Water Supply

Water Supply Vol 23 No 9, 3563 doi: 10.2166/ws.2023.203

Effect of planting and irrigation management strategies on growth, yield and water productivity of *indica* rice in Iran

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ABSTRACT

One of the most important problems for rice production is the high water need of this plant. Therefore, the use of modern technologies to increase water-saving in paddy fields is critical to global food security. Hence, the present study aimed to evaluate the effects of different planting methods and irrigation systems on growth, yield and water productivity in rice. The experiment was arranged as a split-plot in a randomized complete block design with three replications. The experimental treatments included the main plot assigned to three planting methods (transplanting at puddled bed [TPB], transplanting at non-puddled bed [TNPB], and direct-seeded rice [DSR]) and the sub-plot assigned to three irrigation systems (continuous flooding irrigation (CFI), alternate wetting and drying [AWD], and drip irrigation [DI]). The results showed that the highest grain yield (3962.7 $kg.ha^{-1}$) and more-water-saving (17.3%) was achieved in the TPB treatment. Total water productivity for TPB, TNPB, and DSR methods were calculated to be 0.56, 0.43, and 0.34 $kg.m^{-3}$, respectively. Grain yield in CFI (3457.6 $kg.ha^{-1}$) and AWD (3410.3 $kg.ha^{-1}$) systems was significantly higher than DI treatment (3150.7 $kg.ha^{-1}$), while no significant difference was observed between CFI and AWD treatments in terms of rice production. However, the AWD system increased water-saving by 24.8% compared with CFI. Our results highlight that combined application of AWD system and TPB method has a great potential to reduce total water input without negatively affecting yield.

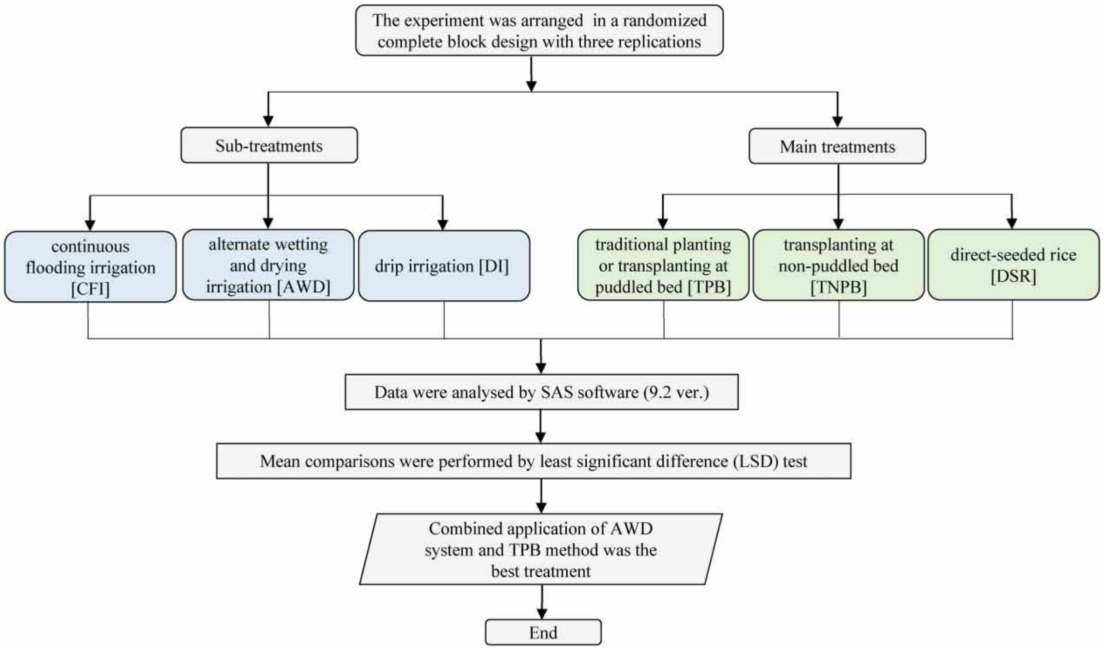
Key words: irrigation system, planting method, water productivity, yield

HIGHLIGHTS

- Rice plants grown at TPB indicated higher growth, greater yield and lower total water input compared with TNPB and DSR methods.
- The plots maintained under DI system had significantly higher water-saving and lower yield than CFI and AWD treatments.
- Application of management strategies of rice planting by TPB under AWD system has noticeable potential to reduce water shortages, while also ensuring high grain yield.

GRAPHICAL ABSTRACT

From: **Effect of planting and irrigation management strategies on growth, yield and water productivity of indica rice in Iran**



INTRODUCTION

Rice (*Oryza sativa* L.) is cultivated in more than 95 countries worldwide (Liu *et al.* 2015). Rice with an annual production of 782 million tons and a harvesting area of 167 million hectares (Ben Hassen *et al.* 2017) provides the food needs of a large part of the world's population (Carrijo *et al.* 2017). In Iran, the area under rice cultivation is approximately 0.62 million hectares with the production of 2,900,000 tons of rice (Pourgholam-Amiji *et al.* 2021). Mazandaran province has the largest share in rice production in Iran with the cultivated area of 214,052 hectares and production of almost 26% (1,113,715 tons) of the total rice produced in Iran (Ahmadi *et al.* 2019).

The volume of input water in traditional irrigation system is significantly high (Zabihpour Roushan *et al.* 2022). In the conventional technique of rice production, a large amount of input water is wasted due to the preparation of the planting bed before transplantation, evaporation and seepage (Kiani *et al.* 2022). At present, traditional transplanted flooded system is used in most areas of rice production in Iran, which resulted in an increase in water input (WI) (Ebrahimi Rad *et al.* 2018). However, a large amount of the total water input (TWI) in a continuous flooding irrigation (CFI) system is lossed by seepage, percolation, and evaporation (Shao *et al.* 2015). Rice has higher water use and lower water productivity (WP) compared to other cereals (Maneepitak *et al.* 2019). The amount of WI in transplanted-flooded rice is two or three times more than other cereals like corn and wheat (Liu *et al.* 2015). In general, the irrigated rice grown under CFI consumes more water than the crop actual needs (Ebrahimi Rad *et al.* 2018). Here, one of the main issues in the food security sector is to produce higher quantities of rice with lower WI to feed the people of the world (Wu *et al.* 2017). These cases make it necessary to adopt management methods to water-saving and increase WP for rice production (Carracelas *et al.* 2019).

Nowadays, various techniques of planting and water management such as direct-seeded rice (DSR) (Xu *et al.* 2019; Ishfaq *et al.* 2020), transplanting at non-puddled bed (TNPB) (Hossen *et al.* 2018), alternate wetting and drying (AWD) irrigation (Carrijo *et al.* 2017; Anning *et al.* 2018) and drip irrigation (DI) (Rao *et al.* 2017; Singh *et al.* 2019) can become alternative options for the traditional method of rice production by reducing WI and increasing WP. Bukhari Syed *et al.* (2021) stated that the application of geomembrane cover plays a vital role in enhancing the water-saving. The use of proper agricultural management techniques such as the principle application of mineral fertilizers and appropriate irrigation methods is of great importance in the agricultural sector (Abdul Rajak 2022).

DSR is a technique of direct sowing of seeds in fields (Kaur & Singh 2017). Direct seeding of rice can replace traditional transplanting due to the reduction in total WI volume, low labor input and high economic benefit (Ishfaq *et al.* 2020). Patel *et al.* (2018) observed that DSR was able to reduce WI by 35–57% and labor force by 67% when compared with traditional planting. In other hand, some studies suggest that the rice grain yield at DSR was significantly lower than TPB (Xu *et al.* 2019).

Transplanting of rice in non-puddling soil helps to establish the plant in time, save energy and thus reduce input costs (Haque *et al.* 2016). Hossen *et al.* (2018) reported that eliminating the puddling operation can reduce the costs of labor, energy and irrigation water input to land preparation for rice plants establishment. Previous studies indicated that some researchers believe that DSR or TNPB can be a suitable alternative to transplanting at puddled bed (TPB) (Kar *et al.* 2018) due to the lower need for energy and labor inputs (Fang *et al.* 2019).

AWD is an irrigation system based on not flooding the fields during the crop growth period (Sandhu *et al.* 2017) that helps reduce WI in paddy fields (Maneepitak *et al.* 2019). One of the advantages of AWD method is the improvement of WP along with maintaining or enhancing grain yield of rice (Zhou *et al.* 2017). Ishfaq *et al.* (2020) documented that the AWD can represent a viable alternative to CFI by water-saving by 25–70%.

The use of DI in rice cultivation can help to increase the water supply capacity (He *et al.* 2022). Singh *et al.* (2019) observed that the water requirement of rice plants in the DI method was in the range of 938–1,838 $L \cdot kg^{-1}$, whereas this value was 4,250–5,508 $L \cdot kg^{-1}$ in CFI. The DI system is able to reduce the rice demand for water (Rao *et al.* 2017). Previous studies showed that the cost of irrigation water was decreased by 2–5.6 times under DI system when compared with CFI (Kruzhilin *et al.* 2015).

The issue of water crisis as well as excessive water losses in the crop production require sustainable use of water (Farahza *et al.* 2020). Thus, it is necessary to compare the different planting methods and various irrigation systems to achieve the best strategy to overcome the challenge of the water crisis as well as to help improve farmers' income. For this reason, the aim of this research was to investigate agronomic parameters, yield components, yield and water productivity of rice under different planting methods and various irrigation systems to identify the best management techniques that enhances water productivity without negatively affecting grain yield.

MATERIALS AND METHODS

Experimental site

This study was performed at the Rice Research Institute of Iran (RRII) (36°28′ N, 52°27′ E; 29.8 m a.s.l., average annual temperature: 16 °C and average annual rainfall: 800 mm), Mazandaran Province, Iran, during the 2019–2020 rice cropping season. Meteorological information of the study site during the rice growing season is shown in Table 1. Figure 1 indicates the geographic location of the test site. The physical and chemical properties of the soil were determined by preparing samples from the depth of 0 to 30 cm and the results were presented in Table 2.

Experimental design and treatments

This experiment was conducted as a split-plot in a randomized complete block design with three replications. The experimental treatments included the planting methods at three levels (transplanting at puddled bed [TPB], transplanting at non-puddled bed [TNPB], and direct-seeded rice [DSR]) as the main factor and the irrigation systems at three levels (continuous flooding irrigation (CFI), alternate wetting and drying [AWD], and drip irrigation [DI]) as the sub factor.

Field experiment

In this study, rice seeds (cv. Tarom Hashemi) were applied for planting. The plots size was 48 m^2 (8 m × 6 m). In order to prevent lateral seepage, the boundaries of the plots were covered with a plastic film placed at a depth of 30 cm in the soil.

Table 1 | Meteorological information of the study site during the rice growing season

Months	Monthly temperature (°C) Min	Max	Average	Rainfall (mm)	Average relative humidity (%)
Apr	10.8	19.7	15.3	7.7	76
May	14.9	23.9	19.4	29.1	72
Jun	20.5	13.1	16.8	3.2	76
Jul	21.3	30.7	26.0	3.0	76
Aug	21.4	29.3	25.4	54.3	79
Sep	21.8	29.5	25.7	31.0	80

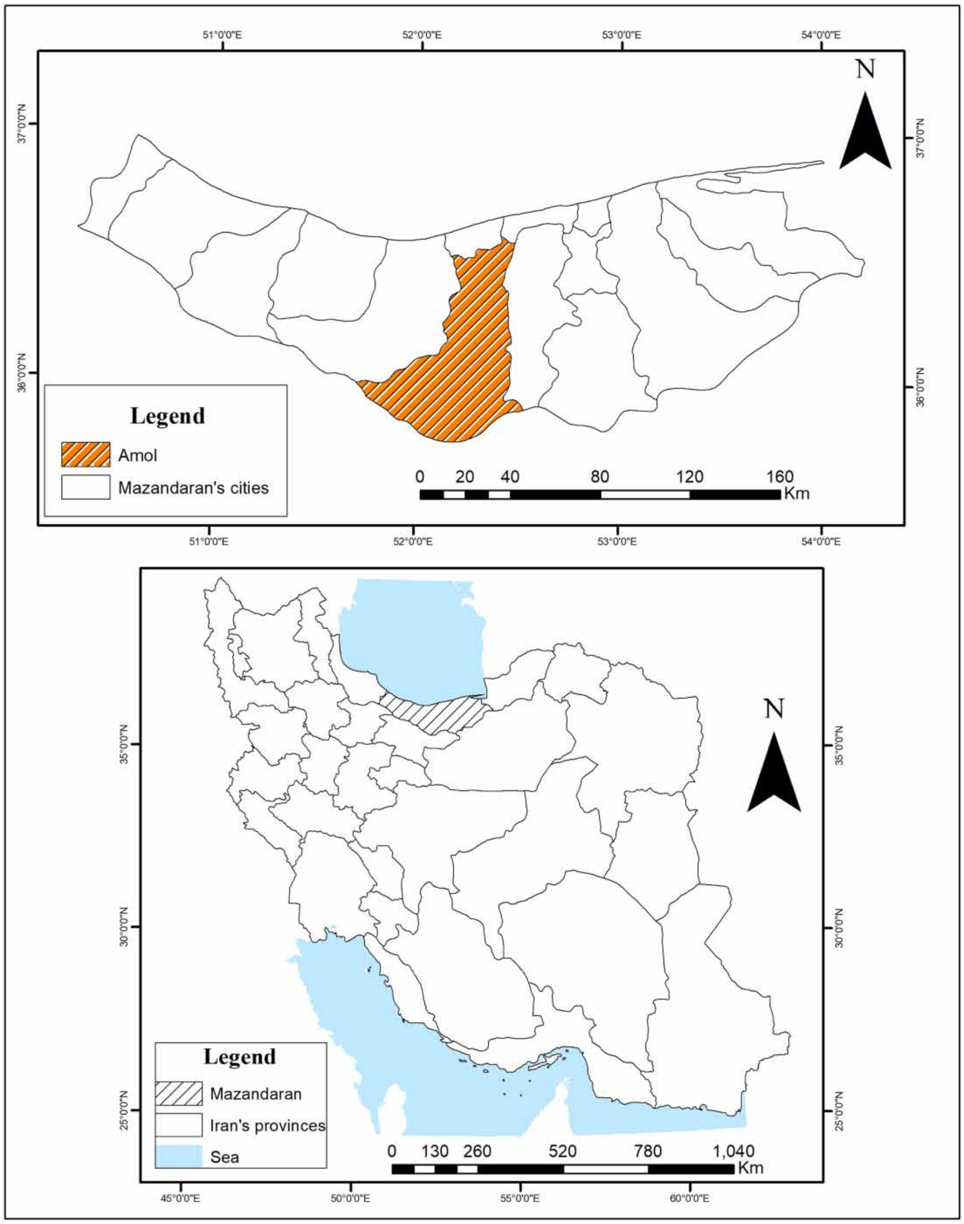


Figure 1 | Geographical location of the test site.

Table 2 | Soil physical and chemical properties

Soil Texture	Sand (%)	Silt (%)	Clay (%)	EC (ds·m^{-1})	pH	Organic carbon (%)	Available P (mg·kg^{-1})	Available K (mg·kg^{-1})
Si-L	21	51	28	0.60	7.68	1.36	10	180

For treatment of TPB, land preparation was done by ploughing, harrowing, puddling and soil leveling, whereas at TNPB, the plots were dry-plowed without puddling and seedlings were transplanted in plots after one irrigation stage. At both transplanting methods, pregerminated seeds were sown in nursery. Then, the 30-day-old rice seedlings were transplanted with one plant per hill at a constant spacing of 25 × 25 cm by manually transplanting. For treatment of DSR, the soil in plot was dry-plowed without puddling and then the seeds were sown directly and manually with a distance of 20–23 cm and a depth of 1.5–2 cm. The amount of seed used for transplanting and DSR methods were 40 and 80 kg·ha^{-1}, respectively.

Under CFI system, the height of irrigation water was 5 cm above the soil level during the whole rice-growing season until 10 days before rice harvest. In the AWD irrigation technique, the polyvinyl chloride tube with a 40-cm-length and 20-cm-diameter and many holes at 2 cm spaces around the pipe were installed to check the depth of water in the soil. After the water level reached the soil depth of 5 cm, the irrigation was done again until the water level reached 5 cm above the soil surface. According to the daily temperature, the AWD cycles varied from 5 to 8 days until drainage at 10 days before harvest. Under DI method, two drip line with emitter spaced at 30 cm and flow rate of 4 liter per hour were laid at an interval of 60 cm in each plot. In this method, irrigation was done with two-day intervals until 5 days before harvest. Figure 2 illustrates the schematic of experimental treatments.

All the plots received phosphorus as triple superphosphate at the rate of 100 kg P_2O_5 ha^{-1} as basal. Nitrogen as urea 46% and potassium as potassium chloride were applied at the rates of 150 and 100 kg·ha^{-1}, respectively, in three stages (40% as a basal fertilizer, 30% at tillering stage and 30% at panicle initiation). To control weeds in transplanted plots at puddled bed, Butachlor (2.5–3 L ha^{-1}) was used 1 week after transplanting and manual weeding was done in 2 week after planting. To control weeds in transplanted plots at non-puddled bed and direct seeding, the Treflan (3–3.5 L ha^{-1}) and Butachlor (3–4 L ha^{-1}) was used. To control *Chilo suppressalis*, diazinon (10% Granule) was used at a rate of 15–20 kg ha^{-1} at two stages and to control blast disease, Win fungicide was used at the rate of 400 ml·ha^{-1} at one stage in all the experimental plots.

Sampling and measurement

At ripening stage, the morphological characteristics of plant height and panicle length were determined by measurement of 15 plants in each plot. The total tillers number per hill and panicle number per hill were calculated from 15 hills per plot. The filled grains number per panicle was determined by counting from 20 panicles. The 1,000-grain weight was obtained by counting 1,000 filled grains and weighing them. Grain yield was determined by harvesting an area of 10 m^2 (5 m × 2 m) from the middle part of the test plots and based on 14% moisture content. In the entrance part of each plot, the flowmeters were placed to enable separate monitoring of irrigation treatments. The irrigation water input for all treatment was pumped from the well and it's Physicochemical properties are provided in Table 3. Total water input (TWI) volume (m^3·ha^{-1}) includes irrigation water input plus rainfall recorded during growing season. Total water productivity (TWP) (kg·m^{-3}) was calculated as the grain yield (kg·ha^{-1}) per unit of TWI. The full names and abbreviations of related terms are shown in Table 4.

Statistical analysis

Statistical data were analysed by SAS software (9.2 ver.). Mean comparisons were performed by least significant difference (LSD) test ($p \leq 0.05$). Figures were drawn using MS-Excel software.

RESULTS AND DISCUSSION

Growth parameters

The two-way interaction between planting method and irrigation system as well as the individual impacts of irrigation system ($p < 0.05$) and planting method ($p < 0.01$) were significant for plant height (Table 5).

As shown in Table 6, the plant height was significantly higher at TPB (128.1 cm) than TNPB (104.9 cm) and DSR (99.8 cm). However, the lower plant height (22.1% reduction) was observed at DSR method. The difference in rice plants growth between planting methods in our study can be significantly affected by climate conditions. At DSR method, the germinated

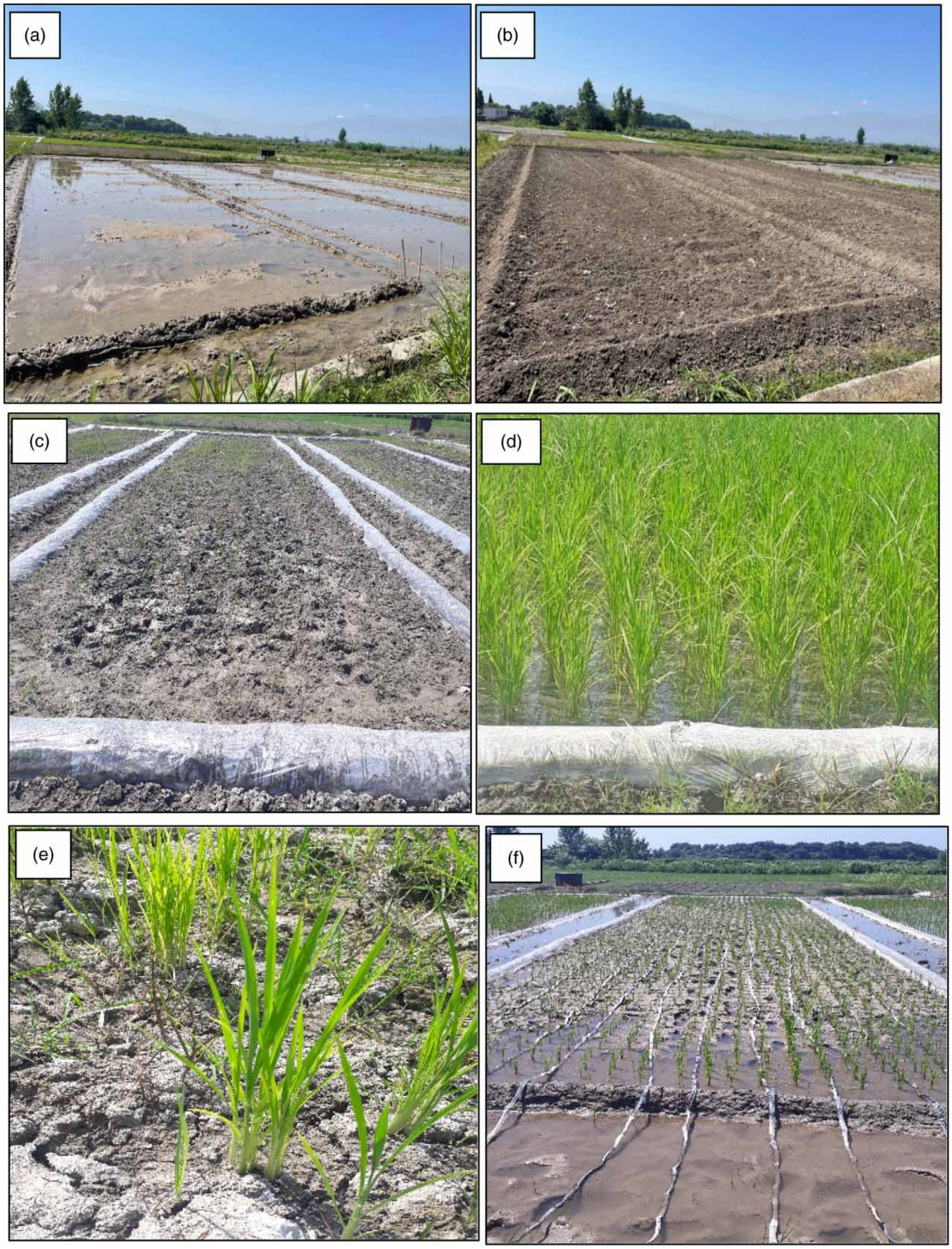


Figure 2 | Schematic of experimental treatments (transplanting at puddled bed [a], transplanting at non-puddled bed [b], direct-seeded rice [c], continuous flooding irrigation [d], alternate wetting and drying irrigation [e], and drip irrigation [f]).

seeds are often exposed to low temperatures, whereas at transplanted-rice (TPR), the seeds in the nursery are protected by plastic covering against cold damage (Xu *et al.* 2018). On the other hand, the low water holding capacity in non-puddling soils caused a decrease in moisture retention in the planting methods without puddling (TNPB and DSR) in this study and as a result reduced vegetative growth and plant height. Increasing the water depth at TPB method causes more root

Table 3 | Physicochemical properties of irrigation water

parameters	Unit	Concentration
EC	$ds \cdot m^{-1}$	0.839
pH	–	7.28
Carbonate	$meq \cdot l^{-1}$	0.6
Bicarbonate	$meq \cdot l^{-1}$	2.1
Total dissolved solids	$mg \cdot l^{-1}$	593
Calcium	$mg \cdot l^{-1}$	277
Total hardness	$mg \cdot l^{-1}$	487

Table 4 | Glossary of terms

Term	Definition
AWD	Alternate wetting and drying
CFI	Continuous flooding irrigation
DI	Drip irrigation
DSR	Direct-seeded rice
DDSR	Dry direct-seeded rice
TNPB	Transplanting at non-puddled bed
TPB	Transplanting at puddled bed
TPR	Transplanted-rice
TWI	Total water input
TWP	Total water productivity
WI	Water input
WP	Water productivity
WUE	Water use efficiency

Table 5 | Analysis of variance for planting method, irrigation system and their interactions on agronomic parameters and yield components of rice

Source of variation	df	Plant height	Panicle length	Total tillers numbe per hill	Panicle number per hill	Filled grains number per panicle	1,000-grain weight
Replication (R)	2	40.1	0.09	2.57	2.73	4.43	0.11
Planting method (PM)	2	2,047.2**	0.76^{ns}	27.7**	35.2**	248.0**	67.4**
Error	4	1.84	0.75	1.09	1.89	9.57	0.22
Irrigation system (IS)	2	77.2*	2.03*	30.0**	35.3**	49.8^{ns}	2.78^{ns}
PM × IS	4	77.2*	3.57**	5.34**	5.29^{ns}	90.9**	1.22^{ns}
Error	12	13.7	0.33	0.97	3.03	13.8	0.85
CV (%)	-	3.35	2.40	7.78	14.28	6.59	2.99

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

development, proper absorption of nutrients and subsequently improves rice growth. Soil moisture stress reduces the vegetative growth of rice by limiting nutrients uptake by plant roots (Anning *et al.* 2018). Our results are in line with the findings of Islam *et al.* (2008), who reported the plant height at TPR method (130.2 cm) was higher than DSR (126.6 cm).

Table 6 | Growth parameters of rice under three planting methods (transplanting at puddled bed [TPB], transplanting at non-puddled bed [TNPB] and direct-seeded rice [DSR]) and three irrigation systems (continuous flooding irrigation [CFI], alternate wetting and drying [AWD] and drip irrigation [DI])

Factor	Plant height (cm)	Panicle length (cm)
Planting method (PM)		
TPB	128.1a	24.24a
TNPB	104.9b	23.99a
DSR	99.8c	23.67a
Irrigation system (IS)		
CFI	114.0a	24.33a
AWD	110.7ab	24.13a
DI	108.2b	23.43b
PM × IS		
TPB + CFI	124.7a	24.97ab
TPB + AWD	131.5a	25.73a
TPB + DI	128.1a	24.10abc
TNPB + CFI	106.6b	24.27abc
TNPB + AWD	100.9b	23.53bc
TNPB + DI	107.3b	23.40bc
DSR + CFI	100.9b	23.16c
DSR + AWD	92.1c	23.73bc
DSR + DI	106.6b	22.87c

Means in columns followed by the same letter(s) are not significantly different by least significant difference (LSD) at $p < 0.05$.

In this research, there were no significant differences in plant height between CFI and AWD irrigation. The rice plants under CFI had 5.1% higher plant height than plants were subjected to DI. Plant height remained similar regardless of irrigation systems at TPB and TNBP, while DSR had significantly lower plant height under AWD than CFI and DI. CFI as a management technique can increase the growth of rice seedlings by preventing weed germination (Wu *et al.* 2017).

Panicle length was not affected by the individual impact of planting method; however, the individual impact of irrigation system ($p < 0.05$) as well as the interaction between planting methods and irrigation systems ($p < 0.01$) was significant on panicle length (Table 5).

In this study, the panicle length was similar in different planting methods, whereas it was significantly lower under DI than CFI and AWD irrigation systems (Table 6). However, the panicle length showed a slight increase in TPB compared with other planting methods. Hosseini *et al.* observed that the rice plants indicated greater panicle length at TPR when compared with DSR. Pourgholam-Amiji *et al.* (2021) also documented that the panicle length of rice was significantly higher under CFI than AWD treatments.

In our study, the panicle length was not affected by planting methods regardless of irrigation systems. The rice plants at TPB under all three irrigation systems and also TNBP under CFI showed higher panicle length when compared with other experimental treatments. However, the greatest panicle length (25.73 cm) was obtained at TPB under AWD, whereas the panicle length was reduced by 11.1% at DSR under DI (Table 6). Ishfaq *et al.* (2020) reported that the panicle length at TPR production system was significantly higher than dry direct-seeded rice (DDSR) in both years of the study (Ishfaq *et al.* 2020).

Yield components and grain yield

The total tillers number per hill was highly significantly ($p < 0.01$) affected by the two-way interaction between planting method and irrigation system as well as the individual effects of planting method and irrigation system (Table 5).

The results presented in Table 7 showed that the total tillers numbe per hill at TPB was 17.8% and 23.3% higher than TNPB and DSR, respectively. There was no significant difference in number of total tillers per hill between the TNPB and DSR.

Table 7 | Yield components of rice under three planting methods (transplanting at puddled bed [TPB], transplanting at non-puddled bed [TNPB] and direct-seeded rice [DSR]) and three irrigation systems (continuous flooding irrigation [CFI], alternate wetting and drying [AWD] and drip irrigation [DI])

Factor	Total tillers numbe per hill	Panicle number per hill	Filled grains number per panicle	1,000-grain weight (g)
Planting method (PM)				
TPB	14.68a	14.32a	62.38a	33.44a
TNPB	12.07b	11.84ab	54.80b	31.22b
DSR	11.26b	10.41b	52.30b	28.00c
Irrigation system (IS)				
CFI	13.75a	13.50a	58.86a	31.44a
AWD	13.69a	13.17a	56.48ab	30.33b
DI	10.56b	9.91b	54.15b	30.90ab
PM × IS				
TPB + CFI	15.67a	15.33a	64.50a	33.67a
TPB + AWD	14.80a	14.70ab	63.80a	33.33a
TPB + DI	13.33ab	12.07abc	58.87ab	33.33a
TNPB + CFI	15.13a	14.13ab	63.57a	32.33ab
TNPB + AWD	13.23ab	9.33cd	52.70bc	30.67bc
TNPB + DI	12.93bc	9.32cd	48.13c	30.50bc
DSR + CFI	11.33bc	10.67bcd	52.93bc	28.67cd
DSR + AWD	9.10c	7.47d	52.70bc	27.00d
DSR + DI	13.10b	12.07abc	49.87bc	28.33d

Means in columns followed by the same letter(s) are not significantly different by least significant difference (LSD) at $p < 0.05$.

Typically, plant density at DSR method is higher than TPR method, so rice seedlings need more nutrients at DSR (Xu *et al.* 2019). Higher competition between rice seedlings to absorb mineral nutrients at greater densities results in a decrease in the tillers number per hill (Alipour Abookheili & Mobasser 2021). On the other hand, reducing the water depth in the methods without puddling (TNPB and DSR) in the present study reduces root development and therefore decreases tiller production.

Our findings illustrated that the two irrigation systems of CFI (13.75 tillers) and AWD (13.69 tillers) resulted in similar total tillers number per hill, whereas the tillers number per hill under DI was reduced by about 23%. The production of a higher total tillers number per hill with the CFI and AWD can be attributed to more suitable moisture conditions in these two methods compared with DI method. Total tillers numbe per hill remained similar at TPB irrespective of irrigation systems, although the plants at TPB under DI had lower tillers number per hill compared with TPB under CFI and AWD. We also observed that the rice plants at TNPB under DI had 14.5% and 2.3% lower number of total tillers per hill than the same planting method under CFI and AWD irrigation treatments, respectively, whereas there was no significant difference between the CFI and AWD at TNPB in terms of number of total tiilers per hill. At DSR method, the plants under DI system indicated 13.5% and 30.5% higher total tillers number per hill than rice plants were subjected to CFI and AWD. However, there was no significant difference in number of total tillers per hill between the DI and CFI at DSR method (Table 7). Our results are consistent with findings of Ishfaq *et al.* (2020) which showed that the total tillers m^{-2} was similar for AWD and CFI methods in both years. AWD can help increase the number of tillers in rice by ameliorating root health, shoot growth and leaf area index (Norton *et al.* 2017).

Number of panicle per hill was not affected by the two-way interaction between planting method and irrigation system; however, the individual effects of planting method and irrigation system was highly significant ($p < 0.01$) on panicle number per hill (Table 5).

As shown in Table 7, the highest panicle number per hill was observed at TPB method (14.32 panicle), whereas DSR reduced the number of panicle per hill by 27.3%. However, there was no significant difference in panicle number per hill between TPB and TNPB treatments. Failure to meet the total transpiration water demand from the deeper layers of the soil by the roots can lead to a reduce in growth and yield (Carrijo *et al.* 2018). Hosseini *et al.* demonstrated that changing the planting method from TPB to DSR resulted in the 60% reduction of fertile tillers per hill. Xu *et al.* (2019) also observed that the number of spikelet per panicle was significantly lower at DSR when compared with TPR.

The plants grown under CFI and AWD had 26.6% and 24.7% higher panicle number per hill compared with rice plants under DI. However, there were no significant differences in number of panicle per hill between CFI and AWD treatments, whereas the DI treatment significantly decreased panicle number per hill (Table 7). Drought stress in the important stages of rice growth affects the agronomic characteristics and yield components of rice (Maneepitak *et al.* 2019). For example, water stress had a significant effect in reducing the number of tillers in rice due to leaf water potential drop, stomata closing and photosynthesis rate reduction (Dass *et al.* 2016).

Number of filled grains per panicle was not affected by the individual effect of irrigation system; however, it was highly significantly ($p < 0.01$) affected by the two-way interaction between planting method and irrigation system as well as the individual impact of planting method (Table 5).

In this study, the TPB had 12.1% and 16.1% greater filled grains number per panicle than TNPB and DSR, respectively (Table 7). Providing the moisture required by the plant, especially at grain filling stage by TPB method, could lead to an increase in the number of filled grains per panicle. In similar results, Karimi Fard *et al.* (2020) documented that the higher number of filled grains per panicle at TPR compared with DSR. Hosseini *et al.* found that the filled grains number per panicle at DSR was reduced by 24.5% and 19.4%, respectively, when compared with TNPB and TPB methods.

Among the three irrigation systems, DI had significantly lower number of filled grains per panicle than CFI and AWD. At TPB and DSR methods, the three irrigation systems resulted in similar filled grains number per panicle, whereas at TNPB, the CFI had 17.1% and 24.3% higher filled grains number per panicle than AWD and DI systems, respectively (Table 7). The application of AWD irrigation method during grain filling phase by increasing root growth improves the nutrients uptake, enhances accumulation of soluble carbohydrates and ameliorates the transport of assimilates to the grain when the nutrients supply is limited (Li *et al.* 2016). In similar results, Maneepitak *et al.* (2019) demonstrated that the difference in filled grain percentage among irrigation regimes (CFI and AWD) was not significant, which is consistent with the results of the present study. In other hand, Pourgholam-Amiji *et al.* (2021) reported that the highest grain filling percentage was observed when the plants were under flooding irrigation.

The simple effect of planting method was highly significant ($p < 0.01$) for 1,000-grain weight. However, the 1,000-grain weight was not affected by the interaction between planting method and irrigation system as well as the simple effect of irrigation system (Table 5). Among the three planting methods, TPB had 6.6% and 16.3% higher 1,000-grain weight than TNPB and DSR, respectively. However, the lowest 1,000-grain weight (28 g) was observed under DSR method. The increase in 1,000-grain weight at TPB method may be due to reducing source limitation, enhancing photoassimilates and better transporting of these assimilates to the grain by enhancing the moisture availability at grain filling stage. Xu *et al.* (2019) indicated that grain weight was significantly lower than that under TPR.

The 1,000-grain weight was similar under two irrigation management practices of CFI and DI, whereas AWD had significantly lower 1,000-grain weight than CFI. However, there was no significant difference in 1,000-grain weight between the DI and AWD. Our results revealed that the 1,000-grain weight remained similar at TPB irrespective of irrigation management practices, and the same was also true for TNPB and DSR under three irrigation systems (Table 7). Ye *et al.* (2013) documented a reduction in 1,000-grain weight under AWD by reduced water availability and lack of nutrient supply due to increased panicle number. By contrast, Maneepitak *et al.* (2019) mentioned that changing the irrigation method from CFI to AWD resulted in an increase in 1,000-grain weight in both dry and wet seasons.

There was no significant interaction between planting method and irrigation system for grain yield; however, planting method ($p < 0.01$) and irrigation system ($p < 0.05$) significantly affected grain yield (Table 8).

The assay for grain yield (Table 9), showed that the maximum grain yield (3,962.7 kg·ha^{-1}) was obtained at TPB, whereas the yield was decreased by 20% and 27.2% at TNPB and DSR, respectively. However, the rice plants at TNPB and DSR produced similar grain yields. The higher yield at TPB method could be attributed to higher total tillers numbe per hill, higher panicle numbe per hill, greater filled grains number per panicle and higher 1,000-grain weight. In similar results, Xu *et al.* (2019) indicated that the rice grain yield at DSR method was 12% lower than TPB method. These researchers stated that yield reduction varies depending on management methods, soil type and weather conditions, and weed and water management had the greatest impact on yield. In similar results, Hosseini *et al.* reported that DSR method reduced the rice grain yield by 42.9% compared with TPB.

Table 8 | Analysis of variance for planting method, irrigation system and their interactions on grain yield, total water input and total water productivity of rice

Source of variation	df	Grain yield	Total water input	Total water productivity
Replication (R)	2	331,241.8	9,372.3	0.007
Planting method (PM)	2	2,805,587.1**	5,582,510.7**	0.10**
Error	4	60,890.7	4,068.1	0.001
Irrigation system (IS)	2	245,756.2*	31,622,049.3**	0.05**
PM × IS	4	13,709.3^{ns}	1,432,153.9**	0.001^{ns}
Error	12	50,364.5	6,122.9	0.001
CV (%)	–	6.72	1.00	8.15

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

Table 9 | Grain yield, total water input and total water productivity of rice under three planting methods (transplanting at puddled bed [TPB], transplanting at non-puddled bed [TNPB] and direct-seeded rice [DSR]) and three irrigation systems (continuous flooding irrigation [CFI], alternate wetting and drying [AWD] and drip irrigation [DI])

Factor	Grain yield (kg·ha^{-1})	Total water input (m^3·ha^{-1})	Total water productivity (kg·m^{-3})
Planting method (PM)			
TPB	3,962.7a	7,181.9c	0.56a
TNPB	3,171.1b	7,517.3b	0.43b
DSR	2,884.8b	8,682.4a	0.34c
Irrigation system (IS)			
CFI	3,457.6a	9,835.0a	0.37c
AWD	3,410.3a	7,397.0b	0.47b
DI	3,150.7b	6,149.7c	0.51a
PM × IS			
TPB + CFI	4,079.2a	8,441.3c	0.49bc
TPB + AWD	4,031.2a	7,105.3e	0.57a
TPB + DI	3,729.2ab	6,595.5f	0.62a
TNPB + CFI	3,351.7bc	9,638.0b	0.35d
TNPB + AWD	3,175.0bcd	6,905.0f	0.47c
TNPB + DI	2,986.7cd	5,998.6g	0.50bc
DSR + CFI	2,941.7cd	11,435.7a	0.26e
DSR + AWD	2,736.0d	8,180.7d	0.33de
DSR + DI	2,976.7cd	7,920.7e	0.38cd

Means in columns followed by the same letter(s) are not significantly different by least significant difference (LSD) at $p < 0.05$.

The results suggested that the plants grown under CFI and AWD indicated 8.9% and 7.6% higher yield when compared with DI-treated plants. However, there were no significant differences in rice grain yield between CFI and AWD treatments, whereas the DI treatment resulted in a significant yield reduction (Table 9). The results of the present work are in line with the findings of He *et al.* (2013), who reported that DI system resulted in greater water use efficiency (WUE) and higher economic benefit in rice, but yield was lower when compared with CFI system. In similar results, Ishfaq *et al.* (2020) found that the application of either CFI or AWD could enhance rice grain yield. Carrijo *et al.* (2017) observed similar increased grain yield under AWD compared with CFI with a significant increase in water-saving under AWD. In another study, Maneepitak *et al.* (2019) suggested that the rice plants under AWD showed higher grain yield in both wet (15%) and dry (7%) seasons when compared with plants grown under CFI.

The difference in yields among irrigation management systems in each of the planting methods was not significant. Overal, the higher grain yield was observed at TPB under CFI (4,079.2 kg·ha^{-1}) followed by statistically similar yield at TPB under AWD (4,031.2 kg·ha^{-1}) and at TPB under DI (3,729.2 kg·ha^{-1}). The findings of present study that the grain yield exhibited a significant increase at TPB under CFI was consistent with Kiani *et al.* (2022) who documented that the rice grain yield was significantly higher at traditional TPR under flooding irrigation than other production systems. These researchers also mentioned that changing the planting method from TPR to DSR in all irrigation systems led to a significant reduction in yield.

Total water input and water productivity

Total water input (TWI) was highly significantly ($p < 0.01$) affected by the two-way interaction between planting method and irrigation system as well as the individual impacts of planting method and irrigation system (Table 8).

The DSR practice resulted in the highest TWI (8,682.4 m^3·ha^{-1}), as shown in Table 9. The plots at DSR showed 13.4% and 17.3% higher TWI than TNPB and TPB, respectively. However, the TPB treatment achieved significant water-saving compared with the TNPB and DSR treatments with an average of 335.4 m^3·ha^{-1} (4.5%) and 1,500.5 m^3·ha^{-1} (17.3%), respectively. The reduction of water consumption at TPB method can be due to the increase in the water holding capacity in the soil through puddling compared with two production systems without puddling in this study. Non-puddling soils may be losing their moisture quickly and eventually become dry soils. Soil drying may also cause contraction and cracking, resulting in increased soil water waste (Wu *et al.* 2017). Kiani *et al.* (2022) observed that changing the planting method from TPR to DSR resulted in an increase in WI and a 40% reduction in yield. By contrast, Liu *et al.* (2015) revealed that not only the WI at DSR was 15% less than conventional planting, but also the yield was similar in both planting systems.

Our results indicated that the plots maintained under CFI had significantly greater TWI than AWD and DI treatments. Previous studies have documented that CFI in paddy fields leads to more water loss due to seepage and penetration (Shao *et al.* 2015). The AWD and DI systems reduced the TWI by 24.8% and 37.5% compared with CFI. However, the largest volume of water-saving was obtained under DI system. Padmanabhan (2019) reported that the DI system increased water-saving by 66.3% compared with CFI. In another research, Kruzhilin *et al.* (2015) mentioned that the DI system showed higher water-saving capacity by reducing WI (60–80% reduction) when compared with CFI. Ishfaq *et al.* (2020) demonstrated that the plots under AWD at TPR indicated lower TWI compared with CFI at same production method. Maneepitak *et al.* (2019) reported that the AWD resulted in a 19 and 39% increase in water-savings in wet and dry seasons, respectively, compared with CFI. Carracelas *et al.* (2019) also found that TWI was reduced by 13.9% under AWD compared with traditional CFI. AWD in rice planting to save irrigation water by 40.7% has been suggested by Monaco & Sali (2018) in northern Italy. In general, rice cultivation under DI system resulted in a significant reduction in TWI in this study, but at the same time, it was faced with a severe drop in yield, thus the AWD can be a feasible option to reduce the TWI while maintaining yield.

In all three planting methods, TWI was higher under CFI than AWD and DI. The higher TWI was recorded at DSR under CFI (11,435.7 m^3·ha^{-1}) followed by at TNPB under CFI (9,638.0 m^3·ha^{-1}) and at TPB under CFI (8,441.3 m^3·ha^{-1}). AWD and DI determined a significant TWI reduction at TPB (15.8% and 21.9%), TNPB (28.3% and 37.8%), and DSR (28.5% and 30.7%) when compared with CFI. However, the lowest water-saving was observed under CFI in all three planting methods, which can be caused by more water losses through seepage, percolation, and evaporation (Shao *et al.* 2015). Kiani *et al.* (2022) observed the higher water consumption (12,490 m^3·ha^{-1}) at DSR under CFI, which is consistent with the results of this research.

Total water productivity (TWP) was not affected by the interaction between planting method and irrigation system; however, the individual effects of planting method and irrigation system was highly significant ($p < 0.01$) on TWP (Table 8).

In our study, the TPB reduced TWI with a corresponding increase in TWP. The TWP at TPB was 23.2% and 39.3% higher than TNPB and DSR, respectively (Table 9). The higher TWP at TPB method can be attributed the greater grain yield and lower TWI. Puddling operation enhances irrigation efficiency and WP due to less percolation losses (Monaco & Sali 2018). Wu *et al.* (2017) reported that one of the strategies of water management was puddling soil to reduce percolation and seepage losses.

In the present research, the plots maintained under CFI indicated lowest TWP (0.37 kg·m^{-3}). AWD and DI systems resulted in an increase in TWP by 21.3% and 27.4%, respectively, when compared with CFI. Although the TWP under AWD was lower than that of DI, the AWD could be improving TWP without yield decline. The results showed that in all three planting

Table 10 | Impacts of planting and irrigation management strategies on rice in selected papers

Management	Impacts	References
AWD	Reduced WI and Increased WP compared with CFI	Ishfaq *et al.* (2020)
AWD	Increased water-saving by 40.7% compared with CFI	Monaco & Sali (2018)
CFI	Increased WI and reduced WP compared with AWD, Produced similar yield with AWD	Pourgholam-Amiji *et al.* (2021)
CFI	Increased rice yield and TWI by 15% and 13.9%, respectively, compared with AWD	Carracelas *et al.* (2019)
CFI	Enhanced grain yield of rice by 13.5% compared with DI	Hosseini *et al.* (2022)
CFI	Increased WI by 60–80% compared with DI	Kruzhilin *et al.* (2015)
DI	Increased water-saving by 66.3% compared with CFI	Padmanabhan (2019)
DI	Increased WP compared with CFI and AWD	Rao *et al.* (2017)
DI	Reduced TWI by 30.7% and increased WUE by 38% compared with CFI	Bansal *et al.* (2018)
DI	Decreased grain yield of rice by 11% and increased WP by 22% compared with CFI	Kiani *et al.* (2022)
DSR	Decreased grain yield of rice by 40% and increased WI compared with TPR	Kiani *et al.* (2022)
DSR	Decreased grain yield of rice by 33.5% and 42.9% compared with TPB and TNPB, respectively	Hosseini *et al.* (2022)
TPB	Enhanced grain yield of rice by 12% compared with DSR	Xu *et al.* (2019)
TPB	Enhanced grain yield of rice by 14.2% compared with TNPB	Hosseini *et al.* (2022)

management strategies, there was no significant difference in TWP between DI and AWD systems. The TWP was higher under DI than CFI in all three planting methods, whereas the TWP under AWD was significantly higher than CFI only at TPB and TNPB (Table 9). The higher volume of TWI under CFI conditions during the growing season led to a significant decrease in TWP. In other hand, the lower TWI under AWD and DI systems resulted in higher TWP. Drip irrigation by reducing water loss due to evaporation from a large area of land leads to a reduction in WI and an increase in WP for crops (Bansal *et al.* 2018). Previous studies indicated a significant enhance in WP by reducing the volume of WI under DI system (Padmanabhan 2019). Carrijo *et al.* (2017) mentioned that the AWD system decreased TWI by 39% and enhanced TWP by 77% in the dry season, when compared with CFI. Ishfaq *et al.* (2020) also observed that the WP was higher under AWD than CFI at both production system (TPR and DDSR) due to higher grain yield and lower TWI. The impacts of planting and irrigation management strategies on rice in selected papers in present study are presented in Table 10.

CONCLUSIONS

Our findings indicated that TPB could help significant increase in the total tillers number per hill, panicle number per hill, filled grains number per panicle, and 1,000-grain weight leading towards higher grain yield by 20% and 27.2% compared with TNPB and DSR methods, respectively. The DSR treatment had the highest total water input and the lowest total water productivity, while the TPB method increased the water-saving by 4.5% and 17.3%, respectively, compared with the TNPB and DSR treatments. Also, the total water productivity at TPB was 23.2% and 39.3% higher than TNPB and DSR, respectively. The grain yield in two CFI and AWD systems was similar and had no significant difference with each other, while the yield obtained from DI treatment was significantly lower than the CFI and AWD techniques. The AWD system could be recommended without a significant reduction in grain yield (1.36% reduction) along with an increase in water-saving (24.8% increase) and enhance in total water productivity (21.3% increase) when compared with CFI. In general, the results indicated that choosing the appropriate planting method is of greater importance in improving grain yield and using the correct irrigation system has a vital role in increasing water-saving. Therefore, TPB method under AWD system is recommended to reducing total water input and increasing grain yield for Indica rice in Iran.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 28 February 2023; accepted in revised form 28 July 2023. Available online 10 August 2023