

Effect of water and rice straw management practices on yield and water productivity of irrigated lowland rice in the Central Plain of Thailand



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ABSTRACT

Rice cultivation techniques with less irrigation water input are crucial for global food security in the context of changing climate scenarios. Alternate wetting and drying (AWD) is among such water-saving techniques, which could potentially reduce irrigation water input for rice cultivation through alteration of soil submergence period with period of soil non-submergence (unsaturated soil conditions) during the growing season. Rice straw is often scattered in the field after harvest or burned in intensive rice cultivation systems. Response of irrigated lowland rice with respect to grain yield and water use under different water and rice straw management practices largely remains unknown. Field experiments were conducted at the Ayutthaya Rice Research Center, Ayutthaya, Thailand, in two consecutive rice-growing seasons (wet and dry) of 2016–2017 to evaluate the growth, yield and water productivity of irrigated lowland rice under different water and rice straw management practices. The treatments included were two water (continuous flooding [CF] and AWD) and three rice straw management practices (rice straw incorporation [RS-I], rice straw burning [RS-B] and without rice straw incorporation and burning [WRS-I + BJ]). AWD increased grain yield by 15% in the wet season and by 7% in the dry season compared with CF. Other yield components such as panicle number m^{-2} , spikelet number panicle $^{-1}$ and 1000-grain weight were also higher under AWD compared with CF depending on the growing season. AWD reduced total water input by 19% in the wet season and by 39% in the dry season resulting in an improvement in total water productivity by 46% in the wet season and by 77% in the dry season relative to CF. Rice straw application either as soil incorporation or open-field burning had no effect on grain yield, water-saving potential and water productivity of the tested variety regardless of the growing season. Although its positive role in supplying plant nutrients and maintaining soil fertility, rice straw incorporation in the field or burning should be discouraged due to negative environmental impacts. AWD (15 cm threshold water level below the soil surface for irrigation or with soil water potential of ≥ -20 kPa [AWD15]) is recommended for irrigated lowland rice cultivation from a point of view of reducing total water input without jeopardizing yield.

1. Introduction

Thailand is among the major producers of rice (*Oryza sativa* L.) on a global scale (Ullah et al., 2018a). The Central Plain with its almost 30% rice production contributes the largest share in the national production where rice is cultivated both in the rainy season (May–October) and to irrigated area in the dry season (November–April). The soils in the Central Plain are predominantly composed of clay with a high water holding capacity. Both traditional transplanting and direct seeding methods of rice establishment are commonly practiced in the Central

Plain of Thailand. The area under direct seeding or broadcasting method was 1.72 million hectares (mha) in 2016 and 1.62 mha in 2017, whereas the area under transplanting was 0.12 mha in 2016 and 0.06 mha in 2017 (Office of Agricultural Economics (OAE, 2018)). Transplanting is increasingly being replaced by seeding of pre-germinated seed to wet soil in irrigated rice production system to reduce production costs. Like most of the rice-producing countries, farmers' in Thailand usually apply more water than required to suppress weed populations causing excessive seepage and percolation losses and a resultant reduction in water productivity (WP). The area under

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irrigation and its associated cost (energy/fuel consumption in pumping) has significantly increased in the country in the past several years. The sustainability of irrigated rice production system has also been challenged by water scarcity due to climate change, and rapid urbanization and industrialization are further depleting water reserves and limiting the availability of irrigation water (Bouman and Tuong, 2001; Yan et al., 2015). These necessitate the adoption of water-efficient techniques to reduce water use in agricultural sector, while maintaining or increasing yield to support a growing population (Carrijo et al., 2017; Rijsberman, 2006). Cultivation techniques with less water demand, higher yield, less greenhouse gas (GHG) emission and more WP are ideally needed for sustainable rice production systems to improve food security in many Asian countries.

The popular continuous flooding (CF) system provides a favorable water and nutrient supply as well as weed management under anaerobic conditions; however, rice cultivation under this traditional system demands higher water input than other cereal crops (Datta et al., 2017; Nguyen et al., 2009). Various water-efficient techniques have been developed for rice cultivation in the context of decreasing irrigation water availability (Liu et al., 2015; Nie et al., 2011). Alternate wetting and drying (AWD) is among the most widely promoted water-saving irrigation technique introduced by the International Rice Research Institute (IRRI) to cope with increasing threat of water scarcity in rice cultivation (Belder et al., 2004; Bouman and Tuong, 2001; Datta et al., 2017). Under this system, fields are subjected to intermittent flooding (alternate cycles of saturated and unsaturated conditions) where water of about 2–5 cm is applied at an interval of 2–7 days depending on the soil type and weather condition followed by disappearance of ponded water from the soil surface and appearance of visible sign of some fine cracks on the soil surface (Tuong and Bouman, 2003).

AWD irrigation is an efficient technique that helps maintain sustainable rice production by saving water and reducing methane emission rate into the atmosphere (Watanabe et al., 2013; Liang et al., 2016). A reduction of 23% in water input has been reported under AWD compared with continuously flooded rice systems (Bouman and Tuong, 2001). Belder et al. (2004) reported that AWD technique can save water and reduce water use by 15–20% without jeopardizing yield. Moreover, AWD irrigation can help reduce annual methane emission by 57–78% from rice fields (LaHue et al., 2016). AWD can significantly reduce total water input in Thailand (Ullah et al., 2018b), thereby reducing input costs and improving farmers' livelihoods. In Thailand, the cost of water input for rice production is about US\$ 142.3 ha⁻¹ crop⁻¹ and a slight reduction in irrigation water input could be financially remunerative for the farmers (Office of Agricultural Economics (OAE, 2018)). Apart from reducing water input, while maintaining or increasing yields and methane emission, some other benefits associated with AWD include enhancement in nutrient uptake, better root growth, more grain filling rate, remobilization of carbon reserves from vegetative tissues to grains and reduction of energy/fuel consumption where irrigation is supplied by pumping (Chu et al., 2014; Liu et al., 2013; Nalley et al., 2015; Tuong et al., 2005; Ullah and Datta, 2018; Yao et al., 2012; Zhang et al., 2008, 2009, 2012). Poor management of rice straw in intensive rice cultivation systems is an environmental concern and its proper utilization could help achieve better yield.

In Thailand, a total of about 42 mt of rice straw is produced annually and out of which almost 10 mt is generated in the Central Plain (Office of Agricultural Economics (OAE, 2018)). About 69% of rice straw produced in the country is burnt (open-field burning) due to limited time availability to prepare the field for the next crop and easiness in field maintenance. Rice straw is also left scattered in the field after harvest. Rice straw incorporation has positive relationship to soil fertility and ecological environment (Wang et al., 2015). The burning practice is less laborious than straw incorporation, but has environmental consequences in the form of air pollution and emission of GHG (Wang et al., 2015, 2016). The inefficient use of freshwater and rice straw is a major concern in rice production systems in Thailand. Grain

yield and water use of irrigated lowland rice under different water and rice straw management practices are not well documented. We hypothesized that rice straw incorporation along with AWD (15 cm threshold water level below the soil surface for irrigation, AWD15) would be a better approach for maintaining soil moisture status and supplying nutrients, thereby reducing water input and increasing yield. Pathumthani 1, released for lowland rice fields in the Central Plain, is a photoperiod-insensitive variety (Ullah et al., 2017; Ullah and Datta, 2018; Ullah et al., 2018b), and is commonly grown in the Central Plain of Thailand having a yield potential of 4.45 t ha⁻¹ (Office of Agricultural Economics (OAE, 2018)). The objective of the present study was to evaluate the growth, yield and water productivity of irrigated lowland rice (Pathumthani 1) under different water and rice straw management practices.

2. Materials and methods

2.1. Experimental site

Two field experiments were conducted during the wet (July–October 2016) and dry (November 2016–February 2017) rice-growing seasons of 2016–2017 at the Ayutthaya Rice Research Center (14°21'54.79"N, 100°36'19.71"E, 2 m above mean sea level), Ayutthaya Province, Thailand. The study area has two distinct seasons (wet and dry) and belongs to the tropical savanna climatic zone characterized by warm temperature throughout the year. The area receives an annual rainfall of 1000–1400 mm (almost all in the wet season) and experiences mean annual temperature of around 27 °C. The dry season lasts from November–April and the wet season lasts from May–October. The soil of the experimental field is classified as Ayutthaya soil series originated from a marine sediment-mixed riverine alluvium having a ground water depth of > 2 m. The soil is poorly-drained clay at 0–15 cm depth with the main soil properties as follows: sand 14%, silt 22%, clay 64%, pH (1:1 soil-water) 6.0, organic matter 1.41%, total C (w/w) 0.95%, total N (w/w) 0.16%, available P 17 mg kg⁻¹, available K 201 mg kg⁻¹, available Ca 5129 mg kg⁻¹, available Mg 953 mg kg⁻¹ and electrical conductivity 0.81 dS m⁻¹. The mean monthly temperature and total rainfall during the experimental period in the wet and dry seasons were 28.6 °C and 577.7 mm, and 27.7 °C and 80.8 mm, respectively (Fig. 1).

2.2. Experimental design and agronomic management

The experiment was repeated over seasons using split-plot design with three replications. The main plot was two irrigation management: CF and AWD (under AWD irrigation, irrigation was applied to a depth of around 5 cm when field water level dropped to 15 cm (soil water potential at -10 to -15 kPa) below the soil surface [AWD15]), whereas the subplot was three rice straw management: rice straw incorporation (RS-I), rice straw burning (RS-B) and without rice straw incorporation and burning (WRS-I + B). The individual plot size was 5 m × 7 m and plots were separated by a 1 m wide alley. Bunds (dikes) of 30 cm height were constructed along each side of the plot to prevent lateral water movement and were covered with black plastic film inserted to a depth of 30 cm below the soil surface.

In the wet season, seeds of Pathumthani 1 rice variety were sown by pre-germinated broadcasting method (wet direct seeding) into the main field on 5 July and harvested on 18 October 2016. The field was left idle for a short fallow period (about two weeks) after rice harvest in the wet season, and the same field was used for rice cultivation in the dry season. In the dry season, seeds of the same variety were broadcasted on 31 October 2016 and crops were harvested on 26 February 2017. The seed rate was 125 kg ha⁻¹ in both seasons. Pathumthani 1 is a photoperiod-insensitive variety, and the maturity period ranges between 106 and 126 days.

In the wet season, the plot under the CF treatment was continuously

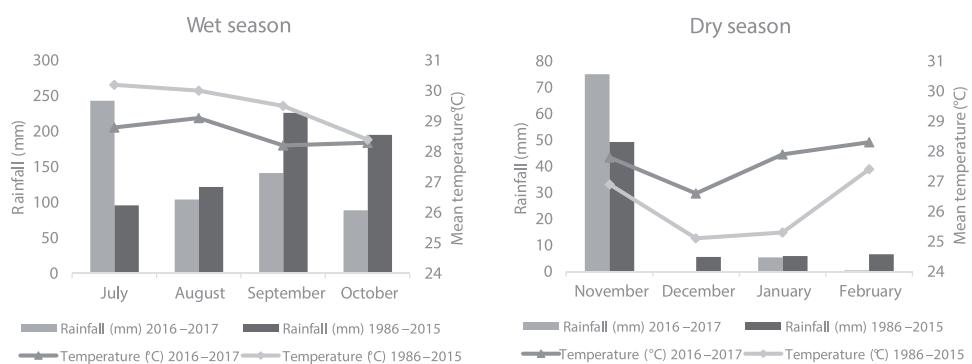


Fig. 1. Mean monthly temperature and total monthly rainfall at the experimental site in the wet and dry rice growing seasons of 2016–2017 and of the past 30 years (1986–2015).

Table 1

Irrigation water input and total monthly rainfall during the wet and dry rice growing seasons of 2016–2017 under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) treatments.

Season	Water management	Rice straw management	Irrigation water input ($\text{m}^3 \text{ha}^{-1}$)				Rainfall ($\text{m}^3 \text{ha}^{-1}$)			
			July	August	September	October	July	August	September	October
Wet season	CF	RS-I	–	7758.29	2297.71	–	2433	1039	1414	891
		RS-B	–	7441.43	2080.57	–	2433	1039	1414	891
		WRS-I + B	–	7325.57	2003.43	–	2433	1039	1414	891
	AWD	RS-I	–	4014.29	2429.71	–	2433	1039	1414	891
		RS-B	–	3754.72	2781.29	–	2433	1039	1414	891
		WRS-I + B	–	4434.29	2481.72	–	2433	1039	1414	891
	Dry season	RS-I	–	9944.29	2145.71	–	751	0	55	4
		RS-B	–	9831.86	2137.14	–	751	0	55	4
		WRS-I + B	–	9721.43	1928.57	–	751	0	55	4
		RS-I	–	4580.00	2162.00	–	751	0	55	4
		RS-B	–	4086.42	2571.57	–	751	0	55	4
		WRS-I + B	–	5157.14	2126.86	–	751	0	55	4

flooded by maintaining a constant surface water depth of 1–2 cm during 1–14 days after broadcasting (DAB), 5 cm water during 15–92 DAB and irrigation was stopped 2 weeks before harvest (106 DAB). In the dry season for the same treatment, the plot was flooded with 1–2 cm water during 1–14 DAB, 5 cm water during 15–105 DAB and irrigation was stopped 2 weeks before harvest (119 DAB). For the AWD treatment (AWD15), the plot was flooded with 1–2 cm water from the first day of broadcasting until 25 and 30 DAB in the wet and dry seasons (seedling stage), respectively, and then irrigation was stopped. The plot was irrigated again to a depth of around 5 cm above the soil surface whenever the water level dropped to 15 cm below the soil surface as indicated by perforated field-water tube installed in each plot. This AWD cycle continues throughout the tillering stage until the initial flowering stage as indicated by panicle initiation (60 and 61 DAB in the wet and dry seasons, respectively) followed by continuously maintaining a standing water depth of 5 cm until 2 weeks before harvest. The data on irrigation water input and total monthly rainfall during both rice growing seasons are presented in Table 1. In the RS-I plots, rice straw from the preceding season was soaked in water for 2 days and was manually spread onto the soil surface at the rate of 5000 kg ha^{-1} . In the RS-B plots, $5000 \text{ kg rice straw ha}^{-1}$ was burned under open-field burning conditions. Straws were ignited by a butane-fueled lighter and the burning typically lasted for 3–5 min in each plot. The RS-I and RS-B treatments were applied around 2 weeks before broadcasting the rice seeds in both seasons followed by tillage operations with a power tiller. The WRS-I + B plots did not receive any rice straw incorporation and burning.

All treatments received the same synthetic fertilizer in both growing seasons. Fertilizer was applied at the rate of 156 kg ha^{-1} at 21 and 24 DAB in the wet and dry seasons, respectively, in the form of NPK

(16:20:0) as a basal dose. Urea (46:0:0) was top-dressed at the rate of 94 kg ha^{-1} at 65 and 69 DAB in the wet and dry seasons, respectively. Insect pests, diseases and weeds were chemically controlled to avoid yield loss by following the recommended plant protection measures for rice cultivation in Ayutthaya Province.

2.3. Data collection

The seasonal and long-term temperature and rainfall data were collected from the Ayutthaya Rice Research Center. Data on growth parameters such as plant height, leaf area index (LAI), shoot and root dry matter were collected at three growth stages of tillering, flowering and maturity. In the wet season, data on growth parameters were collected at 60 DAB corresponding to tillering (26–60 DAB), at 84 DAB corresponding to flowering (61–93 DAB) and at 98 DAB corresponding to maturity stage (94–106 DAB). In the dry season, data on growth parameters were collected at 60 DAB corresponding to tillering (26–61 DAB), at 84 DAB corresponding to flowering (62–103 DAB) and at 112 DAB corresponding to maturity stage (104–119 DAB). The required data were collected from ten hills in each plot from a demarcated area of 1 m^2 . Plant height was measured from the ground level to the top most tiller/panicle and LAI was measured nondestructively with the help of an app (PocketLAI) using a smartphone (Confalonieri et al., 2013). Fresh shoot (leaves, stems and panicles if any) and root samples were oven dried at 75°C until constant weight, weighted and shoot and root dry matter measured. At maturity, grain yield was measured from a 10 m^2 harvest area within each plot excluding the plants at the border areas, and was adjusted to 14 kg kg^{-1} moisture content basis. Data on yield components such as panicle number m^{-2} , spikelet number

panicle⁻¹, filled grain (%) and 1000-grain weight were collected from a 1 m² area in each plot at the same day of harvesting for both seasons. Data were not collected from the plants at the border areas in each plot to avoid the border effect.

2.4. Determination of water input and water productivity

In both seasons, data on total water input (m³ ha⁻¹) and total water productivity (kg m⁻³) were also collected. Total water input included water input from both irrigation and rainfall. In both seasons, water volume input from irrigation to each plot was measured using a flow meter installed in the irrigation pipeline, whereas rainfall data were collected from the Ayutthaya Rice Research Center. Total water productivity (TWP) was calculated by dividing the grain yield (kg) by total water input (m³) (Liang et al., 2016; Ullah et al., 2018b).

2.5. Statistical analysis

A two-way ANOVA was performed using the statistical package SPSS 20.0 to test the significance of treatment combinations and their interactions on the basis of growth, grain yield, yield components, total water input and TWP. Means for significant treatment effects were separated by Fisher's protected least significant difference (LSD) at the $P < 0.05$ probability level.

3. Results

3.1. Growth parameters

The two-way interaction between water and rice straw management was highly significant ($P < 0.01$) for plant height at flowering stage, whereas the individual effect of water management was highly significant at tillering stage and rice straw management at tillering and maturity stages in the wet season (Table 2). In the wet season, plant height was significantly higher under CF than AWD at tillering stage. RS-I had significantly lower plant height than plant height at RS-B and WRS-I + B at both tillering and maturity stages. Plant height remained similar at RS-B irrespective of water management practice, whereas RS-I had significantly higher plant height under AWD than CF and WRS-

I + B had significantly lower plant height under AWD than CF at flowering stage in the wet season. Plant height was not affected by either water or rice straw management practice in the dry season regardless of growth stage.

Water and rice straw management did not influence LAI in the wet season regardless of growth stage, and the same was also true for tillering and flowering stages in the dry season (Table 3). LAI was significantly affected ($P < 0.05$) by rice straw management at maturity stage in the dry season. LAI was the highest (4.8) at RS-I, which was statistically at par with LAI at RS-B, but 17% higher than LAI at WRS-I + B.

Shoot dry matter was highly significantly ($P < 0.01$) affected by the two-way interaction between water and rice straw management at flowering stage in the wet season, and by the individual effect of rice straw management at flowering and maturity stages in the dry season (Table 4). In the wet season, shoot dry matter was significantly higher under AWD at RS-I, which was reduced by 42% at the same rice straw management under CF. The two water management practices resulted in similar shoot dry matter at WRS-I + B, whereas RS-B under CF had 60% higher shoot dry matter than the same rice straw management under AWD. In the dry season, RS-I had significantly lower shoot dry matter than both RS-B and WRS-I + B at flowering and maturity stages.

Root dry matter was not affected by water and rice straw management in the wet season, except at flowering stage where the individual effect of water management was highly significant ($P < 0.01$) (Table 5). The two-way interaction between water and rice straw management at flowering stage and the individual effect of water management at maturity stage were highly significant ($P < 0.01$) for root dry matter in the dry season. In the wet season, root dry matter under AWD was 36% higher than CF at flowering stage. In the dry season, there was no significant difference in root dry matter between the two water management practices at RS-B and WRS-I + B at flowering stage; however, root dry matter was reduced by 73% at RS-I under CF compared with the same rice straw management practice under AWD. Root dry matter under AWD was 42% higher than root dry matter under CF at maturity stage.

Table 2

Plant height of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Plant height (cm)					
	Wet season			Dry season		
	Tillering	Flowering	Maturity	Tillering	Flowering	Maturity
Water management (W)						
CF	86.3 ± 2.57a	100.5 ± 2.27	118.3 ± 5.07	62.9 ± 2.57	87.7 ± 3.27	107.6 ± 1.39
AWD	81.0 ± 2.37b	99.8 ± 2.39	123.1 ± 2.41	63.4 ± 3.30	88.3 ± 3.66	108.7 ± 1.75
Rice straw management (R)						
RS-I	79.5 ± 2.04b	96.8 ± 2.38b	114.8 ± 6.52b	60.9 ± 3.14	85.0 ± 3.55	106.9 ± 1.68
RS-B	85.1 ± 2.96a	103.4 ± 2.28a	127.3 ± 2.14a	66.4 ± 3.10	99.2 ± 3.93	109.3 ± 1.49
WRS-I + B	86.3 ± 2.42a	100.3 ± 2.33a	119.9 ± 2.56a	62.2 ± 2.57	86.7 ± 2.92	108.2 ± 1.55
W × R						
CF + RS-I	83.2 ± 1.75	94.2 ± 2.23b	111.2 ± 10.28	59.3 ± 2.85	82.8 ± 3.67	106.1 ± 1.48
CF + RS-B	86.8 ± 3.01	103.9 ± 2.22a	123.5 ± 2.10	68.2 ± 2.39	93.6 ± 3.26	110.1 ± 1.53
CF + WRS-I + B	88.8 ± 2.95	103.4 ± 2.35a	120.3 ± 2.82	61.3 ± 2.47	86.7 ± 2.89	106.5 ± 1.17
AWD + RS-I	75.8 ± 2.32	99.4 ± 2.53a	118.3 ± 2.75	63.3 ± 3.42	87.3 ± 3.43	107.7 ± 1.87
AWD + RS-B	83.3 ± 2.91	102.9 ± 2.33a	131.2 ± 2.17	65.3 ± 3.80	90.8 ± 4.59	108.5 ± 1.45
AWD + WRS-I + B	83.8 ± 1.89	97.1 ± 2.30b	119.7 ± 2.30	61.8 ± 2.67	86.7 ± 2.95	109.8 ± 1.92
F-value						
W	6.48**	0.13ns	1.50ns	0.05ns	0.44ns	0.74ns
R	4.11**	3.97**	3.54**	1.64ns	2.27ns	1.13ns
W × R	0.29ns	3.03**	0.47ns	0.21ns	0.55ns	1.12ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and ** non-significant and significance at $P < 0.01$, respectively.

Table 3

Leaf area index of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Leaf area index					
	Wet season			Dry season		
	Tillering	Flowering	Maturity	Tillering	Flowering	Maturity
Water management (W)						
CF	2.4 ± 0.37	5.0 ± 0.25	5.3 ± 0.36	1.6 ± 0.28	3.4 ± 0.27	4.3 ± 0.29
AWD	2.4 ± 0.34	4.9 ± 0.30	5.4 ± 0.24	1.5 ± 0.26	3.3 ± 0.28	4.5 ± 0.35
Rice straw management (R)						
RS-I	2.7 ± 0.34	5.2 ± 0.26	5.7 ± 0.15	1.7 ± 0.33	3.6 ± 0.24	4.8 ± 0.30a
RS-B	2.1 ± 0.36	4.7 ± 0.34	5.1 ± 0.30	1.3 ± 0.21	3.0 ± 0.28	4.2 ± 0.33a
WRS-I + B	2.3 ± 0.36	5.0 ± 0.24	5.1 ± 0.45	1.6 ± 0.26	3.3 ± 0.29	4.1 ± 0.34b
W × R						
CF + RS-I	2.5 ± 0.40	5.4 ± 0.14	5.6 ± 0.24	1.7 ± 0.28	3.6 ± 0.28	5.0 ± 0.26
CF + RS-B	2.2 ± 0.39	4.7 ± 0.30	4.9 ± 0.37	1.3 ± 0.26	3.1 ± 0.21	4.1 ± 0.30
CF + WRS-I + B	2.4 ± 0.31	4.9 ± 0.31	5.3 ± 0.48	1.4 ± 0.29	3.4 ± 0.28	3.9 ± 0.32
AWD + RS-I	2.9 ± 0.28	5.1 ± 0.37	5.8 ± 0.06	1.7 ± 0.38	3.6 ± 0.20	4.7 ± 0.34
AWD + RS-B	2.1 ± 0.33	4.7 ± 0.37	5.3 ± 0.23	1.3 ± 0.16	2.9 ± 0.35	4.4 ± 0.35
AWD + WRS-I + B	2.3 ± 0.40	5.1 ± 0.16	4.9 ± 0.42	1.7 ± 0.23	3.3 ± 0.29	4.4 ± 0.35
F-value						
W	0.03ns	0.06ns	0.15ns	0.21ns	0.22ns	0.28ns
R	1.41ns	1.62ns	2.02ns	1.01ns	2.24ns	2.90*
W × R	0.28ns	0.37ns	0.74ns	1.94ns	0.01ns	0.82ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and * non-significant and significance at $P < 0.05$, respectively.

Table 4

Shoot dry matter of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Shoot dry matter (kg ha^{-1})					
	Wet season			Dry season		
	Tillering	Flowering	Maturity	Tillering	Flowering	Maturity
Water management (W)						
CF	3589.8 ± 645.60	9717.9 ± 1269.70	17891.9 ± 3560.93	1797.5 ± 392.03	7925.9 ± 1121.46	11600.7 ± 1419.33
AWD	3705.9 ± 869.81	9463.8 ± 1089.77	17559.5 ± 3344.49	2084.4 ± 570.79	8127.7 ± 1610.85	13253.5 ± 1780.75
Rice straw management (R)						
RS-I	3594.8 ± 936.59	10460.2 ± 1408.69	19064.2 ± 4644.03	1608.9 ± 412.58	5159.7 ± 1045.75b	8398.6 ± 1063.38b
RS-B	3212.5 ± 240.80	10362.1 ± 1103.07	19321.8 ± 3251.87	2242.8 ± 591.52	8932.5 ± 1509.48a	14335.3 ± 1767.23a
WRS-I + B	4136.4 ± 389.20	7950.3 ± 1027.44	14791.3 ± 2462.23	1971.2 ± 440.14	9988.2 ± 1543.25a	14547.3 ± 1969.52a
W × R						
CF + RS-I	2836.3 ± 367.17	7697.8 ± 1232.97b	19115.6 ± 4925.18	1323.3 ± 319.10	4244.2 ± 784.01	6896.8 ± 751.67
CF + RS-B	3137.5 ± 501.55	12751.5 ± 1465.52a	19074.1 ± 3078.77	2404.3 ± 461.69	9973.5 ± 1197.79	15034.3 ± 1703.7
CF + WRS-I + B	4795.7 ± 1068.08	8704.5 ± 1110.60b	15486.1 ± 2678.83	1685.0 ± 395.31	9560.0 ± 1382.58	12871.0 ± 1802.62
AWD + RS-I	4353.2 ± 1506.01	13222.8 ± 1584.41a	19012.7 ± 4362.87	2068.0 ± 506.06	6075.21 ± 1307.48	9900.5 ± 1375.09
AWD + RS-B	3287.5 ± 431.10	7972.6 ± 740.62b	19569.4 ± 3424.97	1993.4 ± 721.35	7891.5 ± 1821.16	13636.4 ± 1830.76
AWD + WRS-I + B	3477.2 ± 672.32	7196.0 ± 944.28b	14096.4 ± 2245.63	2202.0 ± 484.97	10416.5 ± 1703.92	16223.6 ± 2136.41
F-value						
W	0.03ns	0.07ns	0.01ns	0.49ns	0.03ns	1.49ns
R	0.58ns	2.74ns	1.01ns	0.79ns	6.50**	8.85**
W × R	1.36ns	9.40**	0.04ns	0.32ns	1.05ns	1.27ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and ** non-significant and significance at $P < 0.01$, respectively.

3.2. Yield components and grain yield

Number of panicle m^{-2} was not affected by the two-way interaction between water and rice straw management; however, the individual effect of water management was highly significant ($P < 0.01$) in the wet season and that of water as well as rice straw management were highly significant ($P < 0.01$) in the dry season (Table 6). AWD had 23% and 9% greater number of panicle m^{-2} than CF in wet and dry seasons, respectively. Among the three rice straw management practices, WRS-I + B had significantly lower number of panicle m^{-2} than

RS-I and RS-B in the dry season.

The individual effect of water management was highly significant ($P < 0.01$) for spikelet number panicle^{-1} in the wet season, whereas it was highly significantly affected by the two-way interaction between water and rice straw management as well as the individual effect of rice straw management in the dry season (Table 6). AWD had 12% higher spikelet number panicle^{-1} than CF in the wet season. In the dry season, the two water management practices resulted in similar spikelet number panicle^{-1} at RS-I, whereas AWD had 12% and 7% higher spikelet number panicle^{-1} than CF at RS-B and WRS-I + B, respectively.

Table 5

Root dry matter of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Root dry matter (kg ha^{-1})					
	Wet season			Dry season		
	Tillering	Flowering	Maturity	Tillering	Flowering	Maturity
Water management (W)						
CF	1224.2 ± 532.36	1419.3 ± 245.39b	1420.2 ± 265.70	731.4 ± 151.40	802.8 ± 123.66b	954.3 ± 142.26b
AWD	1284.7 ± 260.79	1934.6 ± 349.91a	1749.6 ± 335.15	994.2 ± 281.94	1180.8 ± 259.03a	1358.2 ± 193.55a
Rice straw management (R)						
RS-I	1103.9 ± 259.66	1600.6 ± 260.64	1684.4 ± 318.52	811.3 ± 208.47	892.4 ± 172.36	1027.5 ± 146.04
RS-B	1315.5 ± 219.94	1837.8 ± 308.40	1658.1 ± 298.17	806.6 ± 206.96	994.3 ± 151.53	1229.1 ± 201.09
WRS-I+B	1343.9 ± 177.78	1592.9 ± 324.02	1412.1 ± 284.59	970.6 ± 234.59	1088.4 ± 250.16	1212.1 ± 156.60
W × R						
CF + RS-I	1025.1 ± 169.83	1146.9 ± 185.35	1480.2 ± 273.06	547.5 ± 124.76	375.5 ± 50.73b	674.5 ± 120.04
CF + RS-B	1449.0 ± 265.86	1729.4 ± 271.29	1487.3 ± 162.61	874.4 ± 183.97	965.9 ± 157.55a	1179.8 ± 186.69
CF + WRS-I+B	1198.4 ± 96.67	1382.6 ± 279.54	1293.1 ± 361.44	772.3 ± 145.48	1067.1 ± 162.71a	1008.6 ± 120.04
AWD + RS-I	1182.8 ± 349.48	2054.4 ± 335.93	1888.7 ± 363.97	1075.1 ± 292.17	1409.3 ± 293.99a	1380.5 ± 172.03
AWD + RS-B	1181.9 ± 174.02	1946.1 ± 345.50	1828.9 ± 433.73	738.8 ± 229.95	1022.7 ± 145.5a	1278.5 ± 215.48
AWD + WRS-I+B	1489.5 ± 258.88	1803.3 ± 368.30	1531.2 ± 207.74	1168.8 ± 323.69	1109.6 ± 337.61a	1415.6 ± 193.15
F-value						
W	0.80ns	4.03**	1.64ns	1.96ns	4.69**	8.24**
R	0.02ns	0.51ns	0.45ns	0.45ns	0.42ns	0.84ns
W × R	0.18ns	0.77ns	0.04ns	0.77ns	3.54**	1.55ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and ** non-significant and significance at $P < 0.01$, respectively.

There was no significant difference in filled grain percentage regardless of water and rice straw management practices in the wet season, whereas the two-way interaction between water and rice straw management as well as the individual effect of rice straw management

were highly significant ($P < 0.01$) in the dry season (Table 6). In the dry season, the three rice straw management practices resulted in similar filled grain percentage under AWD and the same was also true for RS-B under both water management practices. At RS-I and WRS-I + B,

Table 6

Yield components of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Wet season				Dry season			
	Panicle number m^{-2}	Spikelet number panicle^{-1}	Filled grain (%)	1000-grain weight (g)	Panicle number m^{-2}	Spikelet number panicle^{-1}	Filled grain (%)	1000-grain weight (g)
Water management (W)								
CF	446.9 ± 16.70b	104.6 ± 2.25b	88.2 ± 0.75	26.2 ± 0.18b	540.3 ± 23.00b	110.1 ± 3.62	76.0 ± 1.32	25.4 ± 1.24b
AWD	549.2 ± 10.30a	117.6 ± 4.15a	87.5 ± 0.69	26.9 ± 0.30a	587.1 ± 13.00a	118.7 ± 3.26	76.3 ± 1.30	28.4 ± 0.87a
Rice straw management (R)								
RS-I	515.5 ± 9.05	114.2 ± 3.72	87.7 ± 0.75	26.7 ± 0.28	598.7 ± 7.72a	119.1 ± 3.11a	76.1 ± 1.09a	27.9 ± 0.84
RS-B	486.0 ± 11.90	109.9 ± 3.92	88.1 ± 0.68	26.5 ± 0.27	553.5 ± 16.43a	112.0 ± 4.16b	77.9 ± 1.43a	26.9 ± 0.99
WRS-I+B	496.7 ± 19.10	109.2 ± 3.64	87.7 ± 0.74	26.5 ± 0.18	539.0 ± 29.85b	112.0 ± 3.05b	74.5 ± 1.41b	25.9 ± 1.34
W × R								
CF + RS-I	461.3 ± 6.89	107.9 ± 3.05	88.3 ± 0.77	26.1 ± 0.15	592.0 ± 5.03	117.8 ± 3.44a	75.5 ± 1.18b	25.2 ± 0.71
CF + RS-B	434.0 ± 16.80	102.5 ± 3.32	88.1 ± 0.74	26.2 ± 0.24	531.3 ± 27.95	105.6 ± 3.68b	79.9 ± 1.30a	26.7 ± 1.32
CF + WRS-I+B	445.3 ± 26.41	103.6 ± 3.72	88.1 ± 0.74	26.3 ± 0.14	497.7 ± 36.01	106.7 ± 3.73b	71.9 ± 1.47b	24.2 ± 1.68
AWD + RS-I	561.7 ± 12.12	120.7 ± 4.39	87.1 ± 0.73	27.2 ± 0.40	605.3 ± 10.40	120.4 ± 2.78a	76.7 ± 0.99a	30.6 ± 0.96
AWD + RS-B	538.0 ± 7.00	117.3 ± 4.52	87.9 ± 0.61	26.8 ± 0.29	575.7 ± 4.91	118.4 ± 4.63a	76.1 ± 1.56a	27.1 ± 0.66
AWD + WRS-I+B	548.0 ± 11.79	114.7 ± 3.55	87.4 ± 0.74	26.7 ± 0.22	580.3 ± 23.68	114.3 ± 2.37a	76.0 ± 1.35a	26.7 ± 0.99
F-value								
W	69.20**	17.44**	1.64ns	11.59**	7.04**	0.01ns	0.06ns	11.61**
R	1.45ns	1.04ns	0.19ns	0.42ns	4.16**	31.53**	3.28**	1.47ns
W × R	0.01ns	0.12ns	0.29ns	0.97ns	1.29ns	3.55**	3.72**	2.62ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and ** non-significant and significance at $P < 0.01$, respectively.

Table 7

Grain yield, total water input and total water productivity of Pathumthani 1 rice variety under two water (continuous flooding [CF], alternate wetting and drying [AWD]) and three rice straw management (rice straw incorporation [RS-I], rice straw burning [RS-B], without rice straw incorporation and burning [WRS-I + B]) practices in the wet and dry seasons of 2016–2017.

Factor	Wet season			Dry season		
	Grain yield (kg ha^{-1})	Total water input ($\text{m}^3 \text{ha}^{-1}$)	Total water productivity (kg m^{-3})	Grain yield (kg ha^{-1})	Total water input ($\text{m}^3 \text{ha}^{-1}$)	Total water productivity (kg m^{-3})
Water management (W)						
CF	3709.9 ± 182.45b	15413 ± 591.29a	0.24 ± 0.02b	3909.8 ± 60.08b	12713 ± 487.16a	0.31 ± 0.02b
AWD	4281.0 ± 157.60a	12409 ± 196.03b	0.35 ± 0.02a	4195.1 ± 60.56a	7705 ± 274.26b	0.55 ± 0.02a
Rice straw management (R)						
RS-I	3889.0 ± 162.89	14027 ± 354.68	0.29 ± 0.02	4063.0 ± 63.82	10226 ± 162.48	0.43 ± 0.02
RS-B	4122.1 ± 98.17	13806 ± 320.51	0.30 ± 0.02	4095.5 ± 23.36	10123 ± 200.44	0.44 ± 0.01
WRS-I + B	3975.3 ± 249.02	13899 ± 505.80	0.29 ± 0.03	3998.8 ± 95.29	10277 ± 779.22	0.42 ± 0.03
W × R						
CF + RS-I	3590.9 ± 221.31	15833 ± 633.36	0.23 ± 0.02	3855.9 ± 60.95	12900 ± 162.38	0.30 ± 0.01
CF + RS-B	4047.8 ± 65.14	15299 ± 544.13	0.26 ± 0.01	4048.8 ± 26.19	12779 ± 307.90	0.32 ± 0.01
CF + WRS-I + B	3490.8 ± 260.91	15106 ± 596.38	0.23 ± 0.02	3824.7 ± 93.10	12460 ± 991.20	0.31 ± 0.03
AWD + RS-I	4187.0 ± 104.46	12221 ± 75.99	0.34 ± 0.01	4270.1 ± 66.69	7552 ± 162.58	0.57 ± 0.02
AWD + RS-B	4196.3 ± 131.20	12313 ± 96.88	0.34 ± 0.02	4142.3 ± 20.53	7468 ± 92.97	0.55 ± 0.01
AWD + WRS-I + B	4459.69 ± 237.13	12693 ± 415.22	0.35 ± 0.03	4172.9 ± 94.47	8094 ± 567.23	0.52 ± 0.03
F-value						
W	14.27**	65.46**	44.13**	27.27**	154.57**	206.36**
R	0.81ns	0.12ns	0.31ns	1.08ns	0.05ns	0.66ns
W × R	2.46ns	0.87ns	0.75ns	3.20ns	0.64ns	1.24ns

Data are means ± standard errors of three replications. In a column, numbers followed by same letters are not significantly different by least significant difference (LSD) at $P < 0.05$. ns and ** non-significant and significance at $P < 0.01$, respectively.

CF had significantly lower filled grain percentage than the corresponding filled grain percentage at the same rice straw management practices under AWD. Filled grain percentage at RS-B was 6% and 11% higher than filled grain percentage at RS-I and WRS-I + B under CF.

The individual effect of water management was highly significant ($P < 0.01$) for 1000-grain weight in both wet and dry seasons (Table 6). AWD had significantly higher 1000-grain weight than CF irrespective of growing season.

Water management highly significantly ($P < 0.01$) affected grain yield in both seasons (Table 7). Overall, a higher grain yield was obtained from plants maintained under AWD than under CF in both seasons. AWD had 15% and 7% higher grain yields than CF in the wet and dry seasons, respectively. The difference in yields among rice straw management practices was not significant. In the wet season, the highest grain yield (4122 kg ha^{-1}) was obtained at RS-B plots, whereas it was the lowest (3889 kg ha^{-1}) at RS-I. In the dry season, grain yield was the highest (4096 kg ha^{-1}) at RS-B followed by statistically similar grain yield at RS-I (4063 kg ha^{-1}) and at WRS-I + B (3999 kg ha^{-1}).

3.3. Water use and water productivity

Total water input and TWP were highly significantly ($P < 0.01$) affected by the individual effect of water management in both seasons (Table 7). The plots maintained under CF had the highest total water input in both rice growing seasons. AWD irrigation reduced total water input by 19% and 39% compared with CF in the wet and dry seasons, respectively. AWD water-saving technique reduced total water input in both seasons with a corresponding increase in TWP. TWP was significantly higher under AWD than CF in both growing seasons. AWD resulted in 46% and 77% higher TWP than CF in the wet and dry seasons, respectively.

4. Discussion

4.1. Water management, rice growth and grain yield

Safe or moderate AWD (AWD15) is a comparatively new and easy-to-use technique developed for Asian farmers to reduce water input

while maintaining yield in irrigated rice production system (Liang et al., 2016). Some studies have observed similar or even increased grain yield under AWD compared with CF (Yang et al., 2007; Yao et al., 2012; Zhang et al., 2009), whereas a reduction in yield under AWD has also been reported (Belder et al., 2004; Bouman and Tuong, 2001). The main constraints in wider adoption of this technology include difficulty in handling, reliability and effectiveness (Liang et al., 2016). Extensive studies under different soil and environmental conditions are, therefore, needed for a wider acceptability of this technique.

We observed higher grain yields under AWD compared with CF in both growing seasons. These higher yields under AWD irrigation could be attributed, at least in part, to greater panicle number m^{-2} (wet and dry seasons), spikelet number panicle $^{-1}$ (wet and dry seasons), filled grain percentage (dry season) and 1000-grain weight (wet and dry seasons) (Table 6). Water stress at critical growth stages affects growth and yield contributing factors of rice. Liang et al. (2016) observed more unfilled grains under severe AWD (30 cm threshold water level below the soil surface for irrigation [AWD30]) and claimed the yield reduction under this treatment as a result of reduced grain filling. We observed no difference in filled grain percentage between AWD15 and CF in both wet and dry seasons. Overall, rice straw management had no significant effect on most of the yield components including filled grain percentage under AWD irrigation. From these findings, it can be concluded that better rice straw management (avoiding soil incorporation or burning) could help increase filled grain percentage of rice leading towards higher grain yield, and AWD could be safely recommended without a significant reduction in filled grain percentage. Application of AWD (soil drying) during grain filling stage of rice enhances root growth for maximum uptake of nutrients, which causes soluble carbohydrate accumulation and promotes faster remobilization of these assimilates to the grain (Li et al., 2016; Yang and Zhang, 2006). Based on this mechanism, yield enhancement could be possible by imposing AWD at grain filling stage as it will direct maximum photoassimilate transport from source to inferior spikelet grain filling when supply of nutrient is limited (Li et al., 2016).

There is an inconsistency among the published literature regarding the success in maintaining grain yields of rice subjected to AWD irrigation technique possibly because of differences in the specification of

AWD technique and experimental conditions such as climate, soil type, ground water depth, crop management and rice variety (Carrijo et al., 2017; Liang et al., 2016; Ullah et al., 2018b). The threshold for re-watering in most growth stages of rice under AWD irrigation could be based on either field water level or soil water potential. Bouman et al. (2007) mentioned that reflooding of the field when field water level reaches 15 cm below the soil surface as observed in perforated field water tubes installed into the soil would not affect grain yield of rice, and is termed as ‘safe AWD’ (AWD15). The same technique has been applied in the present study, and the results are in line with the findings of Lampayan et al. (2015), who also observed an increased grain yield of rice under AWD compared with traditional CF irrigation. In a similar study, Carrijo et al. (2017) found comparable grain yield between safe AWD and CF with a significant reduction in irrigation water input and GHG emission under AWD. It can be concluded from the present findings that application of AWD could maintain or even increase grain yield of lowland irrigated rice along with a significant reduction in total water input compared with CF. Therefore, this water-saving irrigation technique could be a feasible option in reducing total water input and maintaining grain yield for soil and weather conditions comparable to the present study.

Extensive root system is vital for growth and development of aerial plant parts and grain yield (Ullah et al., 2017; Ullah and Datta, 2018). Similarly, shoot dry matter, panicle number and harvest index are closely associated with grain yield of rice (Fageria, 2007; Liang et al., 2016). Optimum panicle density and uniform maturity are also important parameters for higher grain yield (Li et al., 2014). Overall, there was no difference in shoot and root dry matter between water management practices (CF and AWD); however, the two-way interaction between water and rice straw management practices significantly affected shoot dry matter in the wet season as well as root dry matter in the dry season at flowering stage with better performance of RS-I under AWD than CF (Tables 4 and 5). RS-I had the lowest shoot and root dry matter under CF, which might be responsible for lower grain yield under this treatment. The effect of rice straw management on root dry matter was not clearly visible under AWD as the three rice straw management practices had similar results indicating better performance of this irrigation technique in maintaining root growth of rice regardless of rice straw management practice. Other growth parameters such as plant height (Table 2) and LAI (Table 3) were also similar for most of the rice straw management practices suggesting no benefit of rice straw management (incorporation or burning).

Incorporation of rice straw to the paddy field has become a prevailing agricultural practice as it can supply plant nutrients to the present crop, leave substantial residual effect on succeeding crops in the system and also positively influence various soil properties (Surekha et al., 2006). However, these benefits could be offset by an enhanced methane emission. The analysis of the impacts of rice straw incorporation is critical as it can significantly increase grain yield of rice (Huang et al., 2013). As against the previous findings of Zhang et al. (2017), who observed a significant increase in rice grain yield with rice straw incorporation, we found no significant effect of rice straw incorporation on grain yield compared with no straw incorporation regardless of water management practice. Rice straw is an important source of plant nutrients and organic carbon resulting in an increase in soil organic matter and an improvement in soil fertility (Zhang et al., 2017). In the present study, the poor performance of rice straw under CF could be caused by the accumulation of some toxic materials such as H₂S due to fast decomposition of rice straw under anaerobic conditions (Zhang et al., 2017). Awio et al. (2015) observed no significant effect of rice straw incorporation on grain yield of rice under field conditions, but a significant effect was evident under screenhouse conditions. In another study, Supapoj et al. (1998) found that types of crop residue (e.g., rice straw, rice husk) had significant residual effect on crops where more pronounced effects were evident with rice straw than rice husk. Rice straw incorporation could increase grain yield of rice, but its

application should be discouraged as straw incorporation creates favorable conditions for methane production in rice paddy fields (Bhattacharya et al., 2012; Wang et al., 2016).

Rice straw burning, which is a common practice in the study area, had beneficial effects on some of the yield components such as panicle number m⁻² and filled grain percentage in the dry season under CF (Table 6). These could be due to substantial nutrient contribution through the ash of rice straw under flooded conditions as most of the elements will remain in the ash, and become water soluble and readily available for plant uptake (Surekha et al., 2006). However, these benefits were not translated in the form of grain yield and TWP, which were significantly lower under CF than AWD regardless of rice straw management practice. Burning of rice straw in the fields should be discouraged as it produces gaseous and non-gaseous matter, which pollutes the atmosphere (Surekha et al., 2006). Based on our results, AWD irrigation is, therefore, recommended in lowland rice cultivation without rice straw incorporation or burning.

4.2. Total water input and water productivity

Total water input was reduced by 19% in the wet season and by 39% in the dry season under AWD compared with CF (Table 7). Studies dealing with water-saving potential of AWD compared with CF mostly reported varying degrees of irrigation water savings, but with a yield penalty. Carrijo et al. (2017) observed an average reduction of 27.5% in irrigation water input under AWD compared with CF, but with a grain yield reduction of 5.4%. The authors suggested that severe AWD (where soil water potential was allowed to drop below –20 kPa) should be avoided because of higher yield loss, although the water-saving potential was 33.4%. In contrast to these findings, we observed more water-saving potential and an increase in grain yield of rice under AWD depending on growing season. A significantly higher TWP of 46% in the wet season and 77% in the dry season was observed under AWD compared with CF. Carrijo et al. (2017) also reported an increased WP of 25.9% under AWD compared with CF. Higher TWP observed during the present study was due to reduced total water input and higher grain yield under AWD compared with CF. Moreover, reduced rate of seepage and percolation under AWD could also be partly responsible for this higher TWP (Carrijo et al., 2017). Increased WP and better grain yield are critically important for sustainable rice production in the changing climate scenarios, and this goal could be achieved with wider adoption of AWD (Ullah et al., 2018b). However, economic analysis of using this technique is also essential as Nalley et al. (2015) investigated the viability of various AWD practices and observed that AWD method with the highest WP was economically the most unfeasible.

5. Conclusion

Contrasting results regarding the yield performance of rice under AWD irrigation and rice straw management exist necessitating the evaluation of these practices in diverse soil and weather conditions. We observed a significant reduction in total water input and higher TWP under AWD compared with CF along with an increase in grain yield. Rice straw application (either soil incorporation or burning) had little or no effect on grain yield and its components. Rice straw incorporation creates favorable conditions for methane production in rice paddy fields and burning pollutes the atmosphere by producing gaseous and non-gaseous matter. Our findings highlight that AWD irrigation (AWD15) could be used as a water-saving technique for irrigated lowland rice production system under soil and weather conditions comparable to the present study. Rice straw application should be discouraged due to its associated environmental concern compared with its role in enhancing grain yield and WP.

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