



Research article

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

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Abstract

Importance of the work: Saving water and preventing small particulate matter emissions generated from the open burning of rice straw are essential for sustainable rice production in Thailand.

Objectives: To investigate the effects of alternate wetting and drying (AWD) and rice straw and cattle manure incorporation in the dry season.

Materials and Methods: Pathum Thani 1 rice seedlings were transplanted to the paddy in January and harvested in April 2022. Plant growth parameters and grain yield data were collected from four treatments with four replications. The redox potential (Eh) values of paddy water were measured, and costs were recorded.

Results: AWD water-saving technology with extra rice straw and cattle manure incorporation increased the grain yield by 64%. In contrast, even if the chemical fertilizer and rice straw rates were halved, the grain yield increased by 51% compared to continuously flooded (CF) paddy without rice straw and cattle manure. If chemical fertilizers were replaced with organic fertilizer, the grain yield could be maintained at the same level as for CF paddy. However, plant height, soil plant analysis development value and tiller number were significantly lower than those of CF. Due to the extra rice straw and cattle manure, the cost of the AWD treatment was higher; however, the higher grain yields offset this in determining the cost-benefit ratios.

Main finding: The integrated effects of rice straw and AWD reduced chemical fertilizers usage. Fewer chemical fertilizers needed to be applied by incorporating rice straw and manure under AWD as ways to achieve sustainable rice production in the dry season in central Thailand.

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Introduction

Global warming by 1.5°C is expected 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 water and food security risks of extreme concern (Intergovernmental Panel on Climate Change, 2021). Due to global warming effects, climate changes have been observed in Thailand over the decades, such as an increase in air temperature, a decrease in the frequency of rainfall events and an increase in precipitation intensity (Beule et al., 2016; Limsakul and Singhruck, 2016). Hence, drought cases are expected to occur more often (Faisal et al., 2014). The total water footprint of rice is greater than 5,000 m³/ha, with more than half of the irrigation water requirements distributed to rice crops in Thailand (Gheewala et al., 2014). Climate change acceleration has caused widespread water shortage problems in Thailand, especially for irrigated rice production (Kumar and Saxena, 2021). In addition, the rise in air temperature can cause severe yield loss, which offsets the effect of increased photosynthetic activity, while increased temperature, severe pest infestation and weed flora changes are expected (Chandrasekaran et al., 2008). Rice producers must practice environmentally sustainable management and adapt to climate-related problems, namely water shortage and reduction of grain yields.

Rice straw is the residue of rice plants. Rice straw has various nutrients which positively influence soil fertility (Dobermann and Fairhurst, 2002; Van Hung et al., 2020), with sufficient rice straw being easily accessible to most rice farmers (Dobermann and Fairhurst, 2002). Thus, rice straw has been used as an organic fertilizer after being fermented or burned to ash. The most prevalent practice of the disposal method of rice straw is open burning in the field, which also aids weed, pest and disease control (Van Hung et al., 2020). However, rice straw burning causes major air pollutants, including CO, CO₂ and fine dust, known as particulate matter smaller than 2.5 µm (PM_{2.5}) and smaller than 10 µm (PM₁₀), which cause climatic changes and deterioration of public health (Amk, 2020). The total area of rice straw burned in Thailand has been estimated at 3.90 million ha, and the total amount of black carbon (PM_{2.5}, CO, and CO₂) released from in-field open burning is as much as 11,891 t/year, or 34,278 t of CO₂ annually (Kanokkanjana et al., 2011). High air pollutant concentration has become a major concern in hotspot areas of rice-straw burning in Thailand (Tipayarom and Oanh, 2007).

It is important to avoid rice straw burning and to find alternative ways to recycle the rice straw to prevent air pollutants and greenhouse gas emissions that cause PM_{2.5} and global warming.

Incorporating rice straw into the soil returns many nutrients and helps to conserve soil nutrient reserves long-term (Dobermann and Fairhurst, 2002). Rice straw incorporation increases soil organic matter and improves soil fertility (Bi et al., 2009). Hence, rice straw can reduce fertilizer usage (Van Hung et al., 2020). Furthermore, rice straw incorporation helps to promote soil aeration, reduce irrigation water requirements, lessen soil cracking and improve rice yield components. On the other hand, the decomposition of rice straw under anaerobic conditions produces some matter toxic to rice growth, such as H₂S, which causes root rot, negative effects on plant height, a reduction in yield and offsets the benefit of straw incorporation on rice growth (Gao et al., 2002). Hence, aeration for rice straw decomposition is important to suppress the negative effects of rice straw incorporation. Alternate wetting and drying (AWD) water management could achieve a regular supply of oxygen in the soil.

AWD is one of the best practical water management methods to help to save water for paddy rice, as once the water level decreases to 15 cm above the surface, irrigation water is supplied to re-flood the paddy until 5cm depth is achieved (International Rice Research Institute, 2021). The AWD irrigation system involves the repetition of flooded and non-flooded situations. Thus, the paddy has alternate aerobic and anaerobic environments. The water availability in AWD paddy is lower than in CF paddy; consequently, lower rice yields are expected. However, some studies found no significant yield decrease or yield increase by 8–22% from using AWD treatments (Liang et al., 2016; Maneepitak et al., 2019; Ruensuk et al., 2021).

The implementation of rice straw incorporation and AWD water management to improve rice yields and reduce chemical fertilizer needs to be researched, since the long-term use of chemical fertilizer could lead to as little as 1% soil organic contents in the paddy soil (Chandrasekaran et al., 2008; Maneepitak et al., 2019). In addition, overuse of chemical fertilizer deteriorates the environment through the runoff and leaching of chemicals from the paddy (Chandrasekaran et al., 2008). In addition, the cost of chemical fertilizers has increased rapidly and the prices of chemical fertilizers in 2021 were about 130% of 2010 levels (International Bank for Reconstruction and Development, 2022). The cost-benefit structure of rice production needs to be clarified for sustainable farming.

Rice is a vital economic crop in Thailand (Chandrasekaran et al., 2008); assessing its financial viability is essential when farmers adopt new agronomic management. AWD suggests positive economic viability in field experiments due to the reduced irrigation water and labor requirements. Incorporating affordable rice straw and reducing chemical fertilizer usage or replacement with organic fertilizer could improve the cost-benefit ratio of rice production. Thus, the objectives of this study were: 1) to investigate the effects of rice straw incorporation for rice crops under AWD on rice plant growth and grain yields; (2) to investigate the effects of a reduction in chemical fertilizer for rice crops under rice straw incorporating AWD conditions; and (3) to investigate the economic variability of AWD with rice straw incorporation management.

Materials and Methods

Experimental site

The field experiments were conducted in the dry season (December 2021–April 2022) in a research field on the Kamphaeng Saen Campus, Kasetsart University, Nakhon Pathom, central Thailand. The total research area, including ridges, was around 3,000 m². This study area was in the tropical savanna climate zone and comprised two distinct seasons: a dry season from November to April and a rainy season from May to October. The soil in the experimental site was investigated in the Soil Science Laboratory on the Kamphaeng Saen Campus. The soil was classified as sandy loam, with its major characteristics being pH 6.65, bulk density 1.15 g/cm³, electric conductivity 0.37 dS/m, organic matter 1.25%, available P 31.75 mg/kg and exchangeable K 133.62 mg/kg. The mean temperature and total rainfall during the experiment were 27.0°C and 74.1 mm, respectively, based on weather data collected using a WatchDog 2000 Series Weather Station (Spectrum Technologies, Inc.; USA) installed in the center of the experimental field.

Experimental design and agronomic management

The field experiments were conducted using a randomized complete block design (RCB) with four treatments and 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, with the water provided by irrigation from a canal alongside the field. The experimental conditions in the four treatments are shown in Table 1. Treatment 1 was the control plot using herbicides and chemical fertilizers (CF). Treatments 2–4 were AWD plots. In plots 2 and 3, herbicides and chemical fertilizers were used. The chemical fertilizer application rate was the same in treatments 1 and 3 (0.375 t/ha of 18-8-8 at 15 d after transplanting (DAT) and 0.188 t/ha of 46-0-0 at 45 DAT). The total amounts of N, P₂O₅ and K₂O were 153.75 kg/ha, 13.2 kg/ha and 24.9 kg/ha, respectively. One-half these rates of the fertilizers was applied to treatment 2 on the same day. Treatment 4 received two organic fertilizer applications (totaling 3.70 t/ha) instead of the chemical fertilizer; the weeds were controlled physically. Rice straw and cattle manure were applied in treatments 2–4. The application rate of rice straw was 2.5 t/ha for treatment 2 and 5.0 t/ha for treatments 3 and 4. The three treatments were supplemented with 3.75 t/ha of cattle manure.

On 30 November 2021, the paddy field was plowed using disk harrows at 40 d before transplanting (DBT) after removing plant residues from the field. The rice straw and cattle manure were manually applied over plots 2–4 at 38 DBT and soaked for 1 wk. At 37 DBT, seeds of Pathum Thani 1 were sown. At 31 DBT, rotary plowing was conducted to incorporate the rice straw into the soil. At 3 DBT, puddling was conducted using a drive harrow. Seedlings aged 37 d were transplanted manually on 8 January 2022. Three seedlings were transplanted on a hill with 25 cm × 25 cm spacing. Chemical fertilizer (18-8-8) was applied in treatments 1–3 at 15 DAT. The second chemical fertilizer dose (46-0-0) was applied in treatments

Table 1 Rice growth conditions in the four experiment treatments

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

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application, CF = continuously flooded.

1–3 at 45 DAT. Organic fertilizers were applied twice at 17 DAT and 57 DAT. Herbicide was applied at 11 DAT for treatments 1–3. Manual weeding was conducted at 10 DAT and 20 DAT in treatment 4. Other crop management to prevent yield loss was conducted according to local practices.

Data collection

The weather data were collected every 30 min automatically using the WatchDog Weather Station from 2 DAT until the day of harvest. The soil sampling was conducted before the start of field experiments at the end of November. The Kasetsart University Soil Science Laboratory, Kamphaeng Saen Campus analyzed the paddy soil. The oxygen redox potential (ORP) of the paddy water in pani-pipes was measured using an ORP meter that recorded the redox potential (Eh), which describes the oxidation-reduction status (measured in millivolts). The measurement of ORP was conducted weekly from 2 wk after rice straw incorporation until 80 DAT.

Plant growth was assessed based on the plant height, tiller number and soil plant analysis development (SPAD) value of the leaf. Data samplings for plant growth were conducted every 10 DAT. Data were collected from five rice plants in each replication. The plant height, measured from the ground to the topmost tiller or panicle in a shoot, was measured using a measuring scale. The tiller number per stool was counted manually. The SPAD values of the rice leaves were measured using a SPAD–502Plus instrument (Konica Minolta Sensing Inc.; Japan). At 90 DAT, the rice plants in 1 m² in every replication were harvested. The total grain yields and four rice yield components based on a panicle were collected (panicle number per square meter, spikelet number per panicle, filled grain rate and 1,000-grain weight data was calculated from 100-grain weight), with the first three components manually counted one-by-one. The sampling area did not include the border area to avoid the influence of border effects.

Cost-benefit analysis

The production costs were calculated from each bill payment of materials and agronomic practices. The weeding cost was estimated from the time spent and the irrigation cost was estimated from the number of irrigation times. Labor costs associated with weeding and irrigation were calculated using a unit cost of THB 331/person/d (Labor Office Nakhon Pathom Province, 2022), which is equivalent of 9.45 USD. The rice straw revenue was calculated from the rice straw weight multiplied by the purchase price (66.6 USD/t). The revenue from the grain was calculated from the unit rice price multiplied by the rice yield. The unit rice price was 212 USD/t for conventional rice and 347 USD/t for organic rice (Suwanmaneepong et al., 2022). The gross margin was calculated from the total revenues minus total production costs. The cost-benefit ratio was calculated from the gross margin divided by the total production cost. (Sriphirom et al., 2020).

Statistical analysis

The data were analyzed using analysis of variance and means were compared using Duncan's multiple range test. The tests were considered significant at $p < 0.05$. The software package R-STAT was used for data analyses.

Results and Discussion

Paddy soil and water properties

The soil properties before first plowing and after harvesting are shown in Table 2. Considering nutrition, the organic matter slightly decreased, while available P nearly doubled, and exchangeable K more than halved in treatments 1–3. As shown in Fig. 1, the Eh values of paddy water were in the range 20–230 mV. There were no significant differences among the paddy water Eh values for the four treatments.

Table 2 Soil properties before first plowing and after rice harvesting

Soil	Organic Matter (%)		Available P (mg/kg)		Exchangeable K (mg/kg)	
	Before	After	Before	After	Before	After
Trt.1	1.3	1.2±0.00 ^a	31.8	63.6±2.4 ^c	133.6	45.0±1.4 ^c
Trt.2		1.0±0.05 ^c		66.9±1.3 ^c		37.1±1.5 ^d
Trt.3		1.1±0.05 ^b		82.2±1.7 ^b		46.4±1.0 ^b
Trt.4		1.2±0.06 ^{ab}		88.3±4.1 ^a		114.1±1.3 ^a

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application.

Values (mean ± SD) in each column superscripted with different lowercase letters are significantly ($p < 0.05$).

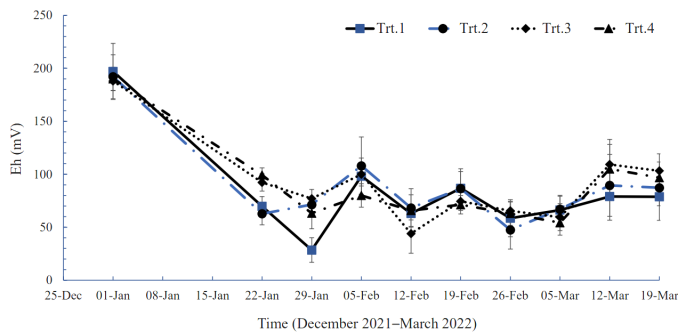


Fig. 1 Weekly changes in redox potential (Eh) values in paddy water inside pani-pipes from 35 d before transplanting to 70 d after transplanting, where values are presented as mean $\pm$ SD, Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application

The organic matter percentages in all treatments decreased slightly during the rice cultivation period. Research indicates that rice straw incorporation improves the organic matter contents (Saothongnoi et al., 2014). However, several years might be required to obtain measurable nutrient changes based on rice straw applications (Dobermann and Fairhurst, 2002). The results indicated that AWD treatments 2–4 were not suitable for the accumulation of soil organic matter. Rice straw incorporation could increase 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 P and K values in treatments 1 and 2 had significantly lower values after harvesting. The average Eh value after transplanting was 80 mV, which was within the recommended range (59–177 mV) for rice plant uptake in the four treatments (Sahrawat, 2005). The Eh changes could be related to the flooded and non-flooded paddy conditions (Ishfaq et al., 2020). However, the Eh values of the paddy water were all similar in the current study, which have been influenced by frequent irrigation water application.

Plant growth and grain yield

The changes in plant height, the number of tillers and SPAD value for each treatment are shown in Figs. 2–4, respectively. As shown in Fig. 2, the plant height was around 45 cm at 20 DAT for all treatments; however, treatment 4 was significantly lower than other treatments from 50 DAT to 90 DAT. The plant height in treatment 3 increased continuously until 70 DAT and decreased slightly from 70 DAT to 90 DAT. In contrast, the plant

heights in the other treatments increased continuously throughout the growing period until 90 DAT. The maximum plant height of treatments 1–3 was around 110 cm, while for treatment 4, it was just a little above 100 cm, which was significantly lower than the others.

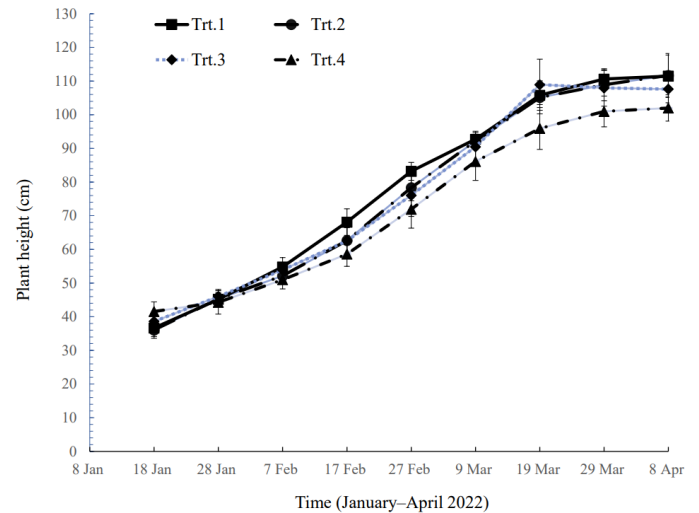


Fig. 2 Changes in plant height every 10 d from 10 s to 90 d after transplanting, where values are presented as mean $\pm$ SD, Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application

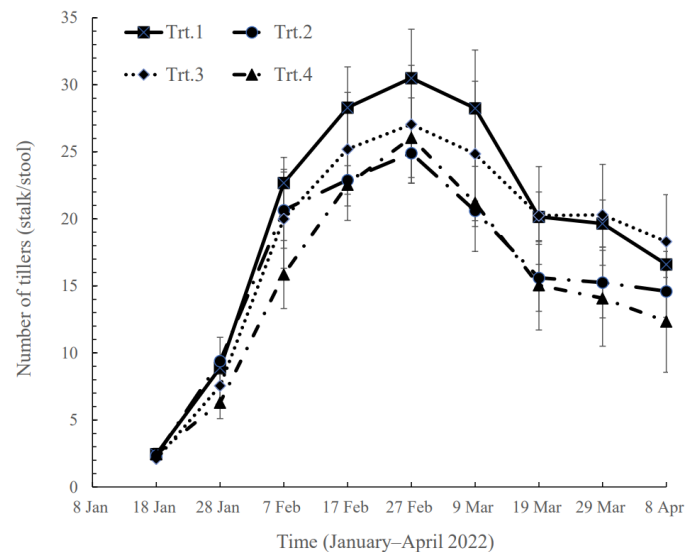


Fig. 3 Changes in number of tillers every 10 d from 10 d to 90 d after transplanting, where values are presented as mean $\pm$ SD, Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application

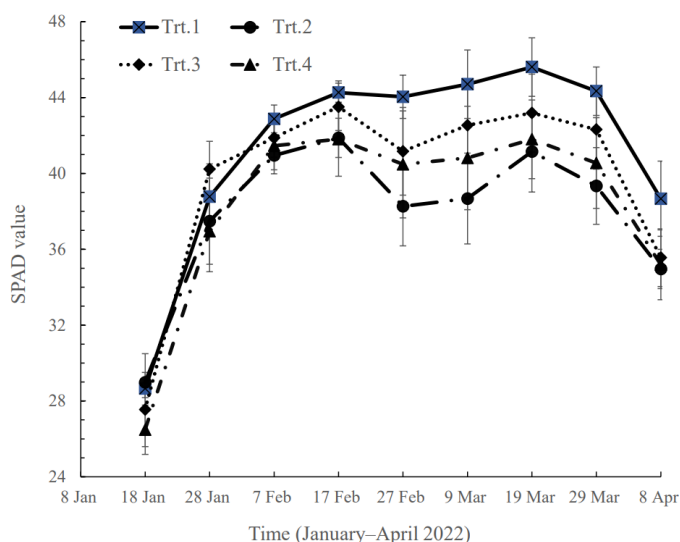


Fig. 4 Changes in soil plant analysis development (SPAD) value every 10 d from 10 d to 90 d after transplanting, where values are presented as mean $\pm$ SD, Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application

In all the treatments, as shown in Fig. 3, the number of tillers increased continuously from 10 DAT to 50 DAT, then decreased rapidly from 50 DAT to 70 DAT, before decreasing slowly from 70 DAT to 90 DAT. The maximum tiller numbers were observed on 50 DAT, with scores of 25–30. The overall changes in tiller numbers were similar. However, significant differences were detected between 20 DAT and 40 DAT and between 0 DAT and 90 DAT. At 30 DAT, only treatment 4 was significantly lower than other treatments. At 40 DAT and 60 DAT, treatment 1 was significantly higher than treatments 2 and 4, while from 70 DAT to 80 DAT, treatments 1 and 3 were significantly higher than treatments 2 and 4. At 90 DAT, treatment 3 was significantly higher than treatments 2 and 4. The number of tillers in treatment 1 remained the highest until 50 DAT; However, it dropped more rapidly than treatment 3, with the tiller number in treatment 3 continuing to be the highest, from 60 DAT to 90 DAT.

Table 4 Yield components of rice cultivated using different practices

Treatment	Panicle (number /stool)	Spikelet (number/stool)	Filled grain rate (%)	Grain weight (g/1,000 seeds)
Trt.1	13.0 $\pm$ 1.6 ^b	1,561 $\pm$ 317.3 ^a	57.8 $\pm$ 11.7 ^a	29.5 $\pm$ 1.1 ^a
Trt.2	16.3 $\pm$ 1.5 ^{ab}	1,568 $\pm$ 398.6 ^a	67.5 $\pm$ 4.2 ^a	30.3 $\pm$ 2.0 ^a
Trt.3	18.5 $\pm$ 3.4 ^a	1,892 $\pm$ 274.5 ^a	61.4 $\pm$ 5.1 ^a	30.8 $\pm$ 1.1 ^a
Trt.4	15.5 $\pm$ 0.6 ^{ab}	1,432 $\pm$ 93.5 ^a	57.8 $\pm$ 8.7 ^a	31.2 $\pm$ 1.5 ^a

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application.

Values (mean $\pm$ SD) in each column superscripted with different lowercase letters are significantly ($p < 0.05$) different.

As shown in Fig. 4, the SPAD values increased rapidly from 10 DAT to 20 DAT in all treatments. From 20 DAT to 80 DAT, the SPAD values fluctuated, with two peaks found at 40 DAT and 70 DAT. After that, the SPAD values drop rapidly from 80 DAT to 90 DAT. The general trend of the changes in SPAD values was the same in all four treatments. However, significant differences were found between the 30 DAT and 90 DAT values. The first peaks at 40 DAT, for treatments 1 and 3, were significantly higher than for treatments 2 and 4. The second peak at 70 DAT for treatment 1 was significantly higher than for treatments 2 and 4. In addition, treatment 1 was significantly higher than treatments 2–4 at 50 DAT, 60 DAT, 80 DAT and 90 DAT.

As shown in Table 3, the highest grain yield was produced in treatment 3, which was significantly higher than in treatments 1 and 4. In contrast, the lowest grain yield was observed in treatment 1, being significantly lower than in treatments 2 and 3. The yield of treatment 2 was the second highest, with treatment 3 the next highest. The irrigation times were 12 d, 8 d, 8 d and 9 d in treatments 1, 2, 3 and 4, respectively. In addition, the harvest index of treatments 2 and 3 was significantly higher than treatment 1, which was as much as 14% lower compared to 2 and 3. As shown in Table 4, no significant differences were found between the treatments in all four yield components.

Table 3 Grain yield, number of irrigation periods and harvest index of rice cultivated using different practices

Treatment	Grain yield (t/ha)	Irrigation (number)	Harvest index (%)
Trt.1	3.3 $\pm$ 0.4 ^c	12	29.8 $\pm$ 4.8 ^b
Trt.2	5.0 $\pm$ 0.3 ^{ab}	8	44.0 $\pm$ 7.1 ^a
Trt.3	5.4 $\pm$ 0.4 ^a	8	43.8 $\pm$ 4.5 ^a
Trt.4	3.9 $\pm$ 0.2 ^{bc}	9	36.0 $\pm$ 6.0 ^{ab}

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application.

Values (mean $\pm$ SD) in each column superscripted with different lowercase letters are significantly ($p < 0.05$) different.

AWD water-saving technology has been investigated widely, especially in Asian countries. Many studies have reported that the application of AWD did not cause grain yield reduction and could lead to higher yields with some experimental conditions (Liang et al., 2016; Maneepitak et al., 2019). Comparing treatments 1 and 3, the grain yield in the AWD field was 64% higher than in the CF field on the condition that an additional 5.0 t/ha of rice straw and 3.75 t/ha of cattle manure were applied as AWD paddy at 1 mth before transplanting. Significant differences were not evident in the four yield components, nor for plant height and tiller number on 90 DAT, while SPAD values at 90 DAT showed significant differences between treatments 1 and 3. One of the reasons for the lower SPAD value in treatment 3 was that rice plants could use most of the absorbed nutrition for grain-yielding activity, effectively in the maturity stage. Thus, AWD water-saving techniques would enable rice plants to concentrate on yielding activity more effectively than CF water management and result in higher grain yield. However, many differences did not appear in the yield components.

Different fertilization methods have been researched to improve rice plant growth and increase grain yields. Rice straw has been considered one of the beneficial amendments to soil fertility (Bi et al., 2009). However, studies have pointed to the negative effects of incorporating rice straw to plant growth due to slow decomposition in the flooded paddy (Gao, 2002). One-half of the rice straw and chemical fertilizer in treatment 3 were applied in treatment 2. The grain yield harvested in treatment 2 was just 8.1% lower than in treatment 3, and there were no significant differences in grain yield between the above two treatments. Among the four yield components, only the filled grain rate of treatment 2 was higher than that of treatment 3 by 6.1%. The earlier transition might promote a higher filled grain rate in the maturity stage since the extra nutrition was left in the soil of treatment 2 compared to treatment 3. Even more so, grain yield in the treatment was significantly higher than in treatment 1. Therefore, with rice straw and cattle manure application in AWD paddy, half the amount of chemical fertilizer is sufficient to obtain a larger grain yield than conventional continuous-flooded rice production. The lower rice yield of organic rice production was an issue since the organic fertilizer needed to be quickly changed into easy-to-absorb nutrients. In treatment 4, 5.0 t/ha of rice straw and 1.88 t/ha of cattle manure were applied as in treatment 3, and two organic fertilizer applications were conducted instead of chemical fertilizer. Even though there were no chemical fertilizers in treatment 4, the grain yield

was not significantly lower than in treatment 1, the control CF treatment. AWD could effectively maintain the rice yield of organic rice farming; however, from 60 DAT to 90 DAT, the plant height, tiller number, and SPAD values of treatment 4 were significantly lower than those for treatment 1. Thus, even though the rice yield was maintained at the same level as for the conventional CF paddy, the rice straw incorporated in the AWD organic paddy could not maintain plant growth to the same level, especially after 60 DAT.

Costs and returns of rice production

The rice production cost details are compiled in [Table 5](#). The order from lowest to highest for total cost was treatments 1, 2, 3 and 4, the same order as the fertilization amendment cost from lowest to highest. Treatment 4 had the highest subtotal costs for paddy management and fertilization amendment; however, the subtotal cost for plant protection management was the lowest of all the treatments. [Table 6](#) shows the costs and returns structure of the four treatments. The gross margins and cost-benefit ratios of treatments 2 and 3 were much higher than those of treatments 1 and 4.

Some reports have documented the structure of the costs and returns of rice production (Mehmood et al., 2011; Pornpratansombat et al., 2011). In the current experiment, the total cost of rice production per ha was in the range THB 44,000–63,000, much higher than the study in Thailand by Pornpratansombat et al. (2011) who collected cost data from the farmers who owned more than 1 ha of rice paddy. However, in the current study, the paddy area for each treatment was 539 m²; consequently, the current costs were much higher. However, discussion on cost comparisons between treatments is important. Due to the application of rice straw and cattle manure, the total costs of treatments 2 and 3 were much higher than for treatment 1. However, these costs were completely offset by the higher expected revenue from the improved grain yield. The higher cost-benefit ratio of treatment 2 compared to 3 suggested that AWD with rice straw farming was economically more sustainable. Organic fertilizer cost about THB 18,400/ha and resulted in a lower cost-benefit ratio. Thus, chemical and organic fertilizer costs would be important for rice farmers in undertaking organic rice production to achieve more sustainable rice production.

Table 5 Rice production cost details for 1 ha using different practices

Cost (USD)	Trt.1		Trt.2		Trt.3		Trt.4	
	Cost	%	Cost	%	Cost	%	Cost	%
First plowing	34	3	34	3	34	2	34	2
Second plowing	98	8	98	8	98	7	98	6
Seeds	26	2	26	2	26	2	26	2
Transplanting	278	24	278	21	278	19	278	17
Weeding	-	-	-	-	-	-	64	4
Irrigation	57	5	38	3	38	3	42	3
Bird net installation	106	9	106	8	106	7	106	6
Harvesting	95	8	95	7	95	6	95	6
Subtotal	693	60	674	52	674	45	743	45
Cattle manure	-	-	149	11	149	10	149	9
Rice straw	-	-	99	8	198	13	198	12
Fertilizer (18-20-20)	96	8	48	4	96	6	-	-
Fertilizer (46-0-0)	75	6	37	3	75	5	-	-
Organic fertilizer	-	-	-	-	-	-	525	32
Subtotal	171	15	333	26	518	35	872	52
Herbicides	144	12	144	11	144	10	-	-
Molluscicides	13	1	13	1	13	1	13	1
Insecticides	38	3	38	3	38	3	38	2
Fungicides	99	9	99	8	99	7	-	-
Subtotal	294	25	294	23	294	20	51	3
Total	1,158	100	1,302	100	1,486	100	1,666	100

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application.

Table 6 Costs and benefits details for rice production in 1 ha using different practices

Costs and Benefits (USD)		Trt.1	Trt.2	Trt.3	Trt.4
Costs	Agronomic labor	693	674	674	743
	Chemical fertilizer	171	86	171	-
	Organic fertilizer	-	-	-	525
	RS and cattle manure	-	248	347	347
	Plant protection	294	294	294	51
	Total	1,158	1,302	1,486	1,666
Returns	Rice straw	751	749	827	729
	Rice grain	698	1,057	1,141	1,368
	Total	1,449	1,805	1,968	2,097
Benefits		291	504	482	431
Cost-Benefit ratio		0.25	0.39	0.32	0.26

Trt.1 = conventional practices, Trt.2 = adopt alternate wetting and drying (AWD) and add rice straw (RS) and chemical and manure fertilizer (CM), but reduce RS and chemical fertilizers by half, Trt.3 = adopt AWD and add RS and CM, Trt.4 = adopt AWD, add RS and CM, use organic fertilizers, and adopt weeding instead of herbicide application.

Concluding remarks

AWD water-saving technology with rice straw and cattle manure incorporation increased the grain yield. Even when the chemical fertilizer rate was halved, the grain yield was higher than from conventional CF production. Similarly, the grain yield was maintained at the same level as for the CF conventional system when the chemical fertilizer was replaced with organic fertilizer. Furthermore, AWD and rice straw farming produced a better cost-benefit ratio in the dry season. However, the long-term effects of such agronomic management systems need to be researched further.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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