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Research Progress and the Limiting Factors of Direct Seeding Rice in Central China

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Abstract

Replacement of puddled transplanted rice (PTR) by direct-seeded rice (DSR) can potentially reduce consumption of resources and decrease emissions of greenhouse gases while maintaining grain yields in central China. However, direct seeding has not been widely adopted in this region. This review was undertaken to better understand the problems and opportunities for replacing PTR with DSR in central China. The seeding rate, crop growth, grain yield, water productivity, nitrogen use efficiency, greenhouse gas emissions and root development were compared between DSR and PTR. With good water management, grain yield of DSR is similar to or higher than that of PTR while increasing irrigation water productivity and nitrogen use efficiency, reducing greenhouse gas emissions, and decreasing labor requirement. However, problems that include lodging, weak root development, weed infestations and poor crop establishment under drought, waterlogging, or chilling stresses might limit wide-scale adoption of DSR in central China. Varieties bred and selected for direct seeding, guidelines for improved nutrition, water, and weed management practices, and the development of suitable planting machines and sowing management for DSR are needed. In addition, incorporating DSR into the double season rice systems could be promising strategies to increase rice production in central China.

1. Introduction

Rice (Oryza sativa L.) is the staple food for more than half of the world's population, especially in tropical Latin America and East, South and Southeast Asia (Seck *et al*., 2012). Transplanting is the major rice establishment method and 77% of rice is transplanted globally (Rao *et al*., 2007). In China, 95% of the rice is produced under puddled transplanted conditions with prolonged periods of flooding (Peng *et al*., 2009). However, several problems such as labor shortage, water scarcity and climate change, have severely limited the development of puddled transplanted rice (PTR) in China. Under PTR, large quantities of water are consumed during land preparation and farming process (Bouman, 2009), and most of the water is wasted through surface evaporation and percolation, thus resulting in low water use efficiency (Farooq *et al*., 2011). PTR is considered to be one of the major sources of greenhouse gas emissions in agricultural production systems. It has been reported that rice paddies contribute 11% of global total anthropogenic CH4 emissions (Smith *et al*., 2007). Furthermore, the process of conventional transplanting has a large labor cost, with the labor shortage in China. Taking the disadvantages of high demands of resources and high greenhouse gas emission, PTR is no longer suitable for the sustainable development, and there is a trend that PTR needs to be replaced by mechanized and simplified intensive rice production methods.

Direct seeding rice (DSR), which refers to the process of directly sown the seeds into soil rather than transplanting seedlings in a puddled PTR field (Liu *et al*., 2015), has emerged as an alternative option to PTR. DSR is becoming popular nowadays because of less water consumption, reduced labor intensity, facilitating to mechanization during crop establishment, and less methane emission (Pathak *et al*., 2011). Besides, DSR can be sown under zero tillage (Rao *et al*., 2007), and incorporating DSR into zero tillage planting would largely increase resource use efficiency while simultaneously reduce soil erosion, improve soil properties, and conserve soil moisture (Chauhan *et al*., 2006). The following direct-seeding methods have been suggested for rice in China: (1) dry direct-seeded rice (DDSR), in which dry rice seeds are drilled or broadcasted on non-puddled soil after dry tillage, zero tillage, or on a raised bed, and (2) wet direct-seeded rice (WDSR), in which dry seeds or sprouted rice seeds are broadcast or sown in lines on wet and puddled soil. Another principal method of direct-seeded rice is water seeding, in which sprouted rice seeds are broadcast in soil withstanding water (Kumar and Ladha 2011). Previous studies have compared the variances between different types of direct-seeded rice and traditional transplanted rice for yield, water use efficiency, and establishment methods. Generally, the yield performance of dry direct-seeded rice and wet direct-seeded rice was close to the yield of traditional transplanted rice (Mitchell *et al*. 2004; Rickman *et al*. 2001). Meanwhile, direct-seeded rice required lower irrigation water due to fewer continuous flooded days in the main field and less water use during land preparation compared with traditional transplanted rice. Zhao *et al*. (2007) documented higher grain yields and lower water use for dry direct-seeded rice compared with transplanted rice. In order to evaluate the possibility of replacing PTR with DSR in Central China, present study reviewed the research progress and the limiting factors of direct seeding rice in central China.

2. Effects of pre-sowing seed treatments on seed germination and early seedling growth of direct-seeded rice under drought, water-logging, and chilling stresses.

In central China, poor and uneven crop establishment severely limited the large scale adoption of DSR. After direct sowing, the rice seeds were easily suffered from abiotic stresses, such as chilling, drought, and waterlogging in Central China (Ma *et al*., 2011; Miro and Ismail, 2013). Abiotic stresses delayed or reduced the process of rice seed germination, inhibit the root development and shoot elongation, result in poor and uneven establishment, and finally cause yield decline (Sipaseuth *et al*., 2007; Guan *et al*., 2009). Nevertheless, pre-sowing seed treatments, such as seed coating, seed priming and seed pelleting could improve the seed germination and seedling vigor particularly under unfavorable environmental conditions (Farooq *et al*., 2006). In order to improve crop establishment of DSR, the effects of different pre-sowing seed treatments on seed emergence, seedling growth were examined under various stress condition (**Fig. 1**). The metabolic events associated with seed germination and stress resistance were also incorporated (Zheng *et al*., 2016; Hussain *et al*., 2016a; Hussain *et al*., 2016b; Wang *et al*., 2016). The results revealed that seed priming were effective in promoting seed germination, enhancing seedling growth of DSR under chilling (Hussain *et al*., 2016a; Wang *et al*., 2016), drought (Zheng *et al*., 2016), and waterlogging stresses (Hussain *et al*., 2016b). The positive effects of seed priming treatments on

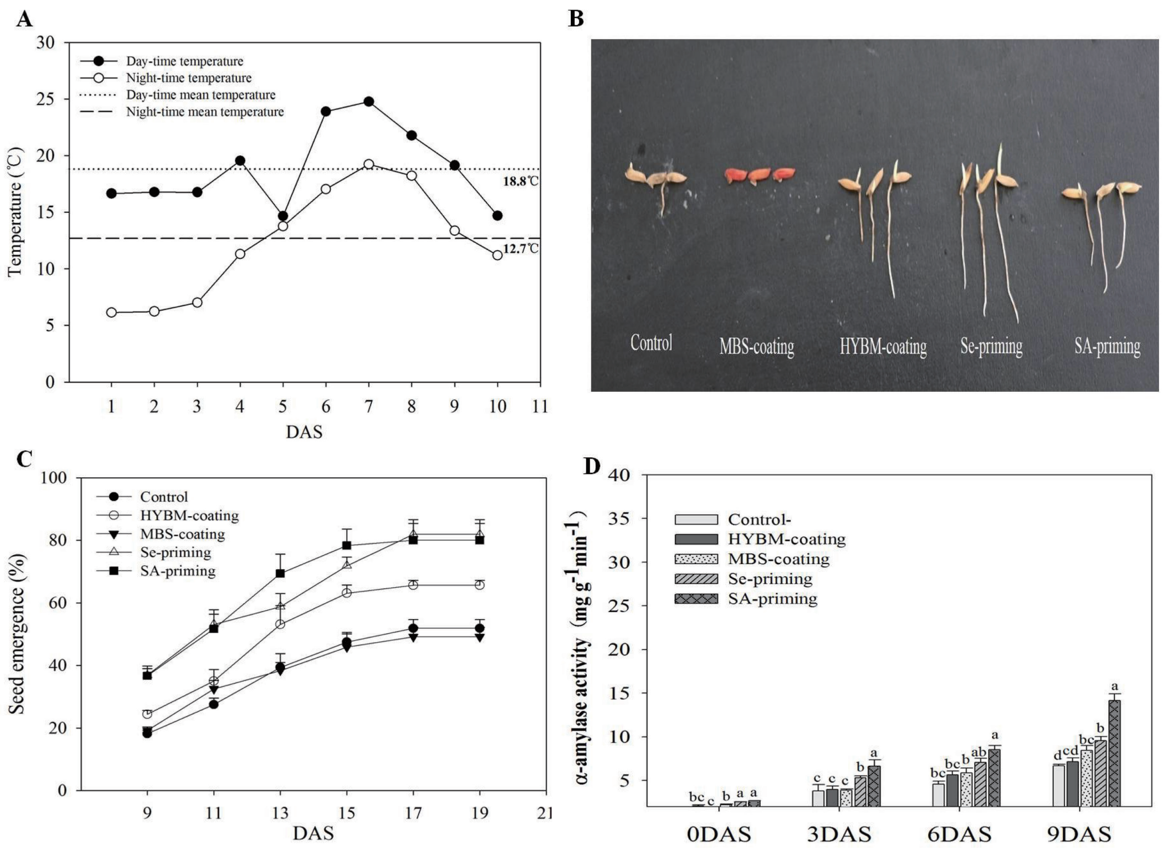

Fig. 1. Effect of pre-sowing seed treatments on seed germination and seedling growth of direct-seeded rice under abiotic stress. A: Air temperatures during seed germination. B: Pictorial illustration of seed germination with pre-sowing seed treatments under chilling stress. C: Germination dynamics of treated and non-treated seeds of rice. D: Variations in α-amylase activity of rice seeds and seedlings with different pre-sowing seed treatments at 0, 3, 6, and 9 DAS.

enhancement of stress tolerance were associated with vigorous starch metabolism, increased respiration rate, better membrane integrity, and the enhanced antioxidant system in the primed seeds and seedlings.

3. Estimation of optimum seeding rate for hybrid rice varieties in direct-seeded rice.

Hybrid rice varieties possess the potential to grow under dry direct seeded rice (DDSR) system and can perform well even at low sowing rate. Present study investigated the yield responses of three hybrid rice varieties to different sowing rates and explored the physiological basis for grain yield formation under DDSR system. An inbred rice variety was grown as control. Results showed that reducing sowing rates of hybrid rice varieties from 240 seeds m^{-2} to 90 seeds m^{-2} did not reduce grain yield, while that of inbred rice varieties declined with decreasing sowing rates. Decreased sowing rates of inbred rice varieties recorded insufficient tillers, and lower panicle number that decreased their yield (**Table 1**). Contrarily, for hybrid rice varieties grain yield was maintained even at reduced sowing rate because of their enhanced tillering capacity, higher specific leaf weight (SLW), and increased spikelet number per panicle (SPP), which might have compensated the reduced sowing rate. Our results suggested that the sowing rate of hybrid rice varieties can be reduced to 90 seeds m^{-2} without compensating yield of DDSR. However, adversities of low sowing rate in DDSR like weeds and poor stand establishment should be overcome to achieve maximum crop yield.

4. Comparisons of rice yields and resource use efficiencies among different rice planting methods.

In central China, the rice yields and resource use efficiencies among different rice planting methods were compared (**Fig. 2**). The grain yield in DSR was significantly influenced by water management. In WDSR, the grain yields were in the range of 9.50-11.59 t ha^{-1}, which was comparable to the grain yields in PTR. However, significant yield reductions were observed in DDSR compared with PTR. When averaged across years, the grain yield in DDSR was 9.47 t ha^{-1}, which was 2.9% lower than that in PTR (**Table 2**).

Table 1. Yield and its components of four rice varieties under three sowing rates.

Variety	Sowing rate (seeds m^{-2})	Yield (t ha^{-1})	Panicles (m^{-2})	Spikelets $panicle^{-1}$	Spikelets m^{-2} ($\times 10^3$)	Grain filling (%)	1000-GW (g)
HHZ	90	8.64 c	272 b	173.8 a	47.0 b	85.5 a	18.4 c
	150	9.07 b	316 ab	161.4 ab	50.5 ab	87.3 a	18.8 b
	240	9.48 a	333 a	154.8 b	51.6 a	86.8 a	19.2 a
FLYX1	90	8.81 a	247 a	167.8 a	38.6 a	86.0 b	22.7 c
	150	8.77 a	261 a	147.9 ab	38.4 a	89.5 a	23.5 b
	240	8.58 a	269 a	133.0 b	34.3 a	88.5 ab	24.2 a
YLY6	90	9.93 a	253 a	174.4 a	43.3 a	83.8 a	26.0 b
	150	10.23 a	254 a	158.3 b	40.1 ab	82.4 a	26.2 b
	240	10.29 a	279 a	134.7 c	38.8 b	80.9 a	27.0 a
YLY1	90	10.21 a	271 b	176.3 a	47.8 a	83.8 a	23.2 b
	150	10.44 a	281 ab	163.4 ab	46.1 a	83.1 a	23.5 ab
	240	10.33 a	298 a	153.4 b	45.4 a	83.7 a	23.8 a

Within a column for each cultivar, means followed by the different letters are significantly different from each other according to LSD (0.05). Inbred rice variety: HHZ (Huanghuazhan); hybrid rice varieties: FLYX1 (Fengliangyouxiang1), YLY6 (Yangliangyou6), YLY1 (Y-liangyou1). ns denotes non-significance based on analysis of variance.

Table 2. Grain yield and yield components of the four rice cultivars under dry direct-seeded rice (DDSR), wet direct-seeded rice (WDSR), and puddled transplanted rice (PTR).

Variety	Establishment methods	Yield (t ha^{-1})	Spikelets ($m^{-2} \times 10^3$)	Panicles (m^{-2})	Spikelets $panicle^{-1}$	Grain filling (%)	1000-GW (g)
HHZ	DDSR	8.59 b	50.48 a	390 b	129.4 a	77.5 b	20.1 b
	WDSR	9.50 a	53.63 a	485 a	110.6 b	81.6 a	20.6 a
	PTR	8.63 b	41.36 b	309 c	133.9 a	83.8 b	20.8 a
LDQ7	DDSR	8.99 b	40.09 a	289 b	138.8 a	84.4 a	24.8 a
	WDSR	10.09 a	43.23 a	355 a	122.9 a	86.6 a	24.0 a
	PTR	9.07 b	35.07 b	260 b	135.5 a	86.4 a	24.6 a
YLY6	DDSR	10.60 b	38.30 b	291 ab	132.8 a	88.5 a	28.3 a
	WDSR	11.59 a	42.63 a	344 a	124.4 a	86.4 a	27.7 a
	PTR	9.54 c	35.29 c	256 b	138.2 a	87.6 a	28.1 a
YLY1	DDSR	9.69 b	39.77 b	345 a	150.2 b	83.0 a	25.8 a
	WDSR	10.65 a	46.72 a	397 a	149.1 b	83.8 a	24.1 b
	PTR	9.55 b	35.92 b	291 b	183.1 a	86.6 a	25.9 a

Note:Means followed by the different lowercase letters are significantly different from each other within the group according to LSD (0.05). Inbred rice varieties: HHZ (Huanghuazhan), LDQ7 (LvdaoQ7); hybrid rice varieties: YLY6 (Yangliangyou6), YLY1 (Yliangyou1).

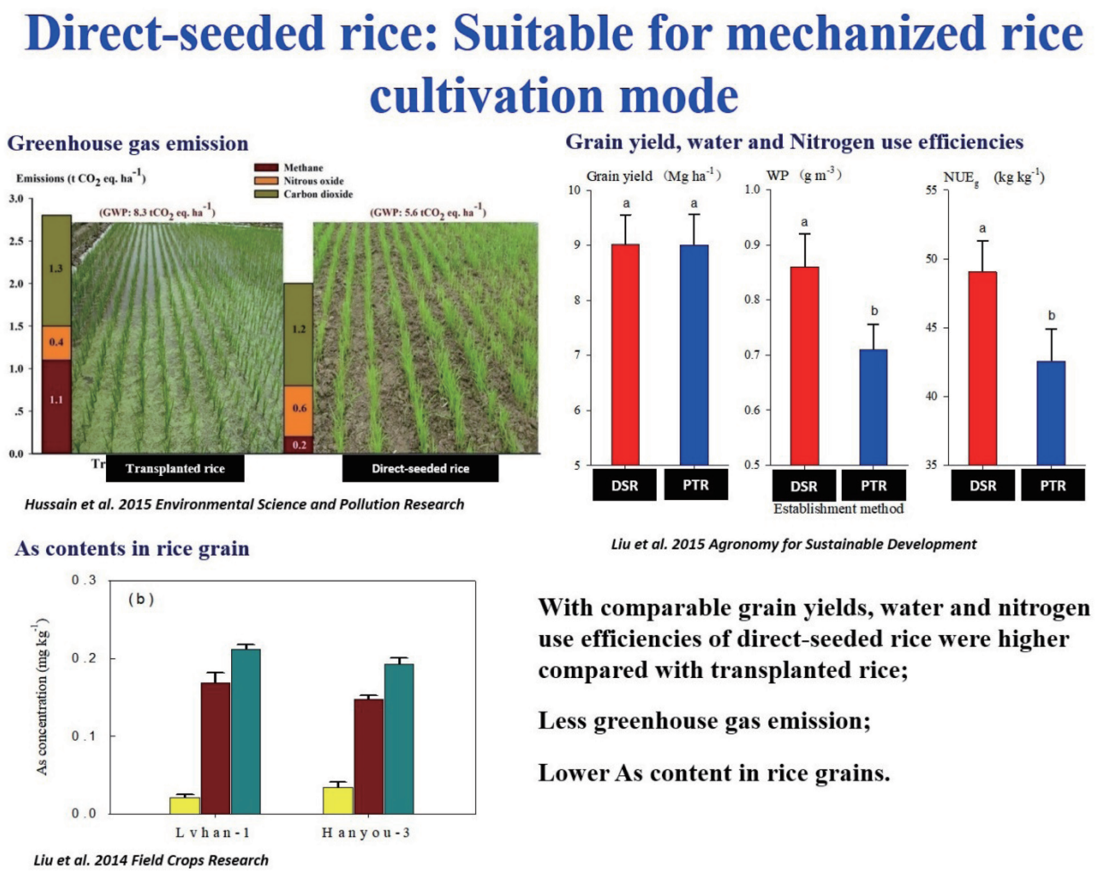

Fig. 2. Comparisons of rice yields and resource use efficiencies among different rice planting methods.

DSR had lower water consumption and higher water productivity than PTR. The minimum water input and irrigation time were observed in DDSR (Liu *et al*., 2015). Compared with PTR and WDSR the irrigation water consumption in DDSR was reduced by 68.3% and 62.3%, respectively. The total irrigation in WDSR was decreased by 15.8% as compared with PTR (Liu *et al*., 2015; Tao *et al*., 2016). Delaying the first flood irrigation time in DDSR decreased the number of irrigation procedures and conserved irrigation water (Jiang *et al*., 2016). When the first flood irrigation was postponed, the number of irrigations was reduced from eight to four in 2014 and from twelve to seven in 2015, respectively. Consequently, the amount of irrigation water was also decreased from 376 to 185 mm in 2014 and from 477 to 283 mm in 2015, respectively.

In order to estimate the future potential impact of greenhouse gas emissions on the ecosystem, the global warming potential (GWP) was calculated in mass of CO_2 equivalents (kg CO_2 equivalent ha^{-1}) over a 100-year time horizon (GWP=CH4×25+N2O×298; Forster *et al*., 2007). The emissions of CH_4 and N_2O varied with different establishment methods and water managements. Recent research revealed that CH_4 emission in DSR was significantly decreased by 77.6% while the N_2O emission was significantly enhanced by 285.7% as compared with those in PTR. Consequently, GWP value was significantly lower in DSR than in PTR. The CH_4 emission from DSR system was even lower than that from PTR systems, while the N_2O emission was drastically increased to 2-3 folds compared with the N_2O emission from PTR and WDSR systems. The lowest GWP was observed in DDSR among different establishment methods and water managements (**Fig. 3**).

5. Problems and Prospects.

Lodging, which could result in sizeable reduction in grain yield due to decreased photosynthesis by self shading, and hamper grain quality due to increased colouring and decreased taste, is one of the most serious problems that influence the stability of DSR (Kano, 1995; Kashiwagi *et al*., 2005). Severe lodging near maturity in DSR was observed in our study (**Fig. 4**). Tao *et al*. (2016) reported that the lodging area in DSR accounted for 45% of the total planting area, which was caused by the decreased breaking resistance of the rice node and increased lodging index as compared with PTR. While in PTR, no lodging was occurred during the course of the study. Previous studies documented that root lodging is very common in DSR because of the rather shallow root system (Terashima, 1997). High seeding rate is another important factor that increases the risk of lodging in DSR. The high planting density would lead to the elongation of the stems, which consequently results in smaller stem diameter and thinner stem walls (Liu *et al*., 2014). On the other hand, the disease and pests at high plant density are frequently occurred due to the high humidity environment under DSR (Balasubramanian and Hill, 2002). In order to reduce lodging risk in DSR, a range of approaches has been suggested. Adjusting seeding rate is one of the most effective practices to reduce lodging risk (Kim *et al*., 1993). Other cultural practices may also minimize lodging risk in DSR include using subsurface or anaerobic seeding, adjusting

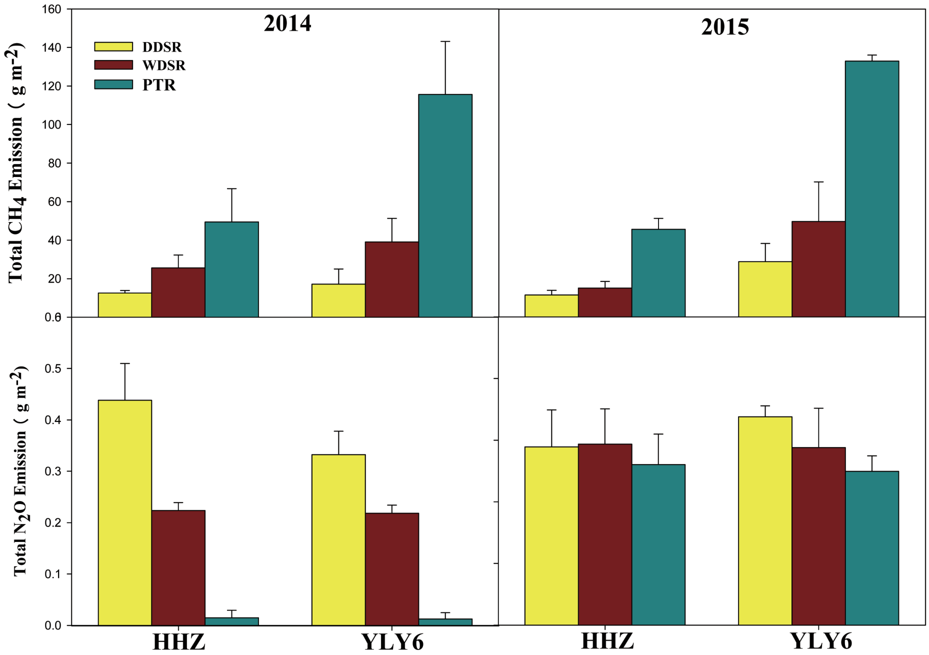

Fig. 3. Total CH_4 and N_2O emissions from dry direct-seeded rice (DDSR); wet direct-seeded rice (WDSR) and puddled transplanted rice (PTR) conditions.

Fig. 4. Photographs of lodging in direct-seeded rice (DSR) during the grain filling stage. DSR: Direct-seeded rice; PTR: Puddled transplanted rice.

the rate and time of N application and midseason drainage (Kim *et al*., 1995; Kim *et al*., 1999).

Weed is one of the major obstacles for developing DSR in central China. DSR are more likely to suffer from weeds infection than PTR (Singh *et al*., 2016), as the transplanted seedlings are more competitive to the emerged weeds (Rao *et al*., 2007). High rate of weed infection could decrease seedling emergence, increase pests and diseases infection, and lead to serious yield losses. Ramzan (2003) suggested that weeds were responsible for 74% yield losses in DSR and sometimes it may result in total crop failure. Many researches have reported that herbicides could successfully control weeds in DSR system (Chauhan *et al*., 2011; Singh *et al*., 2015). Nevertheless, intensive herbicide use may cause environmental contamination and enhance herbicide resistance. Meanwhile, several non-chemical methods have been recommended to successfully control weed without environment pollution. One of effective strategies is to use weed-competitive cultivars. Chauhan (2012) suggested that early seedling vigor and rapid canopy cover ability are the important traits for weed-competitive cultivars in DSR systems. Water management significantly inhibited weed growth. Chauhan and Johnson (2008) suggested that early and continuous, but shallow (<2 cm) flooding suppressed emergence and growth of weeds. Other non-chemical strategies include adjusting the row spacing, mulch covering and sterilizing seedbed before sowing.

Weedy rice (Oryza sativa f. spontanea) is another problem that causes the yield losses in DSR in central China. Weedy rice can take up 60% of the applied N fertilizer (Burgos *et al*., 2006). Li (2012) reported that weedy rice occurred in 80% of the DSR field, which lead to 15%-25% yield losses in Anhui province. One latest research reported that the weedy rice is de-domesticated from the cultivated rice, which suggested that the control of weedy rice is much more difficult than that of other weeds (Li *et al*., 2017). The strategies to prevent weedy rice need to be established based on the homology between weedy rice and cultivated rice. Although most herbicides that are selective for rice are not effective in controlling weedy rice. Shen *et al*. (2013) reported that integrate application of pretilachlor and fenclorim as pre-emergence herbicide could efficiently prevent the spread of weedy rice. Besides, sterilizing the field by non-selective herbicide prior to sowing and the use of weedy rice-free seeds is one of the best preventive measures to control weedy rice (Chauhan 2013; Singh *et al*., 2013).

The double season rice is the important rice cropping system in central China due to increase multiple crop index and thus contributing substantially to rice supply (Ray and Foley, 2013). The dominant rice establishment method in double season rice system is transplanting, which consumes large amount of labors and resources. As the results of continuous migration of labor from rural areas to cities and the crisis of water shortage, the planting area of double season rice is decreasing rapidly (Cai and Chen, 2000). To ensure food safety in central China, it is crucial to replace double season transplanting with more simplified cropping system. Incorporating DSR into double season rice system (Double-dry-seeded-rice) could be a promising strategy. "Double dry seeded rice" refers to the process of crop establishment by dry-direct-sowing the seeds in the field in both early and late seasons. Although double dry seeded rice could significantly increase resource use efficiency and maintain multiple cropping index, some limiting factors constrained the further development of this system. Compared with PTR, DSR lacks the nursery stage, which means rice has a longer field growth stage than transplanted rice. If the sowing date of direct-seeded early rice were postponed, the direct-seeded late rice would not be able mature due to the low temperature during grain filling stage in October to November in China (Gong *et al*., 2013). There are mainly two options to solve this problem, one is the selection of short growth duration varieties. However, very few varieties could achieve relatively high grain yield with short growth durations. The other option is advancing the sowing date of early direct-seeded rice to early or mid-April. However, seeds and seedlings of direct-seeded early rice may easily suffer from chilling stress which could result in poor crop establishment.

6. Conclusion

With good water management, grain yield of DSR is similar to or higher than yield of PTR while increasing irrigation water productivity and nitrogen use efficiency, reducing greenhouse gas emissions, and decreasing labor requirement. However, problems that include lodging, weak root development, weed infestations and poor crop establishment under drought, waterlogging, or chilling stresses might limit wide-scale adoption of DSR in central China. Varieties bred and selected for direct seeding, guidelines for improved nutrition, water, and weed management practices, and the development of suitable planting machines and sowing management for DSR are needed. In addition, incorporating DSR into the double season rice or ratoon rice systems could be promising strategies to increase rice production in central China.

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