



Research article

Effects of alternate wetting and drying water management and rice straw incorporation on sustainable rice production under rainy season conditions in central Thailand

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Abstract

Importance of the work: Alternate wetting and drying (AWD) to save water and rice straw (RS) management are important for sustainable rice production in Thailand.

Objectives: To investigate the synergistic effects of AWD and RS incorporation for rice production in the rainy season.

Materials & Methods: Pathum Thani 1 rice was grown during the rainy season in 2022. Plant growth rates, yields and costs were observed in one control [continuous flooding (CF)] plot and three AWD plots, where for the applied chemical fertilizers, the recommended rates and one-half of these rates and RS, or organic fertilizer and RS were applied.

Results: The irrigation times and oxygen redox values of the paddy water were almost the same in both the CF and AWD treatments. AWD with RS and cattle manure incorporation increased the grain yield by 15%, whereas decreasing the chemical fertilizer rate and the RS rate to one-half the recommended amounts decreased the grain yield by 19% compared to CF paddy without RS and cattle manure. Applying the recommended rate of organic fertilizer instead of chemical fertilizer under AWD did not result in a yield reduction, although lower growth rates of the rice plants were observed. The costs were higher in the AWD treatments due to RS and cattle manure incorporation. The benefit-to-cost ratio (B:C) values were not offset by the higher grain yield and were lower in the AWD treatments.

Main finding: RS incorporation and AWD increased the grain yield in both the conventional and organic practices, using only the recommended rates of fertilizer. However, the increased yield was not sufficient to offset the amendments cost and therefore B:C decreased with the rainy season conditions.

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Introduction

Climate changes, such as the increase in air temperature and in the intensity of precipitation, have been observed in Thailand over the decades due to global warming effects (Beule et al., 2016; Limsakul and Singhruck, 2016). The Intergovernmental Panel on Climate Change reported that global warming is expected to reach 1.5°C during 2030–2050 due to human activities (Intergovernmental Panel on Climate Change, 2021). More extreme hot weather, heavy rainfall and severe droughts are expected, with the risks associated with water and food security are also of great concern (Intergovernmental Panel on Climate Change, 2021). The rise in air temperature would result in severe grain yield loss, which could offset the effect of increased photosynthesis activity (Chandrasekaran et al., 2008).

Chemical fertilizers have played a key role in improving grain yield; however, the rapid increase in the price of chemical fertilizers makes it difficult to achieve farm-level financially sustainable production. Nowadays, the cost of chemical fertilizer has increased rapidly; since 2010, the prices of chemical fertilizers have risen to about 130% in 2021 (International Bank for Reconstruction and Development, 2022). In addition, the long-term use of chemical fertilizer could lead to as little as 1% of soil organic contents in the paddy soil (Chandrasekaran, 2008).

Rice straw (RS) is the residue from rice plants. It is easily accessible to most rice farmers and contains many kinds of nutrients, which positively influence soil fertility (Dobermann and Fairhurst, 2002; Van Hung et al., 2020). However, the most common and easiest disposal of the RS post harvesting is open burning in the field. The total area of RS burned in Thailand reached 3.90 million ha in 2011 releasing as much as 11,891 t/yr of black carbon (particulate matter less than 2.5 µm, CO and CO₂) into the atmosphere (Kanokkanjana et al., 2011). These large amounts of air pollutants cause climatic changes and deterioration of public health (Amk, 2020).

Incorporation of RS into the soil returns most of the nutrients and helps to conserve soil nutrient reserves in the long-term (Dobermann and Fairhurst, 2002). In addition, RS incorporation increases soil organic matter (Bi et al., 2009) and could reduce fertilizer usage (Van Hung et al., 2020). Furthermore, RS incorporation helps to promote soil aeration, reduce irrigation water requirements, lessen soil cracking and improve rice yield components. On the other hand, decomposition of RS under anaerobic conditions produces some toxic substances, such as H₂S, which could cause root rot, negative effects on plant height and yield loss (Gao et al., 2002).

Alternate wetting and drying (AWD) is one of the best practical water management methods for paddy rice that helps to save water. Once the water level decreases to 15 cm below the surface, irrigation water is supplied to re-flood the paddy to a 10 cm depth (International Rice Research Institute, 2021). An AWD irrigation system involves a repetition of flooded and non-flooded situations. Thus, the paddy has an alternate aerobic and anaerobic environment. The water availability in AWD paddy is lower than for continuous flooding (CF) paddy and lower rice yields are expected; however, many studies found no significant yield decrease with AWD treatments (Liang et al., 2016; Maneepitak et al., 2019). In addition, methane emissions were reported to be lower with AWD management, even with RS incorporation in Thailand (Maneepitak et al., 2019).

Rice is a vital economic crop in Thailand and the assessment of financial viability is essential when farmers adopt a new agronomic management. AWD suggests positive economic viability in the field experiments due to the reduction in irrigation water and the reduced labor requirement. Incorporation of affordable RS and a reduction in chemical fertilizer usage or its replacement with organic fertilizer could improve the cost-benefit ratio of rice production. Effects of AWD and RS incorporation in the dry season in central Thailand have been investigated (Suzuki et al., 2023). However, the effects in the rainy season have not yet been researched. Different seasonal effects between the dry and rainy seasons are expected due to the differing amounts and frequencies of rainfall events. Thus, the objectives of the current study were: (1) to investigate the effects of the reduction of chemical fertilizer usage on a rice crop using RS incorporation and AWD conditions; (2) to identify the best treatment for Pathum Thani 1 rice production; and (3) to investigate the economic variability of AWD and RS incorporation management.

Materials and Methods

Experimental site

Field experiments were conducted during the rainy season (June–October 2022) at a research field on the Kamphaeng Saen campus, Kasetsart University, Nakhon Pathom province, central Thailand. The total research area was approximately 3,000 m² including the ridges around the paddy. This study area was in the tropical savanna climate zone with two distinct seasons: a dry season from November to April and a rainy season from May to October. The mean maximum

and minimum air temperatures were 32.2°C and 24.2°C, respectively, and the total rainfall was 3,051 mm during the experimental period, as shown in Fig. 1, based on weather data collected using a WatchDog 2000 Series Weather Station (Spectrum Technologies, Inc.; USA) installed in the center of the experimental field. The soil at the experimental site was investigated in the soil science laboratory at Kamphaeng Saen campus and was classified as sandy loam with the major characteristics of soil being pH 6.8, bulk density 1.4 g/cm³, electric conductivity 0.3 dS/m, organic matter 1.1%, available P 75.2 mg/kg and exchangeable K 60.7 mg/kg.

Experimental design and agronomic managements

Field experiments were conducted using a randomized block design with each treatment having four replications. Each treatment area was 539 m² (11 m × 49 m) and was surrounded by a 1.5 m ridge. There were four replicate plots in one treatment plot and the water was irrigated from a canal alongside the field. The experimental conditions in the four treatments are shown in Table 1. Treatment 1 was a CF control plot using herbicides and chemical fertilizers. Treatments 2–4 were AWD plots. In plots 2 and 3, herbicides and chemical

fertilizers were used. The chemical fertilizer application rates were the same in treatments 1 and 3, namely 0.375 t/ha of 18-8-8 (N-P-K) applied 15 DAT (days after transplanting) and 0.188 t/ha of 46-0-0 applied 45 DAT. Half rates of those fertilizers were applied as treatment 2. Treatment 4 received twice the organic fertilizer application, totaling 3.70 t/ha instead of chemical fertilizers and the weeds were controlled using hand weeding. RS and cattle manure were applied to treatments 2–4. The application rates of RS were 2.5 t/ha for treatment 2 and 5.0 t/ha for treatments 3–4. These three treatments were supplied with 3.75 t/ha of cattle manure.

On 1 June 2022, the paddy field was ploughed using hollow discs. The RS and cattle manure were manually applied over plots 2–4 on 11 June and soaked using irrigation water. The RS was incorporated into the soil using this rotary plow on 27 June. Puddling was conducted using a drive harrow on 8 July; on 10 July, the seedlings were transplanted, with 25 cm by 25 cm spacing and three seedlings per hill. Herbicide was applied 8 DAT to treatments 1–3. Fertilizers were applied 15 DAT and 45 DAT. Manual weeding was conducted 20 and 30 DAT in treatment 4. Other crop management was conducted according to local practices to prevent yield loss (International Rice Research Institute, 2021).

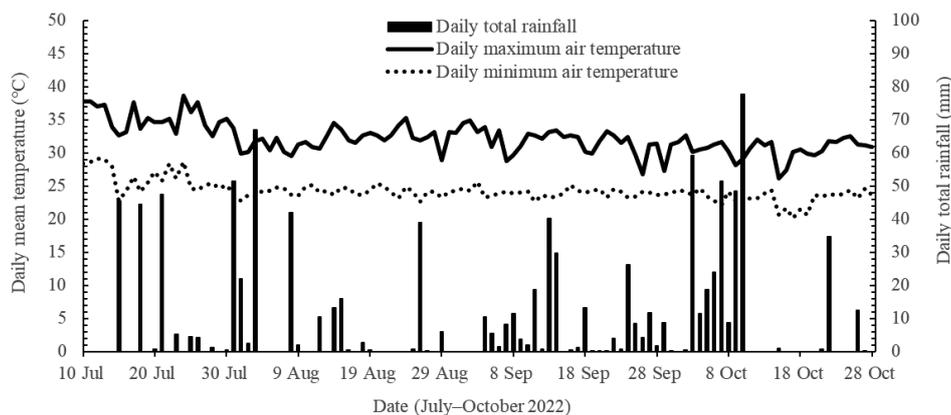


Fig. 1 Daily maximum and minimum air temperatures and daily total rainfall during experimental period (July–October 2022)

Table 1 Rice growth conditions in four experimental treatments

Treatment	Irrigation management	Rice straw (t/ha)	Cattle manure (t/ha)	Fertilizer rate (N-P-K; t/ha)	Weed control
Trt.1	CF	No RS	No CM	18-8-8; 0.375 46-0-0; 0.188	Herbicide
Trt.2	AWD	2.5	3.75	18-8-8; 0.188 46-0-0; 0.094	Herbicide
Trt.3	AWD	5.0	3.75	18-8-8; 0.375 46-0-0; 0.188	Herbicide
Trt.4	AWD	5.0	3.75	Organic fertilizer 1.85×2 times	Weeding

RS = rice straw; CM cattle manure; CF = continuous flooding; AWD = alternate wetting and drying; Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD + RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application.

Data collection

The weather data were collected every 30 min automatically using the weather station. The soil sampling was conducted before the start of field experiments. The paddy soil was analyzed in the soil science laboratory in Kamphaeng Saen campus, Kasetsart University. The oxygen redox potential (ORP) of the paddy water in the pani-pipes was measured using an ORP meter to obtain the redox potential (E_h) value, to describe the oxidation-reduction status in millivolts. Plant growth data, plant height, tiller number and the soil plant analysis development (SPAD) value of the leaf were measured every 10 DAT. Data were collected for five rice plants in each replication. Plant height, from the ground to the topmost tiller or panicle in a shoot, was measured using a measuring scale. The number of tillers was counted manually. The SPAD values of rice leaves were measured using a SPAD-502Plus (Konica Minolta Sensing Inc.; Japan). Root length was defined as the maximum root length of one shoot. The shoot and root were taken from the paddy field and the soil sticking to the roots was removed. Then, the roots were washed thoroughly using water and the root length was measured. After that, the shoot and root were placed in a paper bag and dried in the oven for 72 hr. The dry weights of the shoot and roots were measured using a measuring scale. Grain yields and four yield components (panicle number per stool, spikelet number per stool, filled grain rate and 1,000-grain weight) were measured from a demarcated area of 1.0 m². The 1,000-grain weight was calculated from the weight of 100 grains, while the other three parameters were manually counted. The sampling area did not include the border area to avoid the influence of border effects.

Cost-benefit analysis

Production costs were calculated from the bill payments for materials and agronomic practices. The weeding cost was estimated

based on the time spent and the irrigation cost was estimated based on the number of irrigation events. Both weeding and irrigation costs were calculated based on a unit cost of USD 9.45/person/d (Labor Office Nakhon Pathom Province, 2022). The revenue from the RS was calculated based on the weight of rice straw multiplied by the purchase price (USD 66.6/t). The revenue from the grain was based on the unit rice price multiplied by the yield of rice. The unit rice price was determined as USD 212/t for conventional rice and USD 347/t for organic rice (Llonas et al., 2022). The gross margin was calculated from the total revenue minus the total production cost. The benefit-cost ratio was calculated from the gross margin divided by the total production cost (Sriphirom et al., 2020).

Statistical analysis

The R program (version 4.2.6, 2022; R Core Team, 2020) was used for statistical analysis based on analysis of variance, with treatment means separated based on Duncan's new multiple range test at a significance of $p < 0.05$.

Results

Paddy water and soil characteristics

After transplanting, irrigation water was applied at 14 DAT, with an additional irrigation event for treatments 3 and 4 at 45 DAT. Irrigation was conducted in the tillering stage. Regular natural rainfall events occurred throughout all growing stages, as shown in Fig. 1. More than 30 mm/d were recorded on 14 separate days.

The E_h values in the paddy water increased by around 80 mV between 1 wk before and 2 wk after transplanting, as shown in Fig. 2. From 3 wk after transplanting, the E_h values fluctuated in the range 35–135 mV for all treatments, although there sometimes rapid changes.

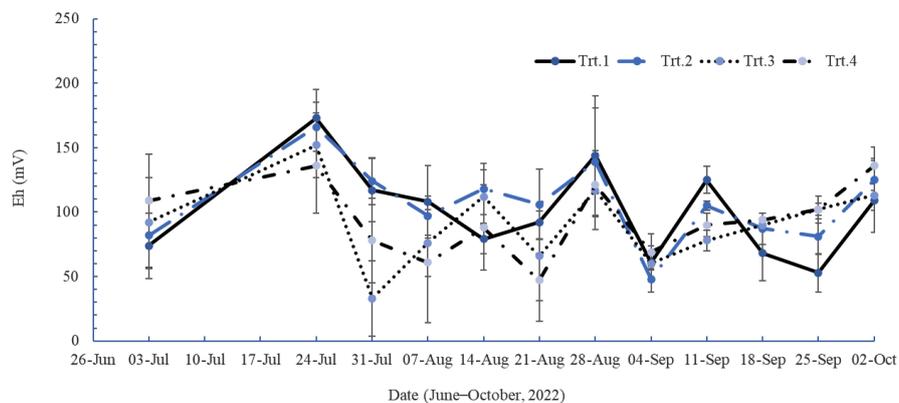


Fig. 2 Weekly changes in redox potential (E_h) values in paddy water, where error bars indicate \pm SD and Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD + RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application

Soil properties before cultivation and after harvesting are shown in Table 2. The bulk density increased slightly in treatment 1, while it decreased in the other treatments. The organic matter percentage in the soil dropped in all treatments and reduced by approximately one-half in treatments 2 and 3. The available P contents in the soil increased and exchangeable K decreased in all treatments. Both P and K after harvesting remained significantly higher in treatment 4 than other treatments.

Rice plant growth

Initially, plant heights increase continuously until 80 DAT, as shown in Fig. 3. The growth rate was approximately 15 cm

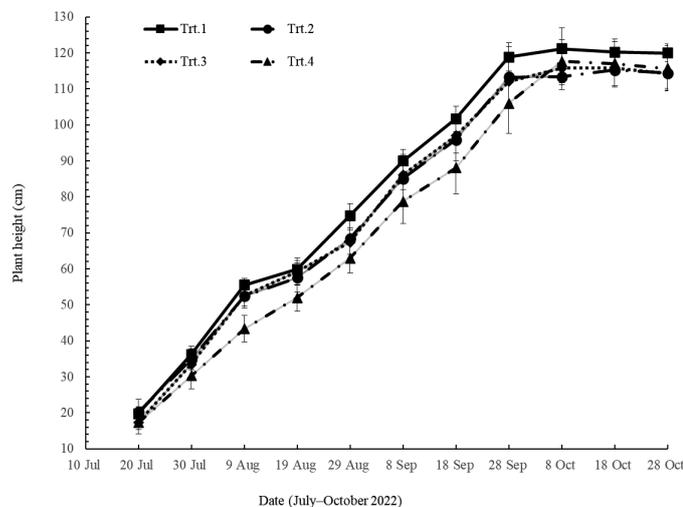


Fig. 3 Changes in plant height every 10 d after transplanting, where error bars indicate \pm SD and Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD +RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application

per 10 DAT in every treatment, except for the period 30–40 DAT, where the heights increased by approximately 5 cm in treatments 1–3 and 10 cm in treatment 4. From 80 DAT, the growth rates slowed; however, only treatment 4 kept growing at approximately 15 cm during 80–90 DAT. There were no significant differences between treatments 1–3 for 20–40 DAT and 60–80 DAT, while treatments 1 and 4 were significantly different from 20–80 DAT continuously. From 90 DAT onward, there were no significant differences among the treatments and plant height increases ceased in all treatments.

The number of tillers rapidly increased during 10–60 DAT and then rapidly dropped during 60–80 DAT, as shown in Fig. 4. After 80 DAT, the tiller numbers decreased slowly. The highest increase in tiller number was approximately 7–9 tillers per 10 DAT,

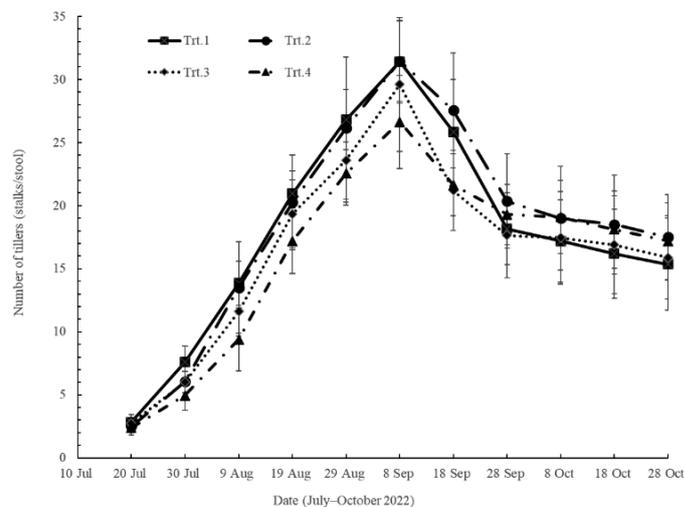


Fig. 4 Changes in number of tillers every 10 d after transplanting, where error bars indicate \pm SD and Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD +RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application

Table 2 Changes in paddy soil properties before cultivation and after harvesting

Soil property	Trt.1	Trt.2	Trt.3	Trt.4
Bulk density (g/cm^3)				
Before			1.38	
After	1.42 ± 0.01^a	1.28 ± 0.01^b	1.23 ± 0.01^d	1.24 ± 0.01^c
Organic matter (%)				
Before			1.7	
After	1.0 ± 0.03^b	0.7 ± 0.01^d	0.9 ± 0.03^c	1.2 ± 0.04^a
Available P (mg/kg)				
Before			41.9	
After	53.8 ± 2.42^b	53.9 ± 3.59^b	54.6 ± 2.11^b	69.0 ± 2.16^a
Exchangeable K (mg/kg)				
Before			133.7	
After	65.7 ± 1.60^b	66.3 ± 1.63^b	65.6 ± 3.33^b	78.2 ± 0.91^a

Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD +RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application.

Values (mean \pm SD) with different lowercase superscripts indicate significant differences for treatments at $p < 0.05$ based on Duncan new multiple range test.

observed during 30–40 DAT, with the maximum tillering numbers recorded at 60 DAT in every treatment. There were significant differences among treatments at 10 DAT, 50 DAT, 60 DAT and 90 DAT. At 30 DAT and 40 DAT, the tiller number for treatment 4 was significantly lower than for treatment 1.

The SPAD values gradually increased during 30–50 DAT and fluctuated or slowly decreased during 50–80 DAT in every treatment, as shown in Fig. 5. After 80 DAT, the SPAD values fluctuated in the range 39–41. During 40–70 DAT, the SPAD value of treatment 1 was significantly higher than the others and during 50–60 DAT, the SPAD values of treatment 2 and 4 were significantly lower than the others. At 80 DAT, there were no significant differences among treatments.

Shoot and root biomass

Significant differences in the shoot dry weight were detected between treatments at every growing stage, as shown in Table 3. At 30 DAT, only treatment 4 had significantly lower weight than the others while significant differences were detected between treatments 1 and 2, 2 and 3, and 3 and 4 at 60 DAT. At 90 DAT and 110 DAT, treatments 1 and 3 were significantly heavier than the others. On the other hand, there were no significant differences from 30 DAT to 110 DAT in both the root dry weight and the maximum root length. The root dry weight peaked at 110 DAT in all treatments, while the maximum root length reached a peak at 90 DAT in all treatments.

Grain yields

Significant differences were observed for grain yield and the number of panicles between the treatments, as shown in Table 4. There were no significant differences for 1,000-grain weight, the number of spikelets and the filled grain ratio. The highest values for both grain yield and the number of panicles were recorded in treatments 3 and 4, followed by treatment 1 and treatment 2, respectively.

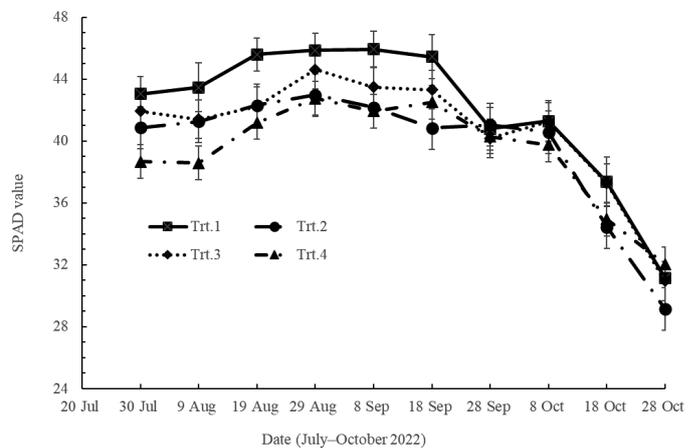


Fig. 5 Changes in SPAD value every 10 d after transplanting, where error bars indicate \pm SD and Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD + RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application

Table 3 Shoot and root dry weight and maximum root length on 30, 60, 90 and 110 DAT

Biomass by treatment	30 DAT	60 DAT	90 DAT	110 DAT
Shoot dry weight (g)				
Trt.1	7.2 \pm 1.6 ^a	81.8 \pm 2.6 ^a	116.5 \pm 9.0 ^a	190.5 \pm 23.8 ^a
Trt.2	6.6 \pm 0.6 ^a	66.5 \pm 5.3 ^b	105.5 \pm 5.7 ^a	129.8 \pm 16.9 ^b
Trt.3	6.0 \pm 1.1 ^{ab}	54.0 \pm 5.8 ^c	110.0 \pm 7.0 ^a	202.0 \pm 8.2 ^a
Trt.4	4.7 \pm 0.8 ^b	45.0 \pm 6.2 ^d	78.0 \pm 14.5 ^b	135.0 \pm 10.1 ^b
Root dry weight (g)				
Trt.1	6.1 \pm 0.8	21.2 \pm 6.7	26.7 \pm 7.8	27.4 \pm 6.8
Trt.2	4.8 \pm 1.8	14.8 \pm 3.9	24.3 \pm 14.6	26.9 \pm 8.4
Trt.3	5.4 \pm 1.4	21.0 \pm 1.1	26.3 \pm 5.6	30.0 \pm 9.8
Trt.4	4.3 \pm 5.8	14.9 \pm 11.0	20.8 \pm 6.3	25.1 \pm 4.0
Maximum root length (cm)				
Trt.1	24.6 \pm 0.6	28.3 \pm 3.7	26.8 \pm 0.6	24.0 \pm 0.7
Trt.2	25.1 \pm 2.1	24.7 \pm 2.6	26.8 \pm 1.4	24.5 \pm 1.8
Trt.3	26.2 \pm 1.5	25.6 \pm 2.4	29.1 \pm 2.4	24.1 \pm 2.2
Trt.4	27.2 \pm 2.0	24.7 \pm 1.3	26.8 \pm 4.1	23.6 \pm 0.9

DAT = days after transplanting; Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD + RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application.

Values (mean \pm SD) with different lowercase superscripts indicate significant differences for treatments at $p < 0.05$ based on Duncan new multiple range test.

Table 4 Grain yield and yield components

Treatment	Yield (t/ha)	Panicle no. (/stool)	Spikelet no. (/panicle)	Filled grain rate (%)	1,000-grain weight (g)
Trt.1	4.58 ± 0.38 ^b	13.9 ± 1.0 ^b	90.5 ± 15.1	72.5 ± 4.1	22.7 ± 1.1
Trt.2	3.76 ± 0.32 ^c	12.7 ± 0.5 ^c	92.7 ± 11.8	73.8 ± 4.0	22.4 ± 0.4
Trt.3	5.27 ± 0.19 ^a	15.4 ± 0.7 ^a	91.9 ± 7.3	74.1 ± 5.6	23.1 ± 0.6
Trt.4	5.25 ± 0.62 ^a	15.7 ± 0.4 ^a	89.8 ± 10.2	72.0 ± 3.6	23.1 ± 1.7

Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD +RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application.

Values (mean ± SD) with different lowercase superscripts indicate significant differences for treatments at $p < 0.05$ based on Duncan new multiple range test.

Costs and benefits of rice production

The cost and benefit structures of the four treatments are shown in Table 5. The cost for agronomic labour in treatment 4 was higher than for the others due to the weeding cost, while plant protection costs were lower in treatment 4 since there no herbicides were used. RS and cattle manure costs were more than 20% in the AWD treatments. As a result, the total cost of rice production was the lowest in treatment 1 and the highest in treatment 4. Due to the low grain yields, B:C was lowest in treatment 2. The market price of organic rice was a little higher, which increased the benefits, so the B:C in treatment 4 was rather higher despite the higher production costs. B:C was highest in treatment 1.

Discussion

Paddy water and soil characteristics

AWD water management has been recognized widely and its application has been reported to reduce the amount of water usage (Liang et al., 2016; Maneepitak et al., 2019). Irrigation water consumption was reduced by 19% in the rainy season

in central Thailand (Maneepitak et al., 2019). In the current study, during the rainy season, irrigation times were almost the same due to the frequent rainfall events. Treatments 3 and 4, (5.0 t/ha of RS incorporated) needed one additional irrigation event compared to the CF plot. Some research has revealed that RS amendments decreased the bulk density of the soil and increased the soil infiltration rate (Mousavi et al., 2012). Shorter intervals between irrigation events could have encouraged the high RS incorporation rates.

After transplanting, the average E_h value was 90 mV, which was within the recommended range (59–177 mV) for rice plant uptake in the four treatments (Sahrawat, 2005). The changes in E_h could be related to the flooded and non-flooded paddy conditions (Ishfaq et al., 2002). However, the E_h values of paddy water were similar in the current study, which could be attributed to the lower frequency of non-flooded conditions in the AWD treatments because of the continuous rainfall events. The E_h range was above 0 mV throughout the experiment, including before transplanting. This means that the paddy water was in the oxidation status through the experiment. An accumulation of organic matter, low water velocity and anaerobic microbial activity cause a decrease in the E_h value, often below 0 mV (Xia et al., 2013).

Table 5 Cost and benefit details of four treatments

Costs and Benefits (USD /ha)		Trt.1	Trt.2	Trt.3	Trt.4
Cost	Agronomic labor	462	462	462	549
	Chemical fertilizer	171	86	171	
	Organic fertilizer				526
	Rice straw and cattle manure		248	347	347
	Plant protection	333	333	333	89
	Total	968	1,129	1,314	1,511
Benefit	Rice straw	483	461	512	356
	Rice grains	919	820	1,066	1,822
	Total	1,403	1,282	1,578	2,178
Profit	435	153	264	667	
B:C ratio	0.50	0.11	0.24	0.44	

Trt.1 = conventional practices; Trt.2 = AWD + RS and CM, but 50% RS and 50% chemical fertilizers; Trt.3 = AWD +RS and CM; Trt.4 = AWD + RS and CM, with organic fertilizers weeding instead of herbicide application.

RS could improve soil fertility by keeping the soil moisture content high (Ruensuk et al., 2010) and the incorporation of organic matter was reported to cause clay particles to form aggregates and reduce the bulk density (Saothongnoi et al., 2014). Thus, the RS incorporated in treatments 2, 3 and 4 resulted in significantly lower bulk density than for treatment 1. The organic matter percentages in all treatments decreased throughout the rice cultivation period. Research had indicated that RS incorporation improves the organic matter content (Saothongnoi et al., 2014). However, several years could be needed to produce nutritional changes based on RS applications (Dobermann and Fairhurst, 2002). Based on the current results, AWD treatments 2 and 3 would not be suitable for accumulating soil organic matter. RS incorporation could increase the exchangeable K content (Saothongnoi et al., 2014), while cattle manure was reported to increase the available P and exchangeable K contents (Lund and Doss, 1980). The available P and exchangeable K values were significantly higher only in treatment 4 compared to conventional practices (treatment 1). Treatment 4 could be the best to maintain soil nutritional conditions.

Plant growth, biomass, and grain yields

RS has been considered one of the beneficial amendments to soil fertility (Bi et al., 2009), although some studies have pointed to the negative effects of incorporated RS on plant growth due to its slow decomposition in the flooded paddy (Gao et al., 2002). It has been pointed out that RS incorporation develops reducing conditions, especially 3–6 wk after incorporation (Gao et al., 2004), which in the current experiment was until the 1 mth after transplanting, since the RS was incorporated 2 wk before transplanting. During the early stage of growth, the plant height and number of tillers increased with no RS incorporation (Fang, 2017). In the current experiment, during the early stage of growth, there were no significant differences among treatments 1–3 regarding plant height and the number of tillers at 30 DAT. The lower SPAD values in treatments 2 and 4 from 30 DAT to 70 DAT could be attributed to the lack of chemical fertilizers. Efficient nitrogen management is necessary in rice and a shortage of chemical fertilizers leads to lower SPAD values (Balasubramanian, 2000).

Shoot and root biomass

Root development is important to improve plant body growth (Ullah et al., 2017) and shoot dry matter is positively

related to grain yield (Liang et al., 2016). In the four treatments, roots were developed without any diseases and there were no significant differences in the root dry weight and maximum root length. There was a reported lower shoot dry weight under CF with RS incorporated in the paddy field (Maneepitak et al., 2019). Treatment 1 had a significantly heavier shoot dry weight than the other RS-incorporated treatments at 30 DAT and 60 DAT. During the rainy season, the AWD plots did not dry up as frequently as during the dry season conditions (supported by Maneepitak et al., 2019; Suzuki et al., 2023); consequently, shoot dry matter in the early growing stages was heavier in the current study. In the latter growing stages, treatments 1 and 3 had the same level of shoot dry weight since decomposition of RS could proceed in the early stages (Gao, 2002).

Grain yields

As well as saving water, many studies reported that the application of AWD would not cause any reduction in the grain yield and could lead to higher yields for many experimental conditions (Liang et al., 2016; Maneepitak et al., 2019). Furthermore, RS plays an important role as an organic fertilizer and enhances rice crop growth and yield since the RS influences the C and N cycle in the paddy system (Liu et al., 2012). In the current experiment, the large amount of rice straw incorporation should not have caused severe problems regarding the yields and yield components; on the contrary it contributed to improving the yields by 15% under both chemical and organic fertilizer usage conditions in the AWD plots. In the four yield components, the number of panicles and spikelets are reported to be improved by AWD management (Maneepitak et al., 2019). With the current experimental conditions and using Pathum Thani 1 rice, the most definitive yield component could be the number of panicles.

Costs and benefits of rice production

Several reports have considered the structure of the costs and returns of rice production, revealing the significant contribution of fertilization amendments costs to the total costs (Mehmood et al., 2011; Pornpratansombat et al., 2011). Similarly, in the current case study, the cost of chemical or organic fertilizers, RS and cattle manure were major expenditures. Converting to organic rice production could help to improve the B:C to around 0.45; however, an organic certification system takes years and much financial investment to achieve successful outcomes (Lee, 2021). In addition, the combination of chemical fertilizer

and RS incorporation did not improve the B:C with either the full or 50% recommended applications. Thus, from a financial viewpoint, the current results do not support recommending that the farmers incorporate RS if they have to buy it, but rather, they should make use of their own RS on their land. The price or availability of rice straw and fertilization amendments would be an important consideration in determining whether to adopt RS incorporation or not.

Conclusion

The application of RS and cattle manure incorporation with AWD water management increased the grain yield by 15% based on both conventional and organic ways of farming. However, if the normal chemical fertilizer rates are halved, the yield decreased by 19%. Compared to a dry season report (Suzuki et al., 2023), only the grain yield with halved application of the chemical fertilizers significantly decreased, with the B:C also reducing significantly. The seasonal effects of AWD water management appeared only when the rates of chemical fertilizer application were halved, since the paddy did not dry up frequently during the rainy season. In addition, considering the cost of RS and cattle manure, the B:C was highest in the conventional CF treatment. Thus, further research is required regarding cost-effective and sustainable fertilization methods under water saving using AWD management.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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