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Plant Physiological Performances, Plant Growth, Grain Yield and Methane Emission of Rice (*Oryza Sativa* L.) in Response to Water Management as Adaptation Strategy for Climate Change

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Continuously flooded rice systems are a major contributor to the greenhouse gases (GHG) emissions in the agriculture sector in Malaysia. Intermittent irrigation has been recommended to replace conventional rice water management to save water and reduce GHG emissions without compromising rice yields. This study was conducted in two growing seasons at Malaysia's largest rice granary area to determine the effectiveness of different water management practices on conserving water, mitigating GHG and maintaining rice grain yields. Three water management treatments were continuous flooding (CF), saturated and wet conditions from transplanting to heading and flooding until maturity (S-F) and continuous saturated and wet conditions (CS). The results showed that S-F and CS reduced water inputs between 15.0-16.8% and 32.0-34.0% as compared to CF, respectively. Water-saving treatments mostly did not significantly affect the plant's physiological performance, plant growth parameters, growth rate, grain yield and yield parameters. The results indicated that soil saturated and wet conditions provided adequate soil moisture content for the plant's requirement similar to flooding conditions. Maintaining soil at saturated and wet conditions during the vegetative stage reduced 24.18-39.76% of methane emissions. However, maintaining soil at saturated and wet conditions throughout the growing season reduced 34.52-55.08% of methane emissions. In conclusion, intermittent irrigation could be an effective adaptation technique for simultaneously saving water and mitigating GHG while maintaining high rice grain yields in rice cultivation systems.

Keywords: Greenhouse gases emissions; methane; water management; net photosynthesis rate; plant growth.

1. INTRODUCTION

Rice is Asia's largest water user, accounting for more than half of all irrigation water demands [1]. In Malaysia, the largest freshwater withdrawal of more than 75% is for irrigation in the agriculture sector and is mainly confined to irrigated rice production [2]. Rice is a heavy consumer of water but its water use efficiency is low. It is estimated about 3,000 litres of water is used to produce 1 kg of rice and that the water productivity index (WPI) of rice is 0.3 kg grain/m^3 water. Fresh water is becoming an increasingly scarce resource which has posed a serious threat to the productivity and sustainability of irrigated paddy systems in many countries [3]. The present global water crisis, climate variability, drought, increasing demands of water from the industrial sectors and contamination of water resources made water more scarce for irrigation [2].

The estimated average water requirement for irrigated rice crops in Malaysia is 1,240 mm per season although most irrigated rice is supplied with much more than the field requirement because farmers maintain a continuous flooding system from crop establishment to maturity [4]. Rice irrigation systems that use continuous flooding require a lot of water and a larger amount of water is wasted due to evaporation, percolation and seepage [5]. Irrigated rice is normally grown in a flooded environment during most of its growing period. Flooding conditions create anaerobic conditions and high levels of organic substrates in soil, increasing the activity of methanogenic bacteria that produce CH_4 [6]. The Fourth Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC) reported that in 2019, rice cultivations in Malaysia produced 90.76 Gg of methane (CH_4) or 2,268.98 Gg CO_2 eq. that contributed to 22.87% of greenhouse gases (GHG) emissions from the agriculture sector [7]. Paddy water management and water-saving irrigation are promising options for CH_4 mitigation [8]. This study was conducted to determine the effectiveness of different water management practices on conserving water, plant growth, plant physiological performance, mitigating GHG and maintaining yields in rice production.

2. MATERIALS AND METHODS

2.1 Experimental Design and Crop Establishment

The study was conducted in the country's main rice granary area of the Muda Agricultural Development Authority (MADA), Kedah which represents 47.25% of the country's rice granary planting area [9]. The experiments were conducted during two growing seasons at Kg. Selarong, Alor Star Kedah (latitude: 6.2078 N, longitude: 100.3589 E). Season 1/2019 was the off-season (June-October 2019) and season 2/2019 was the main season (November 2019-February 2020). The experiment was laid out using a nested design that consists of three (3) water management practices (Table 1) with seven (7) replications. MARDI Siraj 297 rice variety seeds were sown and the seedlings were transplanted after 15 days.

During the first 2 weeks after transplantation, 5 cm standing water was maintained in all plots to avoid weed infestation. Then, the plots were irrigated according to the water management treatments. For flooding treatment, the standing water level was maintained between 10-15 cm throughout the growing season. In saturated and wet conditions treatment, the soil was kept wet without standing water. For better control of the water level, re-irrigation should be done when the water level falls around 15 cm below the soil surface using a PVC perforated tube with 15 cm diameter and 40 cm length. Water from rainfall was maintained in the CS treatment while standing water in S-F and CS treatments after heavy rainfall was drained out from the plot. Due to some limitations, the determination of the total water inputs for main and off-season for continuous flooding conditions was based on the average water requirement as published on the MADA website [10]. The water input for S-F and CS treatments was determined by the difference in the standing water level during re-irrigation as compared to flooding conditions. Total water inputs were computed by adding applied irrigation water, rainfall and water during land preparation. The plants were fertilized with 120:70:80 kg/ha of N, P_2O_5 and K_2O. Pest and disease management were based on farmer's normal practices. Pesticides and weedicides were applied at -5, 5, 17, 39, 58 and 91 days after transplanting (DAT). Weather data was obtained using a weather station (WatchDog-2000). Soil moisture content was determined with volumetric water content (%) (FieldScout Spectrum TDR-150) and matric water potential (kPa) (Irrometer Tensiometer 24in).

2.2 Leaf Physiological Responses Measurement

Plant physiological performances and growth parameters analysis were determined at 3 phenological stages of tillering (25 DAT), heading (70 DAT) and ripening stage (90 DAT). Measurements of net photosynthetic rates, stomatal conductance and transpiration rate were taken using a portable photosynthesis system (LI6400XT, LICOR Inc., Nebrasca, USA). The photosynthetic photon flux density of the leaf chamber was set at 1200 µmol m^{-2} s^{-1}, temperature was maintained at 30 °C, CO_2 reference concentration at 400 µmol mol^{-1} and relative humidity was controlled between 50-70% with flow rate at 500 µmol s^{-1}. Fully expanded leaves were clamped in the sensor cuvette and data were logged after readings reached stable. All measurements were performed between 0900-1200 h.

The chlorophyll fluorescence measurements were made using a portable Plant Efficiency Analyzer (PEA) (FMS 2, Hansatech Instruments Ltd, U.K.). The measurements were done between 0900 - 1030 h. The completely expanded leaves were chosen for these measurements. Leaves were darkened for 30 min with standard leaf clips before the fluorescence responses were induced by LED (1500 µmol$m^{-2}s^{-1}$). Measurements of Fo (initial fluorescence), Fm (maximum fluorescence) and Fv 22 (variable fluorescence) were obtained and Fv was derived as the differences between Fm and Fo. The Fv/Fm ratio was used to determine the leaf chlorophyll fluorescence responses.

Table 1. Water management treatment for rice production

Treatment	Water management	Planting area (ha)
CF	Continuous flooding (10 - 15 cm standing water level)	1.00
S-F	Saturated and wet conditions from transplanting to heading and flooding (10 - 15 cm standing water level) until maturity	1.00
CS	Continuous saturated and wet conditions	1.00

2.3 Growth Parameters Measurements

Quadrat sampling of 25 cm X 25 cm was conducted at 2 points of each replication at 3 phenological stages of tillering (25 DAT), heading (70 DAT) and ripening stage (90 DAT) and plants were harvested for the growth analysis. The parameters determined were plant height, tiller number, leaf number, total leaf area, leaf area index, leaf dry weight, total leaf chlorophyll content, aboveground dry weight and crop growth rate. The plant parts were dried to constant weight at 80 °C for 72 h in a drying oven (Model 100-800, Memmert, Germany). The dried weight was measured using a semi-micro analytical digital balance (GR-200, A&D Company Limited, Japan) for the determination of above-ground dry weight. For total chlorophyll content, 3 cm^2 of fresh leaves were sampled and soaked in 80% acetone (20 mL) in glass bottles covered with aluminium foil in the dark for 7 days or until all the leaves were decolorized. The spectrophotometer (Genesys 1XX, ThermoFisher Scientific, Madison, USA) was then used to measure the chlorophyll extraction at the wavelengths of 664 and 647 nm [11]. Leaf area index (LAI) was determined using an AccuPAR LP-80.

2.4 Grain Yield and Yield Parameters Determination

The rice yields were harvested on 111 and 106 DAT for the season 1 and 2, respectively. The grain yield analysis was carried out using a crop-cutting test (CCT) using an area dimension of 1 m × 1 m. Yield components of tiller number, panicle number and filled grain were determined. The harvested grains were then dried, winnowed, and weighed. The weight was then converted to per unit area crop yield based on 14% grain moisture content and presented as grain yield (kg ha^{-1}).

2.5 Measurement of Methane (CH_4) Emissions

The methane (CH_4) was measured using a static chamber method [12]. Daily CH_4 samples were taken at seven points on each treatment plot where scaffolding or boardwalks had been built around the sampling points. The sampling points were established approximately two meters from the non-submerged land to ensure no soil disturbances that might cause artificial CH_4 ebullition. The chamber dimensions were measured at 110 cm in height and 35 cm in width and length (110 cm × 35 cm × 35 cm). One fan was installed in each chamber for the homogenization of gas. Gas samples were collected from the field using 20 mL syringes with hypodermic needles. Daily flux methane emission samples were collected at 10-minute intervals from 9 a.m. until 9.30 a.m. at 0, 10, 20, and 30 minutes. Meanwhile, gas samples were collected at two-week intervals. The final samples were collected immediately before the water was drained from the field before harvesting. The gas samples were analysed using gas chromatography (GC System Agilent 7890A).

The daily methane flux was calculated using the following formula:

$$CH_{4\ \text{flux}} = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \rho \times \frac{273}{273+T}$$

where $\Delta C\ /\ \Delta t$ is the change in concentration in parts per million (ppm) over time; V is the volume of the chamber in m^3; A is the chamber area in m^2; ρ is the gas density (0.717 kg m^{-3}); and T is the air temperature in the chamber in °C. The total CH_4 emission during the rice planting season was calculated by successive linear interpolation of average gas emissions on the sampling days, assuming that gas emissions followed a linear trend during the periods when no sample was taken using the following formula:

$$\text{Total } CH_{4\ \text{flux}} = \sum_{i=1}^{n-1}(R_i x\ D_i)$$

where n is the number of sampling intervals; R_i is the mean rate of CH_4 flux (mg m^{-2} d^{-1}) within the two sampling intervals; and D_i is the number of days within the sampling interval [13]. All data obtained were subjected to statistical analysis, using a one-way Analysis of Variance (ANOVA) to test the significant effect of all variables investigated. Means separation was performed using the Duncan's multiple range test (DMRT) method at 5% (P = 0.05) by the statistical package of SAS 9.3 Institute Inc. USA.

3. RESULTS AND DISCUSSION

3.1 Water Inputs under Different Irrigation Treatments

During season 2/2019, the MADA area experienced drought conditions without or very minimal rainfall for 2.5 months resulting in 101.3 mm of the total rainfall per season as compared to 500.8 mm in season 1. The temperature in season 2 was significantly higher, especially during the reproductive and maturity stages as compared to season 1. In season 1, saturated soil conditions of S-F and CS reduced 15.0 and 34.0% water inputs, respectively. In season 2, saturated soil conditions of S-F and CS reduced 16.8 and 32.0% water inputs, respectively.

3.2 Soil Moisture Content

Soil moisture in paddy fields represents plant water availability and is necessary for irrigation scheduling, water resource allocation, management and planning [14]. The pattern of evapotranspiration, runoff, and deep percolation in paddy fields is affected by soil moisture variations [15]. The soil moisture content of all water management treatments was not significantly different at all plant stages except for the soils under saturated and wet conditions at the ripening stage in season 2 (Table 4).

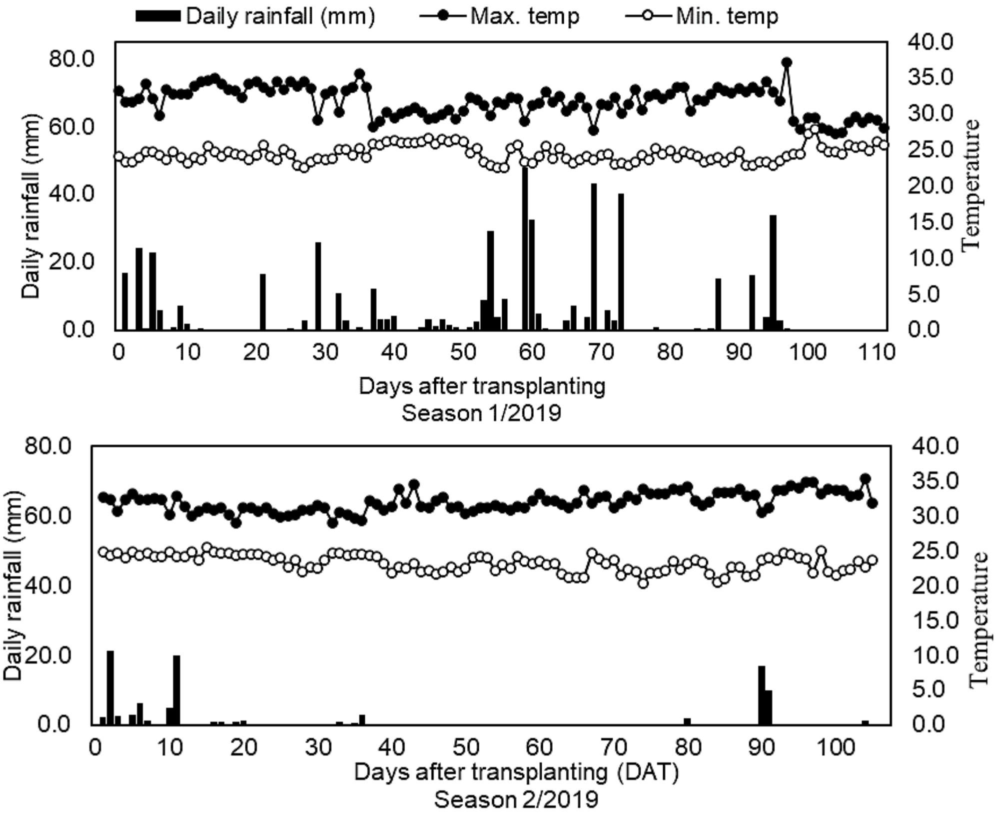

Fig. 1. Seasonal variations in daily rainfall, maximum and minimum temperature during the rice growing season 1/2019 and 2/2019

Table 2. Total rainfall, daily maximum and minimum temperature at vegetative, reproductive and ripening phase during the rice growing season 1/2019 and 2/2019

Growing season	Total rainfall (mm)	Daily max temperate (°C)			Daily min temperate (°C)		
		Vegetative	Reproductive	Ripening	Vegetative	Reproductive	Ripening
Season 1/2019	500.8	32.8^{a*}	31.0^{b}	31.2^{b}	24.3^{a}	24.5^{a}	24.5^{a}
Season 2/2019	101.3	31.0^{b}	32.0^{a}	33.3^{a}	24.1^{a}	22.6^{b}	22.8^{b}

**Means followed by the same letter within the column are not significantly different by Fisher's Least Significant Difference (LSD) test at alpha = 0.05.*

Table 3. Water inputs under different water management treatments

Treatment	Water input (mm)	
	Season 1/2019	Season 2/2019
CF	1201.0	1103.5
S-F	1020.9	917.7
CS	792.7	750.1

Table 4. Soil moisture content as affected by water management treatment

Growing season	Plant stage	Treatment	Volumetric water content (%)	Water potential (kPa)
Season 1/2019	Tillering	CF	62.66^{a*}	1.25^{a}
		S-F	62.77^{a}	1.75^{a}
		CS	60.08^{a}	1.33^{a}
	Heading	CF	56.07^{a}	0.00^{a}
		S-F	62.23^{a}	0.00^{a}
		CS	57.42^{a}	0.00^{a}
	Ripening	CF	60.10^{a}	1.75^{a}
		S-F	62.38^{a}	0.00^{a}
		CS	60.52^{a}	1.75^{a}
Season 2/2019	Tillering	CF	61.59^{a}	0.00^{a}
		S-F	61.99^{a}	1.00^{a}
		CS	61.51^{a}	1.40^{a}
	Heading	CF	61.54^{a}	0.80^{a}
		S-F	62.24^{a}	0.80^{a}
		CS	59.60^{a}	1.00^{a}
	Ripening	CF	58.70^{a}	2.00^{b}
		S-F	59.75^{a}	4.33^{ab}
		CS	53.30^{b}	11.67^{a}

**Means followed by the same letter within the column and growth stages for each growing season are not significantly different by DMRT at P≤0.05.*

3.3 Effect of Water Management Treatments on Leaf physiological responses

Leaf physiological responses of rice plants during season 2 were generally lower compared to season 1 especially during heading and ripening stages (Table 5). These results were probably caused by higher temperatures during the drought conditions in season 2 as heat stress decreased leaf photosynthesis due to stomata closure that affects the intercellular CO_2 [16]. However, most of the leaf physiological performances were not significantly different between all water management at the same stages of each season. Volumetric water content and metric water potential of flooding and saturated soil conditions were not significantly different (Table 4), except for lower soil moisture content in CS treatment during the ripening stage as saturated soil conditions tend to dry faster when the water was drained before harvesting as compared to flooding conditions. These results indicate that both soil conditions of flooding and saturated conditions provided adequate soil moisture content to support leaf physiological activities of photosynthesis, stomatal conductance, and transpiration. Stomatal conductance is measured to determine the degree of stomatal opening and it can be used to indicate the plant water stress [17]. Stomatal conductance and transpiration rate were mostly not affected by different water management conditions except for a few stages with slight reduction. Chlorophyll fluorescence (Fv/Fm ratio) between different water management also showed no significant difference at all plant stages. Chlorophyll fluorescence provides detailed information on the saturation characteristics of electron transport, as well as the overall photosynthetic performance of a plant [18]. In this study, Fv/Fm ratios of flooding and saturated soil conditions of all water management were mostly between 0.75-0.79 (except for the tillering stage) and high Fv/Fm indicated that plants were at higher plant photosynthetic performance and not under water stress conditions.

3.4 Effect of Water Management Treatments on Plant Growth Parameter and Leaf Chlorophyll Content

The effect of different water management treatments on all plant growth parameters were mostly not significant (Table 6). In season 2, total leaf chlorophyll content of saturated and wet conditions was significantly lower as the result of lower soil moisture content (Table 4) however, this did not have significant effect on the plant growth rate. These results showed that saturated soils and wet conditions did not negatively affect the plant growth parameters of rice plants as compared to flooded conditions. Volumetric water content and metric water potential of flooding and saturated conditions were not significantly different, indicating that saturated soil conditions provided adequate soil moisture content for plant growth requirements similar to flooded conditions. Although there was no observable standing water in the field, rice can take up adequate water from the subsurface soil around the root zone [19]. During the drying periods, the 0-15 cm soil layer that remained saturated prevented water stress and rice grain yields were not reduced [20]. This was likely because water was available deeper in the soil and the roots in this layer provided sufficient water uptake for the plant's physiological requirements.

3.5 Effect of Water Management Treatments on Grain Yield and Yield Parameters

Conserving water by maintaining soil water conditions at saturated and wet conditions did not cause any significant reduction in yield components and rice grain yield (Table 7). The grain yields of rice under different water management treatments were between 6.44-6.96 and 5.74-6.1 t/ha in season 1 and 2, respectively. Water management at saturated and wet soil conditions was shown to sustain high soil moisture content thus supporting leaf physiological and plant growth performances that resulted in maintaining high grain yield of rice. Maintaining soil at saturated and wet conditions also could be an effective technique to conserve water, reducing CH_4 emission while preventing reduction of grain yield similar to other adaptation technique such as Alternate Wetting and Drying (AWD). AWD is a water-saving irrigation technique developed by the International Rice Research Institute (IRRI) and has been adopted to replace continuous flooding without compromising rice yields in many countries [21]. However, the effects of AWD on rice grain yields AWD on grain yield is highly variable: while some studies have shown that AWD can decrease up to 16% of rice grain yield [22] or even an increase in yield [23]. This variability is likely due to differences in severity of water management between studies, timing, varietal responses and soil moisture monitoring methodology [24]. The results from this study also indicated that flooding condition is not a requirement for rice production, as others also reported that continuous submergence is not essential for obtaining high rice yields [25,26]. IRRI reported that rice plants only require flooding conditions during the rooting and flowering stages [27].

Table 5. Leaf physiological responses and chlorophyll fluorescence (Fv/Fm ratio) as affected by water management treatment

Growing season	Plant stage	Treatment	Net photosynthetic rate (A) (μmol/m^2/s)	Stomatal conductance (gs) mol/m^2/s	Leaf transpiration rate (E) mmol/m^2/s	Chlorophyll fluorescence (Fv/Fm ratio)
Season 1/2019	Tillering	CF	19.62^{a*}	1.56^{a}	7.19^{a}	0.58^{a}
		S-F	21.57^{a}	1.72^{a}	7.73^{a}	0.59^{a}
		CS	20.02^{a}	1.61^{a}	7.53^{a}	0.61^{a}
	Heading	CF	21.18^{a}	1.83^{a}	5.19^{a}	0.79^{a}
		S-F	21.20^{a}	1.52^{ab}	4.72^{ab}	0.79^{a}
		CS	22.83^{a}	1.14^{b}	4.22^{b}	0.77^{a}
	Ripening	CF	21.65^{a}	2.09^{a}	5.58^{a}	0.75^{a}
		S-F	19.67^{a}	2.33^{a}	6.08^{a}	0.77^{a}
		CS	19.36^{a}	2.08^{a}	5.92^{a}	0.71^{a}
Season 2/2019	Tillering	CF	19.73^{a}	1.75^{a}	6.95^{a}	0.76^{a}
		S-F	19.52^{a}	2.05^{a}	6.46^{b}	0.77^{a}
		CS	18.84^{a}	1.58^{a}	5.85^{c}	0.79^{a}
	Heading	CF	14.50^{a}	1.26^{a}	7.65^{a}	0.78^{a}
		S-F	14.10^{a}	1.16^{a}	7.52^{a}	0.79^{a}
		CS	14.43^{a}	0.98^{b}	6.93^{b}	0.77^{a}
	Ripening	CF	12.59^{a}	0.65^{a}	6.05^{a}	0.70^{a}
		S-F	10.93^{a}	0.54^{a}	5.94^{a}	0.76^{a}
		CS	10.67^{a}	0.51^{a}	5.63^{a}	0.73^{a}

**Means followed by the same letter within the column and growth stages for each growing season are not significantly different by DMRT at P≤0.05.*

Table 6. Plant growth parameters of rice as affected by different water management treatments of growing seasons 1/2019 and 2/2019

Growing season	**Stages**	**Treatment**	**Plant height (cm)**	**Tiller number (No m^{-2})**	**Leaf number (No m^{-2})**	**Total leaf area (cm m^{-2})**	**Leaf area index**	**Leaf dry weight (g m^{-2})**	**Total leaf chlorophyll content (mg cm^{-2})**	**Aboveground dry weight (g m^{-2})**	**Crop growth rate (g m^{-2} d^{-1})**
Season 1/2019	Tillering	CF	69.14^{a*}	656.86^{a}	2363.43^{a}	46427.54^{a}	4.69^{a}	246.43^{a}	10.14^{a}	1074.76^{a}	21.07^{a}
		S-F	73.00^{a}	572.00^{a}	2099.43^{a}	43648.41^{a}	4.41^{a}	253.53^{a}	9.96^{a}	927.14^{a}	18.18^{a}
		CS	64.50^{a}	594.00^{a}	1958.00^{a}	36114.58^{a}	3.65^{a}	199.61^{a}	9.00^{a}	922.53^{a}	18.09^{a}
	Heading	CF	93.57^{a}	575.14^{a}	2360.29^{a}	61693.31^{a}	6.23^{a}	315.20^{a}	9.76^{a}	1189.82^{a}	18.30^{a}
		S-F	93.14^{a}	540.57^{a}	2115.14^{a}	53517.95^{a}	5.41^{a}	316.61^{a}	8.58^{a}	1301.27^{a}	20.02^{a}
		CS	93.29^{a}	474.57^{a}	2005.18^{a}	47548.23^{a}	4.80^{a}	286.44^{a}	8.50^{a}	1482.11^{a}	22.80^{a}
	Ripening	CF	109.14^{a}	521.71^{a}	1543.04^{a}	37847.67^{a}	3.82^{a}	235.93^{a}	5.52^{a}	1947.44^{a}	20.72^{a}
		S-F	111.00^{a}	622.29^{a}	1646.86^{a}	38121.13^{a}	3.85^{a}	228.55^{a}	6.01^{a}	2221.78^{a}	23.64^{a}
		CS	106.00^{a}	524.86^{a}	1684.57^{a}	41399.98^{a}	4.18^{a}	239.74^{a}	6.13^{a}	1956.87^{a}	20.82^{a}
Season 2/2019	Tillering	CF	65.00^{a}	704.00^{a}	1936.00^{ab}	31115.75^{a}	3.14^{a}	157.99^{ab}	9.40^{a}	630.27^{a}	5.95^{a}
		S-F	64.50^{a}	737.00^{a}	1800.86^{b}	27824.22^{a}	2.81^{a}	138.25^{b}	9.05^{a}	534.10^{a}	5.04^{a}
		CS	66.67^{a}	730.00^{a}	2407.43^{a}	34706.18^{a}	3.51^{a}	188.57^{a}	8.31^{a}	720.19^{a}	6.79^{a}
	Heading	CF	78.67^{a}	561.00^{a}	2162.29^{b}	42454.03^{b}	4.29^{b}	281.85^{a}	6.99^{a}	1850.14^{a}	17.45^{a}
		S-F	78.83^{a}	638.00^{a}	2838.00^{a}	59202.74^{a}	5.98^{a}	262.03^{a}	7.15^{a}	1540.63^{a}	14.53^{a}
		CS	76.83^{a}	553.67^{a}	2841.14^{a}	48248.33^{ab}	4.87^{ab}	309.73^{a}	6.75^{a}	2012.84^{a}	18.99^{a}
	Ripening	CF	88.67^{a}	469.33^{a}	2495.40^{a}	32122.92^{a}	3.24^{a}	260.92^{a}	3.62^{a}	3345.60^{a}	31.56^{a}
		S-F	84.67^{a}	561.00^{a}	2379.14^{a}	30375.41^{a}	3.07^{a}	242.47^{a}	4.24^{a}	2789.10^{a}	26.31^{a}
		CS	88.33^{a}	520.67^{a}	1876.29^{a}	25409.72^{a}	2.57^{a}	234.01^{a}	1.98^{b}	2896.45^{a}	27.33^{a}

**Means followed by the same letter within the column and growth stages for each growing season are not significantly different by DMRT at P≤0.05.*

Table 7. Yield component and grain yield of rice as affected by different water management treatment of growing season 1/2019 and 2/2019

Growing season	Treatment	Tiller number/m^2	Panicle number/m^2	Filled grains (%)	1000-grain weight (g)	Grain yield (kg ha^{-1})
Season 1/2019	CF	594.00^{a*}	534.60^a	92.38^a	26.33^a	6440.30^a
	S-F	548.43^a	515.43^a	91.62^a	26.63^a	6888.08^a
	CS	521.40^a	464.20^a	90.97^a	26.01^a	6959.45^a
Season 2/2019	CF	425.66^a	413.78^a	93.28^a	26.16^a	5742.43^a
	S-F	422.12^a	415.82^a	93.36^a	25.93^a	5944.62^a
	CS	443.68^a	429.18^a	94.86^a	26.49^a	6122.81^a

**Means followed by the same letter within the column and growth stages for each growing season are not significantly different by DMRT at P≤0.05*

3.6 Effect of Water Management Treatments on Methane Emission

The dynamics of methane emissions from rice grown under different water management practices at 2-week intervals and total emissions per season were presented in Fig. 2 and Table 8. The results showed that the emissions were significantly affected by water management techniques. Daily fluxes and cumulative methane emissions were the highest in continuous flooding with 183.85 and 306.10 kg ha^{-1} season^{-1} in the season 1 and 2, respectively. S-F treatment decreased 39.76 and 24.18% of methane emissions in seasons 1 and 2, respectively. Maintaining soil saturated and wet conditions throughout the growing season decreased more methane emissions with 55.08 and 34.52% reduction in seasons 1 and 2, respectively. By maintaining soil at saturated and wet conditions, water levels in the soil eventually fell below the soil surface thus allowing aerobic processes in the soil. It has been widely studied that intermittent irrigation can reduce methane emissions by enhancing aerobic processes in the soil [28]. Consequently, the increase in oxygen supply during dry periods creates an aerobic soil environment where methanotrophs can oxidize methane, which is linked to a decrease in methane emission [29].

In this study, the methane emissions were higher in season 2 and this was probably due to the drought conditions that recorded higher temperatures (Table 2). Methanogenic bacteria are thermophiles that tend to be more active in decomposing organic matter and producing more methane at high temperatures [30]. The climate condition in Malaysia which is hot and humid is more favourable for active methanogenesis activity resulting in higher emission factors under CF (1.66 and 2.89 kg ha^{-1} day^{-1}) as compared to the default value of 1.3 kg ha^{-1} day^{-1} by Intergovernmental Panel on Climate Change (IPCC) 2006 [31]. Pardis and Hasfalina [32] also reported that modified rice cultivation systems by applying alternate wetting (2 cm standing water level) and drying (0 cm standing water level) techniques of 6-day intervals after 12 DAT until maturity stage resulted in a significant reduction of 60-64% methane emission and significantly higher grain filling of 1000 rice grain weight as compared to continuous flooding. Other water management such as AWD also has been shown not only effective in reducing water input by 23-33% [21], but also in reducing greenhouse gas emissions (methane and nitrous oxide) by 45-90%, as compared to continuously flooded rice systems [33].

Table 8. The CH_4 emission from rice field under different water management treatments, i.e., continuous flooding (CF), saturated and flooded condition (S-F) and continuous saturated condition (CS), during seasons 1/2019 and 2/2019 in Alor Setar, Kedah, Malaysia

Growing season	Treatment	Average fluxes of CH_4 emissions (mg m^{-2} day^{-1})	Total amount of CH_4 emissions (kg ha^{-1} season^{-1})	Emissions factor (kg ha^{-1} day^{-1})
Season 1/2019	CF	148.31^{a*}	183.85^a	1.66^a
	S-F	89.21^b	110.76^b	1.00^b
	CS	66.10^b	82.58^b	0.74^b
Season 2/2019	CF	269.43^a	306.10^a	2.89^a
	S-F	196.45^b	232.08^b	2.19^b
	CS	154.32^b	200.41^b	1.89^b

**Means followed by the same letter within the column for each growing season are not significantly different by DMRT at P≤0.05.*

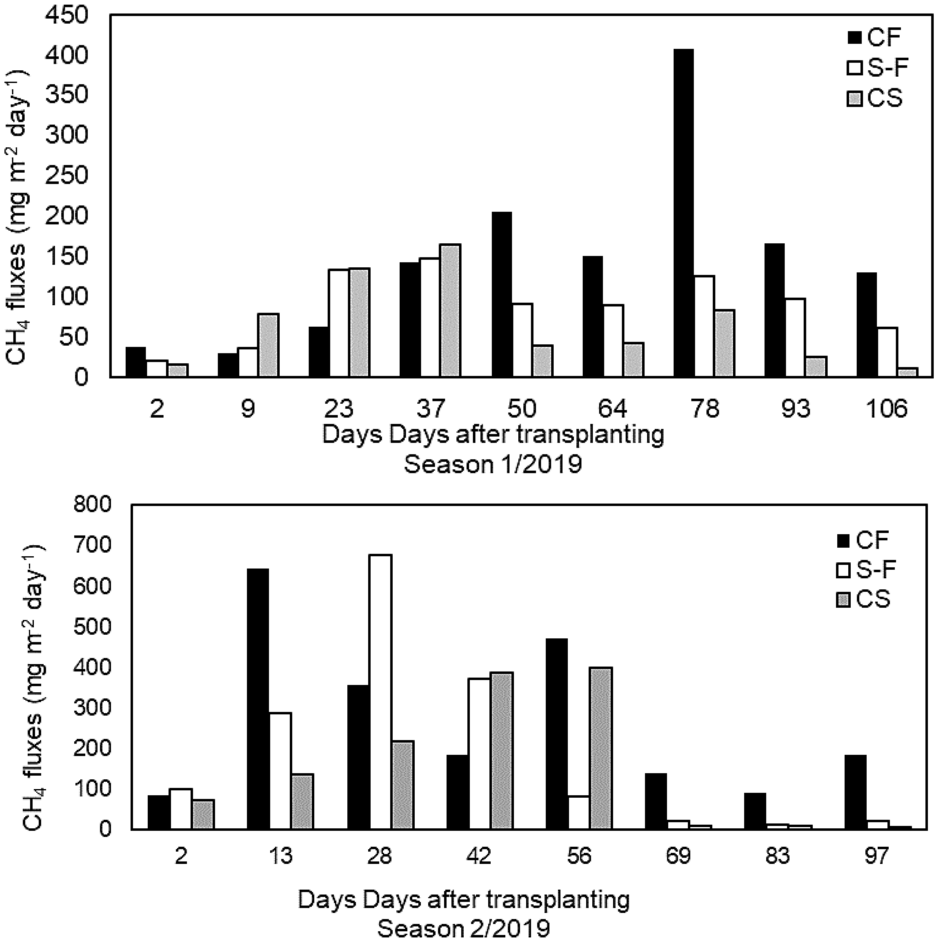

Fig. 2. The CH_4 emissions under different water management treatments, i.e., continuous flooding (CF), saturated and flooded condition (S-F) and continuous saturated condition (CS), during the rice growing seasons 1/2019 and 2/2019

4. CONCLUSION

Plant physiological performances, plant growth parameters and crop growth rate of rice plants were mostly not significantly affected by water-saving irrigation treatments. Saturated and wet conditions were shown to provide adequate moisture in the soil to support leaf physiological requirements and plant growth performance that resulted in high grain yield of rice production. High methane emissions from flooding conditions indicated that conventional water management is not a sustainable water management for rice production system. In conclusion, intermittent irrigation such as maintaining the soils in saturated and wet conditions could be an effective adaptation technique for simultaneously saving water and mitigating GHG while maintaining high grain yields of rice. This sustainable water management in the rice production system could be adopted by farmers and policymakers that can both benefit from carbon credits and improved food security.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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