yuan et al. 2019). The GHGs emissions from each of agricultural inputs and direct and indirect N₂O emissions due to nitrogen fertilizer application were estimated using emission factors given in **Table S2**. The CH₄ emission from rice cultivation was estimated following 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019), using a daily emission factor of 1.32 kg CH₄ ha⁻¹ day⁻¹, using scaling factors accounting for water regime during rice cultivation period, water regime in the pre-season before rice cultivation, and type and amount of organic amendment applied.

As reported previously (IPCC 2007), N₂O and CH₄ were converted into CO₂-eq using GWP equivalent factors of 298 and 25, respectively, over a 100-year time horizon. The GWP from each system was then calculated by multiplying input by its corresponding CO₂-eq emission factor. Yield-scaled GWP (GWPI; kg CO₂-eq Mg⁻¹ grain), also known as GHG intensity, was calculated as follows:

$$\text{Global warming intensity (GWPI)} = \frac{\text{Global warming potential (kg CO}_2\text{-eq ha}^{-1}\text{)}}{\text{Rice yield (kg ha}^{-1}\text{)}} \quad (6)$$

2.5. Economic analysis

This study applied economic input-output analysis to explore economic benefits in each system. This inventory was similar to that for energy input-output analysis, and the same inputs and outputs per hectare were applied. Production cost and gross return were calculated by multiplying inputs and outputs with the corresponding prices and summation of all corresponding components (**Table S3**). The prices of all the inputs and output were defined by market prices in US\$ that prevailed in 2014. Total production cost and gross return were determined by multiplying inputs and output by the corresponding market price and summation of all the corresponding components, respectively. The net return and benefit-cost ratio were estimated as follows:

$$\text{Net return} = \text{Gross return (US\$ ha}^{-1}\text{)} - \text{Total production cost (US\$ ha}^{-1}\text{)} \quad (7)$$

$$\text{Benefit-cost ratio} = \frac{\text{Gross return (US\$ ha}^{-1}\text{)}}{\text{Total production cost (US\$ ha}^{-1}\text{)}} \quad (8)$$

Additionally, eco-efficiency defined as the ratio of economic benefit to environmental impact was investigated as follows (Kumar et al., 2016):

$$\text{Eco-efficiency} = \frac{\text{Net return (US\$ ha}^{-1}\text{)}}{\text{Global warming potential (kg CO}_2\text{-eq ha}^{-1}\text{)}} \quad (9)$$

2.6. Statistical analysis

Data on the energy, environmental, and economic metrics in the two cultivation

195 systems were subjected to statistical analyses of variance, and means were compared
196 using the least significant difference (LSD) at the 0.05 level of probability. Statistix 8.0
197 (Analytical Software, FL, USA) was used as the statistical software. All the figures
198 were generated by SigmaPlot 12.5 (SPSS Inc., Point Richmond, CA, USA).
199

3. Results and discussion

3.1. Energy analysis

The quantities of agricultural inputs and energy input from each item in DSR and TPR are presented in **Table 1**. It showed that the difference in energy use between the two systems was significant during both seasons. In accordance with previous study (Chaudhary et al. 2017), TPR exhibited higher energy input than DSR in this study. Total energy input in TPR and DSR was 33.2 and 22.7 GJ ha⁻¹ in early-growing season and 29.9 and 23.0 GJ ha⁻¹ in late-growing season, respectively (**Table 1**). Higher energy used under TPR was primarily due to extra energy input for nursery and transplanting, which were reported to be large energy-consuming farm operations (Pathak et al. 2013; Chaudhary et al. 2017). Energy consumption of rice production determined in this study was higher than that in Nepal (Pokhrel and Soni 2017), the Philippines (Quilty et al. 2014), and India (Yadav et al. 2017), but lower than it was in China (Yuan and Peng 2017b), Iran (Nabavi-Pelesaraei et al. 2017), and USA (Pagani et al. 2017).

The results clearly suggested that other than seeds and pesticide, energy input from machinery, diesel, labor, fertilizer, irrigation water, and plastic film were higher in TPR than DSR (**Table 1**). Compared with TPR, higher energy use from pesticide was primarily related to more intensive use of herbicide because of aerobic condition in DSR, which favored weed growth (Eskandari and Attar 2015; Canakci et al. 2005). Moreover, seeding rate for DSR in this area was higher than the recommended (Sun et al. 2015). Thus, there is a room to reduce energy use from seed and herbicide use in DSR by optimizing crop management practices.

As illustrated in **Table 1**, energy input from fertilizer contributed the highest proportion to total energy use, accounting for an average of 53.3% (16.8 GJ ha⁻¹) and 60.5% (13.8 GJ ha⁻¹) in TPR and DSR, respectively. Notably, some studies stated that

fertilizer input was excessive for paddy fields in this area (Peng et al. 2010; Xu et al. 2016). Regarding high energy expenditure from fertilizer, adopting improved nutrient management, such as site-specific nutrient management and integrated soil-crop system management (Peng et al. 2006; Chen et al. 2011), in particular for N fertilizer, is a crucial step towards decreasing total energy input and reducing environmental pollution (Mohammadi et al. 2014; Kazemi et al. 2015). On average, diesel was second in the order of importance and accounted for 20.9% and 17.0% of total energy input in TPR and DSR, respectively (**Table 1**). Next, came irrigation water, which was responsible for an average of 13.5% and 11.2% of total energy input for TPR and DSR, respectively (**Table 1**). Energy from fertilizer, diesel, and irrigation contributed more than 85% to total energy input, which indicated that research could be oriented to reduce energy input from these three major sources.

As shown in **Fig. 2**, indirect and nonrenewable energy was higher than direct and renewable energy, respectively. On average, the share of indirect energy to total energy consumption was 63.2% and 69.7% in TPR and DSR, respectively. The results showed that 17.9% of total energy input in rice production was renewable, while the contribution of nonrenewable energy was 82.1%. These results were in conjunction with previous studies that share of nonrenewable energy was much higher than renewable energy (Singh et al. 2007; Aghaalikhani et al. 2013), which further indicated that rice production was heavily based on nonrenewable energy. It has to be noted that renewable and nonrenewable energy forms in DSR declined by 19.9% and 29.2% compared with TPR, respectively. This finding clearly suggested that DSR can effectively reduce energy consumption, especially for energy from nonrenewable form. This result is helpful for promoting the sustainable development of rice production.

Differences in grain and straw yields were observed between the two cultivation systems and, thus, resulted in different energy outputs (**Fig. 3**). Total energy outputs for TPR vs. DSR were 181.3 vs. 201.6 GJ ha⁻¹ during early-growing season and 194.0 vs. 203.4 GJ ha⁻¹ during late-growing season, respectively (**Fig. 3**). The finding of higher energy output for DSR than TPR in the current study was in contrast with that reported by Eskandari and Attar (2015). Total energy outputs were reportedly 114.7 GJ ha⁻¹ for TPR and 98.7 GJ ha⁻¹ for DSR in Iran. In our study, higher energy output of DSR was due to slightly higher crop yield than TPR (**Fig. 3**). Notably, several previous studies found a positive yield response in DSR based on on-station, on-farm, and farmer household survey studies (Chakraborty et al. 2017; Tabbal et al. 2002; Singh et al. 2001). The yield increase in DSR could be the result of earlier planting to achieve timelier crop establishment than TPR (Quilty et al. 2014).

As a result, the differences in NE, EUE, SE, EP, and EPB between the two systems were significant (**Table 2**). On average, NE and EUE were 156.1 GJ ha⁻¹ and 5.98 in TPR, which were significantly lower than a respective of 179.7 GJ ha⁻¹ and 8.87 in DSR. Higher NE and EUE in DSR were due to higher energy output and lower energy input relative to TPR. A higher EUE in DSR than TPR was also reported by others (Eskandari and Attar 2015). The EUE derived in this study was higher than that reported in many studies (Kazemi et al. 2014; Quilty et al. 2014), but still in the range of 1.5-11.0 for rice determined by Mushtaq et al. (2009) and Pishgar-Komleh et al. (2011). The EP was 362.1 kg GJ⁻¹ in TPR and 251.8 kg GJ⁻¹ in DSR, which suggested that less energy input would be required to produce equal amounts of rice in DSR compared with TPR. More importantly, this further indicated that DSR is an alternative system to reduce energy consumption while meeting food demand amid energy crisis worldwide. Average EPB was 7.87 in DSR, which was 58.0% higher than TPR. By contrast, average SE exhibited

the reverse trend, with TPR showing 44.6% higher SE than DSR. This finding indicated that 1 Mg of rice grain produced by DSR could save 1.2 GJ of energy expenditure as compared with TPR.

3.2. Environmental analysis

In this study, GWP and GWPI were significantly influenced by rice cultivation system during both growing seasons. The DSR emitted an average of 5.0 Mg CO₂-eq ha⁻¹, compared with 5.4 Mg CO₂-eq ha⁻¹ in TPR (**Table 3**). A 5.6% lower GWP in DSR was mainly due to lower emissions from agricultural inputs (including N₂O from nitrogen application), though CH₄ emissions from DSR were higher due to longer crop growth duration in the main field as compared with TPR. The environmental impact was also expressed per mass of rice grain produced in this study. On average, GWPI was 618 kg CO₂-eq Mg⁻¹ grain in DSR, which was slightly lower than that of 684 kg CO₂-eq Mg⁻¹ grain in TPR (**Fig. 4**). Lower GWPI in DSR was mainly due to decreased GWP as compared with TPR.

Across growing seasons and cultivation systems, GWP from in-season CH₄ emissions contributed between 56-66% to total GWP, which was in accordance with several previous studies showing that CH₄ accounted for the majority of GWP from rice production (Groenigen et al. 2013; Kumar et al. 2016), suggesting the importance of mitigating CH₄ emissions from rice production. CH₄ emissions are impacted by such several factors as water management, application of inorganic and organic fertilizers, rice cultivars, and properties of paddy soil (Gutierrez et al. 2013). This study indicated that more attention should be paid on determining the role played by these factors in CH₄ emission under TPR and DSR conditions with the goal of reducing GWP. The results also implied that agricultural inputs such as N fertilizer and diesel were principal sources of CO₂ and/or N₂O emissions (Mohammadi et al. 2014; Chaudhary et al. 2017).

Thus, reducing fertilizer and diesel consumptions through increasing N use efficiency and mechanical efficiency are critical for both transplanting and direct-seeding rice. Overall, the results of environmental analysis indicated that DSR could be an important approach reducing GWP from rice farming.

3.3. Economic analysis

The economic input and output of rice production under DSR and TPR are shown in **Table 4**. The results revealed that the differences in total production cost, gross return, net return, and benefit-to-cost ratio were significantly different between the two systems during both growing seasons. Based on the average of two seasons, DSR reduced total production cost by 25.7%, corresponding to 504.3 US\$ ha⁻¹ (**Table 4**). The costs of production estimated in our study were similar to those reported for rice production in China by other studies (Chen and Chen 2011; Liu et al. 2014). Lower production cost for DSR was primarily due to lower cost of machinery, diesel, and labor due to the omit of transplanting relative to TPR. A slightly higher gross return of 140.8 US\$ ha⁻¹ in DSR than TPR was observed in our study.

As a result, average net return for DSR (1800.3 US\$ ha⁻¹) was 55.8% higher than that of TPR (1155.2 US\$ ha⁻¹) (**Table 4**). In this study, higher net return for DSR mainly resulted from its lower production cost compared to TPR. This was in line with result that the financial benefit of DSR (1568.6 US\$ ha⁻¹) was 49.5% higher than TPR determined by Chi et al. (2008). A significantly higher benefit-to-cost ratio was also found in DSR (2.13 and 2.36 in early- and late-growing season, respectively) than in TPR (1.47 and 1.72). As one of the major financial indicators, benefit-to-cost ratio has been well-documented in the literature, and it was reported to range from 0.8 to 3.1 for rice production (Pokhrel and Soni 2017; Gathala et al. 2015). Higher net return and benefit-to-cost ratio of DSR may explain the gradual transition from TPR to DSR

occurred in China.

In this study, eco-efficiency was estimated as represented by the ratio of product or service value to the corresponding environmental cost. DSR valued each Mg of CO₂-eq emitted a respective US\$ 329 and 381 in early- and late-growing season, which was significantly higher than US\$ 182 and 250 per Mg of CO₂-eq under TPR in early and late-growing season, respectively (**Fig. 4**). This finding implied that an average of around US\$ 140 more was obtained from one Mg of CO₂-eq emissions in DSR than TPR. Clearly, DSR was an eco-efficient cultivation system. Eco-efficiency estimated in this study was higher than US\$ 82-134 per Mg of CO₂-eq reported in northeastern Thailand due to lower yield and higher GWP in that study (Thanawong et al. 2014), but lower than an average of 720 US\$ per ton of CO₂-eq across various rice-based cropping systems in Nepal (Pokhrel and Soni 2017). The disparity indicated that the economic return per unit of GHGs emissions could be further improved by innovating cropping systems.

Scaling up of this eco-efficient technology can be realized by issuing policies. The government could place more emphasis on providing farmers with information on DSR technology through increasing investments in farmers' training and education. On the one hand, prioritizing R&D programs for DSR research plays an important role in solving constraints occurred presently and developing advanced agricultural technology, including reducing fossil energy input, increasing the usage of renewable energy, and improving the efficiency of agricultural machinery. On the other hand, researcher and agricultural extension staff should work together to help farmers adopt existing crop management practices and further optimize farming operations of DSR in agricultural fields to reduce external inputs with the goals of reducing energy use and environmental impact.

Overall, direct-seeded rice has a potential decreasing energy input and emissions while increasing economic return, without sacrificing productivity and energy output. There are still constraints for DSR adoption including (a) poor crop establishment due to a range of abiotic stresses, especially low temperature, drought, and waterlogging, (b) high weed infestation especially in dry field conditions, and (c) lodging associated with decreased breaking resistance of the rice internode due to high plant density (Wang et al. 2017). Likewise, while this research was conducted in two growing seasons in a year, future studies may be oriented to advance our understanding of how food-energy-emission nexus perform of DSR and TPR in multiple environments. From the perspective of energy-saving and production cost-reducing as well as emission-mitigation, DSR technology holds very good promise to increase energy use efficiency and economic benefit with reduced environmental impact in the context of energy crisis and environment degradation. Therefore, findings derived from the current study are relevant for other lowland rice systems in the world, especially in regions with high production cost and substantial resources inputs.

4. Conclusions

The aim of this study was to identify a sustainable rice cultivation system using energy, environmental, and financial analyses. Energy input was higher in TPR than DSR, which demonstrated that adopting DSR was an effective way to reduce energy expenditure, especially for nonrenewable energy. Given higher energy output of DSR than TPR, NE, EUE, and EP increased significantly in DSR over TPR. Lower SE for DSR indicated that the energy used to produce one unit of grain can be reduced by 30.8% by DSR compared with TPR. The environmental analysis showed that GWP and GWPI were both lower in DSR than TPR. This result revealed that DSR was a clean production technology and a promising system to reduce emissions from rice production. Moreover, lower production cost and higher gross return indicated that DSR was an economically sound system. This result was also confirmed by the evaluation of eco-efficiency, which noted DSR as an eco-efficient system. Adopting DSR may help rice-producing farmers with limited agricultural inputs to reduce production cost without compromising productivity and energy out.

Acknowledgments

We thank Canjin Zhou, Hantang Liu, and Xing Yu for help with conducting the field experiments and their technological supports. This work was supported by the Earmarked Fund for China Agriculture Research System (CARS-01-20), Program for Changjiang Scholars and Innovative Research Team in University of China (IRT1247), the National Key Research and Development Program of China (2017YFD0300101), China Scholarship Council (Grant 201706760015), and China Postdoctoral Science Foundation (2020M682439). The authors have no relevant financial or non-financial interests to disclose.

Declarations

- **Ethics approval and consent to participate**

Not applicable

- **Consent for publication**

Not applicable

- **Availability of data and materials**

Data analyzed during this study are included in this published article [and its supplementary information files]. Any other data used during the current study are available from the corresponding author on reasonable request.

- **Competing interests**

The authors declare that they have no competing interests.

- **Funding**

Earmarked Fund for China Agriculture Research System (CARS-01-20), Program for Changjiang Scholars and Innovative Research Team in University of China (IRT1247), the National Key Research and Development Program of China (2017YFD0300101), China Scholarship Council (Grant 201706760015), and China Postdoctoral Science Foundation (2020M682439).

- **Authors' contributions**

SP, SY, and XZ designed the project. SY and XZ carried out the field experiments. SY, SP, LX, and XL analyzed the data. SY and SP wrote the paper. All authors reviewed and approved the final manuscript.

- **Acknowledgements**

We thank Canjin Zhou, Hantang Liu, and Xing Yu for help with conducting the field experiments and their technological supports. This work was supported by the Earmarked Fund for China Agriculture Research System (CARS-01-20), Program for

416 Changjiang Scholars and Innovative Research Team in University of China (IRT1247),
417 the National Key Research and Development Program of China (2017YFD0300101),
418 China Scholarship Council (Grant 201706760015), and China Postdoctoral Science
419 Foundation (2020M682439). The authors have no relevant financial or non-financial
420 interests to disclose.
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Table 1 *Agricultural and energy inputs in transplanted and direct-seeded rice cultivation systems during early- and late-growing seasons.*

Particulars	Unit	Early-growing season				Late-growing season			
		Transplanted		Direct-seeded		Transplanted		Direct-seeded	
		Quantity ha ⁻¹	Energy MJ ha ⁻¹	Quantity ha ⁻¹	Energy MJ ha ⁻¹	Quantity ha ⁻¹	Energy MJ ha ⁻¹	Quantity ha ⁻¹	Energy MJ ha ⁻¹
1. Human labor	h	397.0	778.1	214.5	420.4	367.0	719.3	200.5	393.0
2. Diesel	l	116.8	6574.2	69.0	3885.4	116.8	6574.2	69.0	3885.4
3. Chemical fertilizers									
(a) Nitrogen (N)	kg	226.0	14947.6	176.0	11640.6	216.0	14286.2	176.0	11640.6
(b) Phosphorus (P ₂ O ₅)	kg	72.0	895.7	72.0	895.7	72.0	895.7	72.0	895.7
(c) Potassium (K ₂ O)	kg	113.0	1260.0	113.0	1260.0	113.0	1260.0	113.0	1260.0
4. Pesticides									
(a) Herbicides	kg	0.5	123.8	0.9	214.2	0.3	71.4	0.7	166.6
(b) Insecticides	kg	0.5	45.5	0.4	40.5	0.3	28.3	0.2	20.2
(c) Fungicides	kg	0.3	56.2	0.3	56.2	0.1	30.2	0.1	30.2
5. Water	m ³	3600.2	3672.2	2300.0	2346.0	4687.6	4781.4	2700.0	2754.0
6. Plastic film	kg	45.0	3555.0	0.0	0.0	0.0	0.0	0.0	0.0
7. Machinery	kg	12.9	882.3	8.8	601.1	12.9	882.3	8.8	601.1
8. Seed	kg	25.0	367.5	90.0	1323.0	25.0	367.5	90.0	1323.0
Total input			33158.0		22683.0		29896.5		22969.8

Table 2 *Input-output energy analysis for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- and late-growing seasons.*

Growing season	Cultivation system	Net energy GJ ha ⁻¹	Energy use efficiency GJ GJ ⁻¹	Specific energy MJ kg ⁻¹	Energy productivity kg GJ ⁻¹	Energy profitability GJ GJ ⁻¹
Early	TPR	148.2 b	5.47 b	4.32 a	232.1 b	4.47 b
	DSR	178.9 a	8.89 a	2.78 b	361.1 a	7.89 a
Late	TPR	164.1 b	6.49 b	3.71 a	271.6 b	5.49 b
	DSR	180.4 a	8.86 a	2.78 b	363.0 a	7.86 a

Within a column in a growing season, the means followed by different letters indicate statistical significance at $p < 0.05$ according to the least significant difference (LSD)_{0.05}.

Table 3 Global warming potential expressed in CO₂-eq from methane, nitrous oxide, and agricultural inputs (including diesel, fertilizers, machinery, and pesticides) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- and late-growing seasons.

Emission sources	Early-growing season kg CO ₂ -eq ha ⁻¹		Late-growing season kg CO ₂ -eq ha ⁻¹	
	TPR	DSR	TPR	DSR
1. Methane	3005.9	3449.3	3075.7	3219.7
2. Nitrous oxide	1458.4	1135.7	1393.8	1135.7
3. Agricultural inputs				
(a) Diesel	489.8	289.5	489.8	289.5
(b) Fertilizer	336.5	269.0	323.0	269.0
(c) Machinery	62.6	42.7	62.6	42.7
(d) Pesticides	6.6	8.7	3.9	6.0
Total	5359.8 a	5194.9 b	5348.8 a	4962.6 b

Within a row in a growing season, the means followed by different letters indicate statistical significance at $p < 0.05$ according to the least significant difference (LSD)_{0.05}.

Table 4 Cost of production, gross return, net economic return, and benefit-to-cost ratio for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- and late-growing seasons.

Growing season	Cultivation system	Production cost US\$ ha ⁻¹	Gross return US\$ ha ⁻¹	Net return US\$ ha ⁻¹	Benefit-to-cost ratio
Early	TPR	2057.4 a	3031.5 b	974.1 b	1.47 b
	DSR	1517.0 b	3226.8 a	1709.8 a	2.13 a
Late	TPR	1862.3 a	3198.6 b	1336.3 b	1.72 b
	DSR	1394.3 b	3285.0 a	1890.7 a	2.36 a

Within a column in a growing season, the means followed by different letters indicate statistical significance at $p < 0.05$ according to the least significant difference (LSD)_{0.05}.

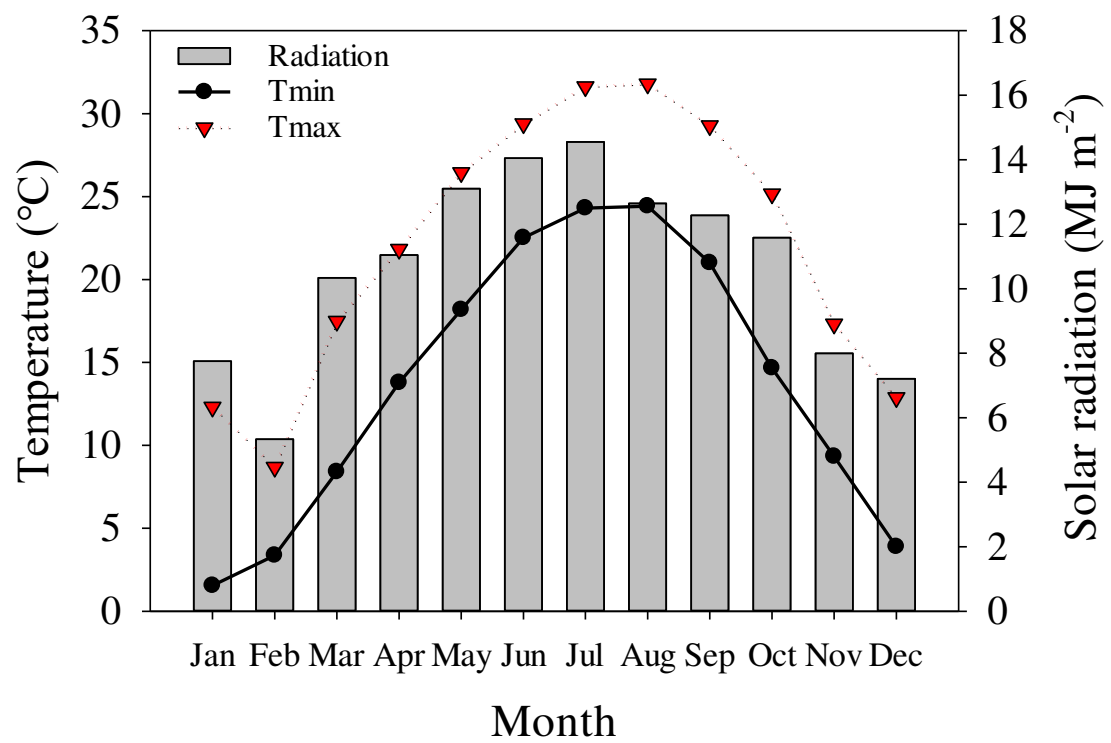


Figure 1. The monthly minimum (*Tmin*) and maximum (*Tmax*) temperatures and solar radiation (*Radiation*) in the experimental site in 2014.

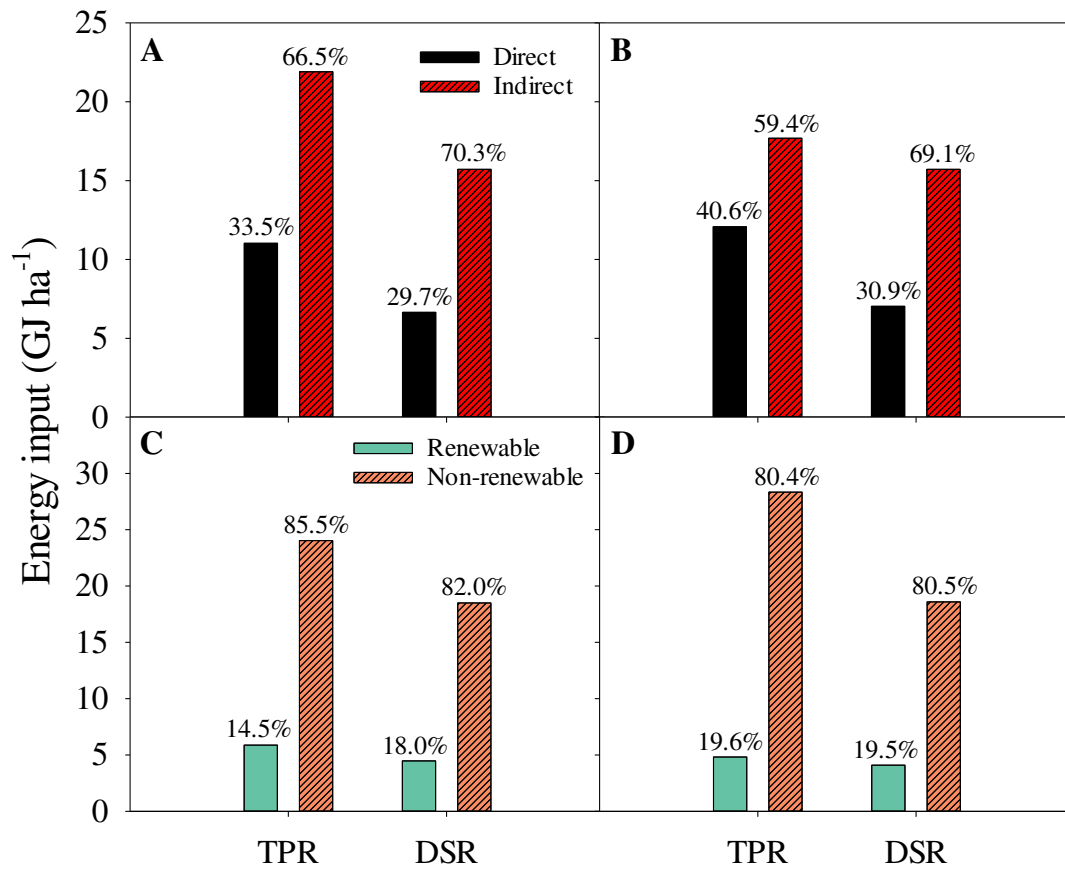


Figure 2. Direct and indirect energy input (A and B, GJ ha⁻¹) and renewable and non-renewable energy input (C and D, GJ ha⁻¹) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D).

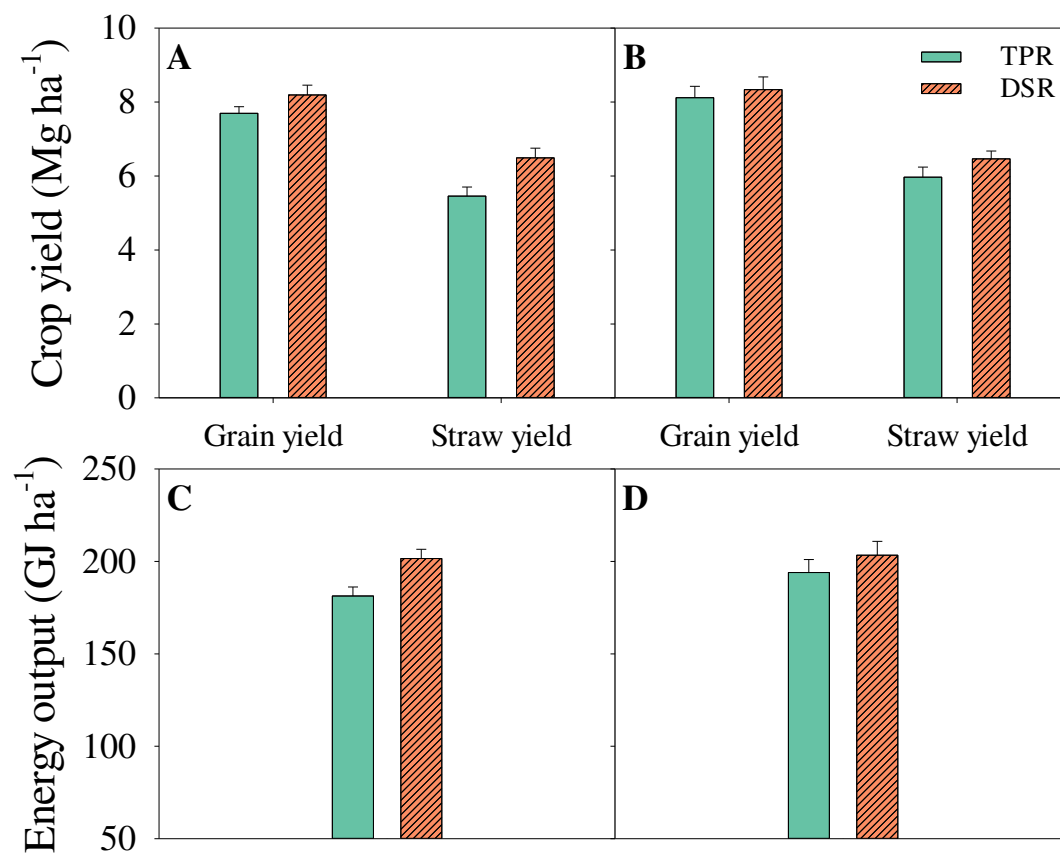


Figure 3. Rice grain and straw yield (A and B, Mg ha⁻¹) and energy output (C and D, GJ ha⁻¹) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D). Data are means \pm standard error.

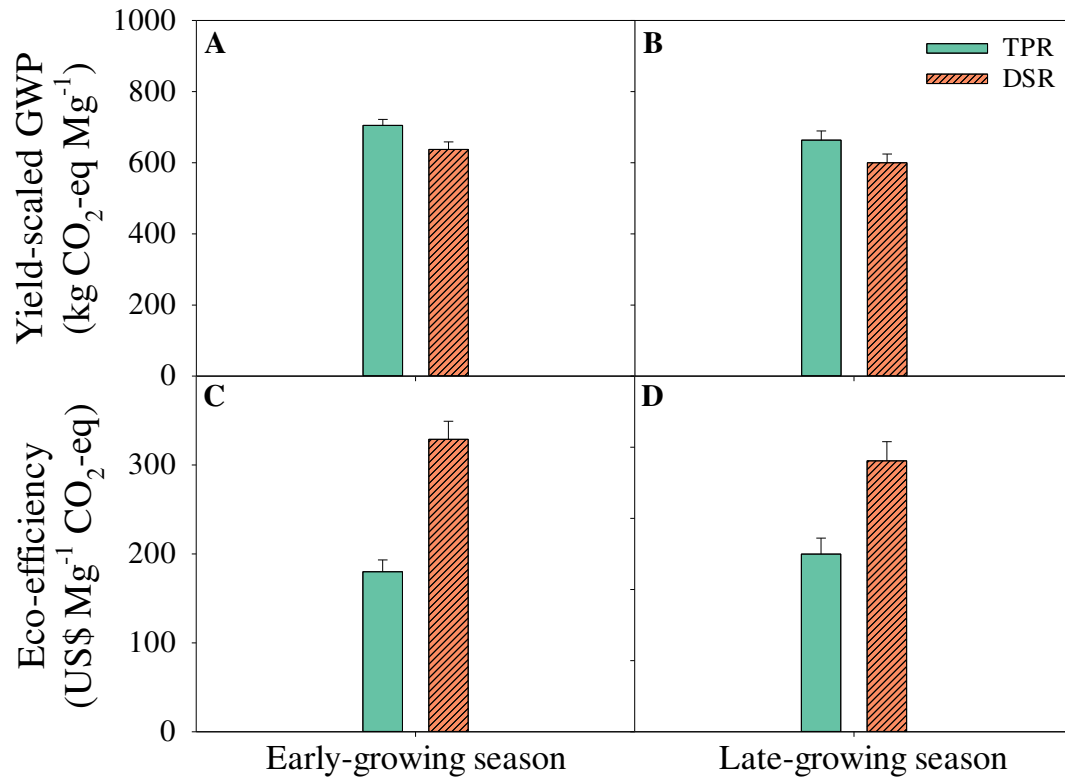


Figure 4. Yield-scaled global warming potential (A and B, kg CO₂-eq Mg⁻¹ grain) and eco-efficiency (C and D, US\$ Mg⁻¹ CO₂-eq) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D). Data are means \pm standard error.

Figures

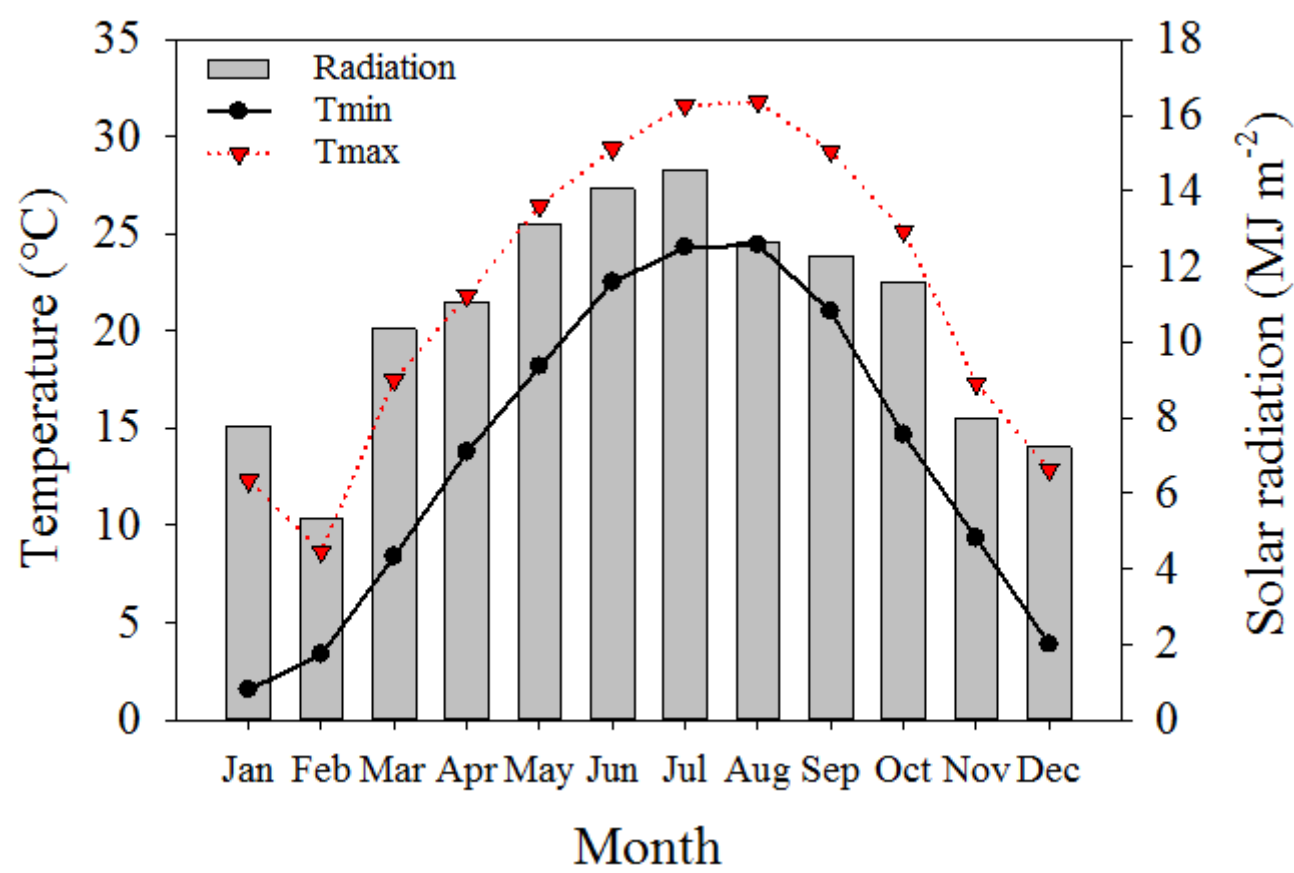


Figure 1

The monthly minimum (Tmin) and maximum (Tmax) temperatures and solar radiation (Radiation) in the experimental site in 2014.

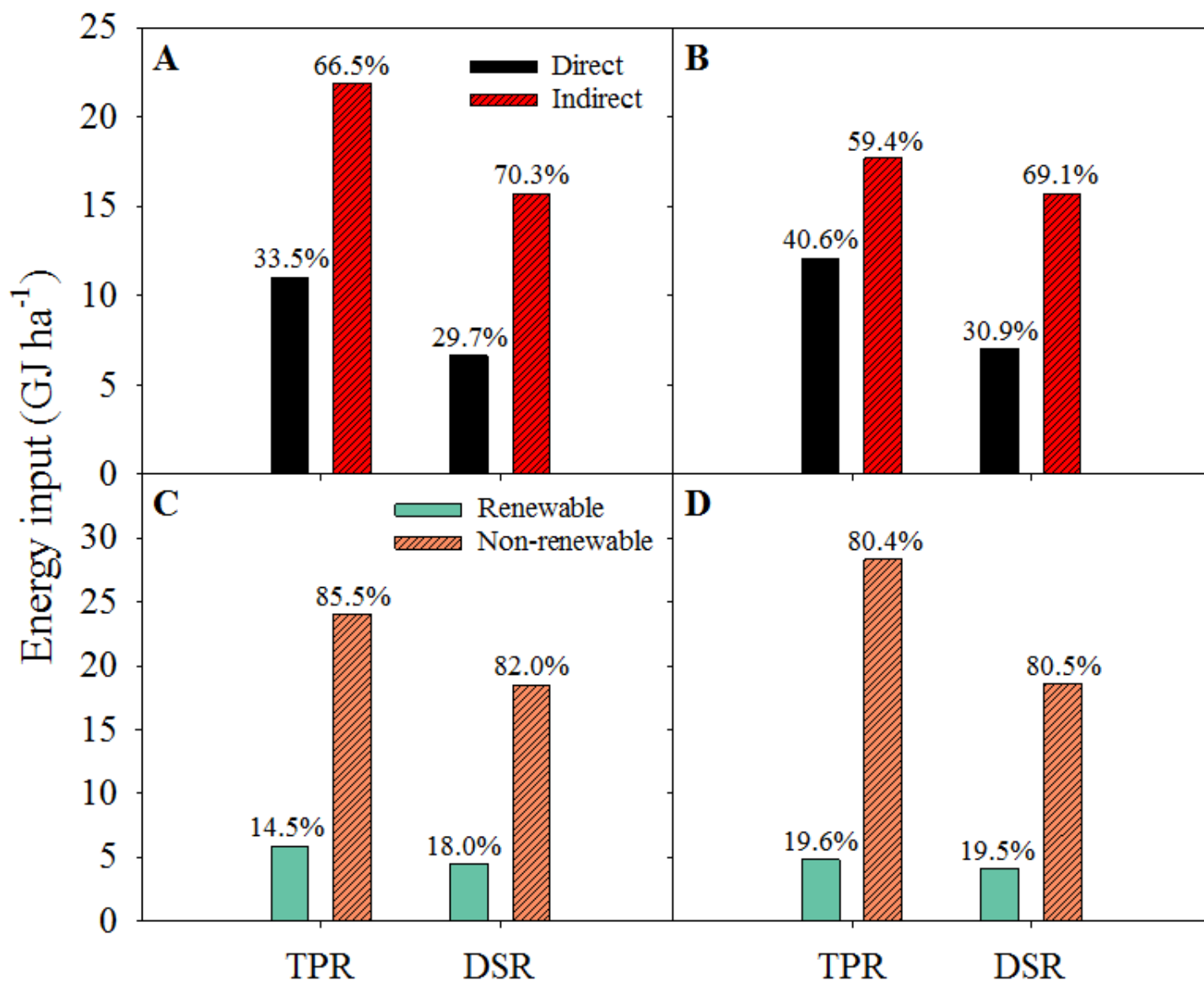


Figure 2

Direct and indirect energy input (A and B, GJ ha⁻¹) and renewable and non-renewable energy input (C and D, GJ ha⁻¹) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D).

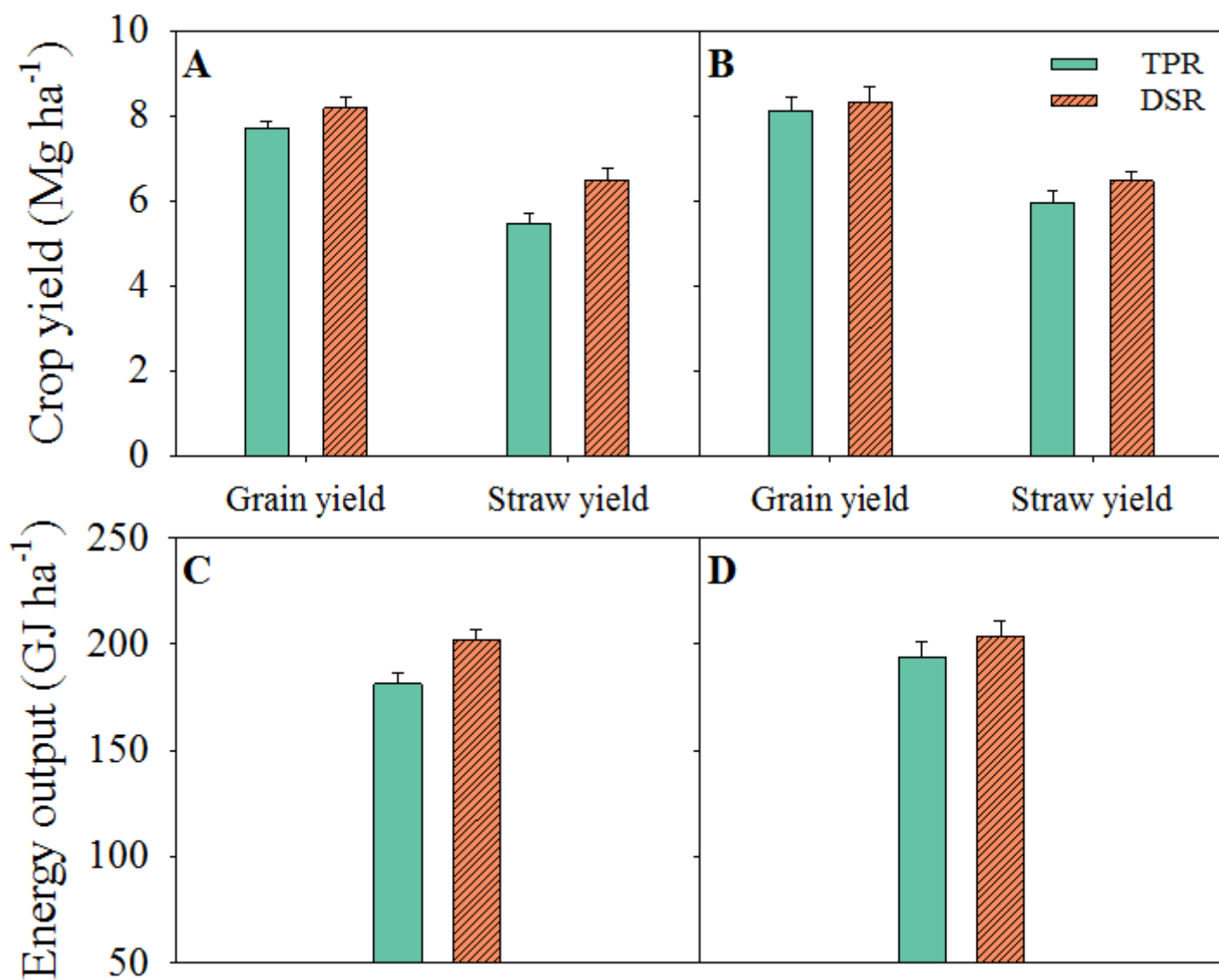


Figure 3

Rice grain and straw yield (A and B, Mg ha⁻¹) and energy output (C and D, GJ ha⁻¹) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D). Data are means \pm standard error.

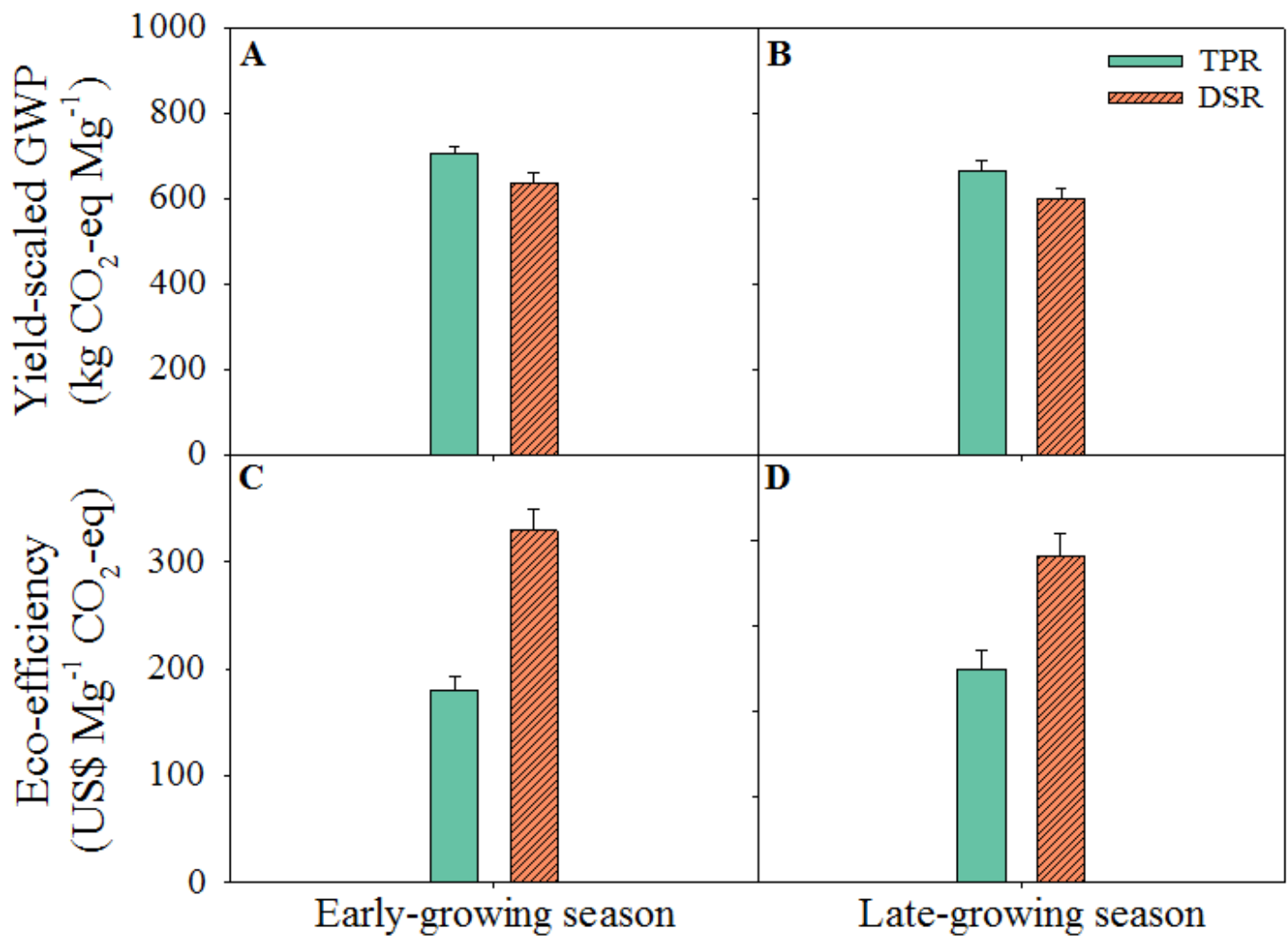


Figure 4

Yield-scaled global warming potential (A and B, kg CO₂-eq Mg⁻¹ grain) and eco-efficiency (C and D, US\$ Mg⁻¹ CO₂-eq) for transplanted (TPR) and direct-seeded (DSR) rice cultivation systems during early- (A and C) and late-growing seasons (B and D). Data are means ± standard error.

Supplementary Files

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