Article

Managing Water for System of Rice Intensification Paddy Fields to Mitigate Greenhouse Gas Emissions and Maintain Yield

Chusnul Arif [*] , Satyanto Krido Saptomo , Budi Indra Setiawan , Muh Taufik , Bayu Dwi Apri Nugroho , Febri Doni , Reskiana Saefuddin , Masaru Mizoguchi

Article

Managing Water for System of Rice Intensification Paddy Fields to Mitigate Greenhouse Gas Emissions and Maintain Yield

Chusnul Arif [1,*], Satyanto Krido Saptomo [1], Budi Indra Setiawan [1], Muh Taufik [2], Bayu Dwi Apri Nugroho [3], Febri Doni [4,5], Reskiana Saefuddin [6] and Masaru Mizoguchi [7]

[1] Department of Civil and Environmental Engineering, Faculty of Agricultural Engineering and Technology, IPB University, Bogor 16680, Indonesia; saptomo@apps.ipb.ac.id (S.K.S); budindra@apps.ipb.ac.id (B.I.S)

[2] Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University, Bogor 16680, Indonesia; mtaufik@apps.ipb.ac.id

[3] Department of Agricultural Engineering and Biosystem, Faculty of Agricultural Technology, Gadjah Mada University, Yogyakarta 55281, Indonesia; bayu.tep@ugm.ac.id (B.D.A)

[4] Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Bandung 45361, Indonesia; febri@unpad.ac.id (F.D)

[5] Department of Global Development, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14850, USA; febri@unpad.ac.id (F.D)

[6] Research Center for Limnology and Water Resources, National Research and Innovation Agency, Jakarta Pusat 10340, Indonesia, resk001@brin.go.id (R.S)

[7] Department of Global Agricultural Sciences, Graduate School of Agricultural and Life Sciences, the University of Tokyo, Tokyo 113-8657, Japan; amizo@mail.ecc.u-tokyo.ac.jp

* Correspondence: chusnul_arif@apps.ipb.ac.id

Abstract: The System of Rice Intensification (SRI) is known to boost rice yields while reducing water use, but its impact on greenhouse gas (GHG) emissions under different water management practices remains unclear. This research aims to determine the effective water management practices in SRI for mitigating greenhouse gas emissions by maintaining yield. This study, conducted from 2016 to 2018, evaluated three irrigation regimes—Flooded (FL: 2–5 cm water depth), WET (0–1 cm), and DRY (-5 cm) in Bogor, Indonesia. Methane (CH_4) and nitrous oxide (N_2O) emissions were measured weekly using a closed chamber system. Results showed an inverse relationship between CH_4 and N_2O: CH_4 was lowest under the DRY regime, while N_2O was lowest in the FL regime. The DRY regime had the lowest global warming potential (GWP), 28% and 33% lower than WET and FL, mainly due to a significant CH_4 reduction (42% and 57%, respectively). Despite reduced water levels, rice yields remained stable in the DRY regime, averaging 6.0–6.18 tons/ha across three seasons. These findings suggest that the DRY irrigation regime in SRI can effectively balance high rice productivity with reduced GHG emissions, offering a sustainable water management strategy.

Keywords: greenhouse gas emission; global water potential; paddy cultivation; water management

1. Introduction

Rice paddy is a key staple crop that sustains the needs of more than half the global population. However, their production heavily depends on water availability, making rice cultivation one of the most water-intensive sectors in agriculture. Traditional water management systems often lead to inefficient water use and heighten greenhouse gas emissions [1], particularly methane, which is produced through anaerobic processes in flooded fields. Given global warming concerns, water management strategies that maintain productivity while reducing emissions have become a critical priority in advancing sustainable agriculture. Water management in rice cultivation affects not only

crop production but also greenhouse gas emissions, particularly methane (CH_4) and nitrous oxide (N_2O) [2]. Commonly in Indonesia, continuous flooding (CF) is widely practiced, primarily to create an anaerobic environment that suppresses weed growth. The lack of oxygen in submerged conditions inhibits the germination and establishment of most weed species, giving rice, which is adapted to thrive in flooded environments, a competitive advantage. CF condition limits the light and nutrient availability of weeds, significantly reducing their population and spread. The practice remains widespread due to its simplicity and historical association with high yields under optimal conditions [3].

Although CF enhances productivity, there are some concerns related to excessive water use and high CH_4 emissions. CF create of anaerobic soil conditions, which promote the activity of methanogenic archaea—microorganisms that produce methane as a by-product of organic matter decomposition in oxygen-deprived environments. CH_4 is a potent greenhouse gas, with a global warming potential much higher than carbon dioxide. Studies have shown that this traditional water management practice in rice cultivation is a primary contributor to agricultural CH_4 emissions globally [4,5]. In addition, CF in rice fields is known to reduce water use efficiency due to significant water losses through processes such as deep percolation, surface runoff, and evaporation. This traditional irrigation method consumes substantial amounts of water. Despite its ability to ensure stable rice yields and suppress weed growth, CF contributes to inefficient water utilization, which is increasingly unsustainable in regions facing water scarcity and growing competition for water resources [6].

Therefore, water-saving technologies such as intermittent irrigation, water-saving irrigation, and alternate wetting and drying (AWD) have been introduced as more environmentally friendly water management practice that is able to reduce greenhouse gas emissions. In addition, alternative rice cultivation systems such as the System of Rice Intensification (SRI) have demonstrated a significant reduction in greenhouse gas emissions [7–9]. SRI has emerged as a promising method for addressing these challenges. By emphasizing controlled irrigation, improved spacing, and organic fertilization, SRI reduces water use and enhances soil aeration, thereby mitigating CH_4 emissions and maintaining or even increasing yields [10].

SRI has been introduced in Indonesia since 1999, and numerous studies on SRI have been conducted in the country, focusing on water management [11–13]. But most Indonesian farmers still prefer CF systems due to concerns that water-saving technologies may reduce yields and problems with weed growing. Further, there is currently a lack of information on optimal water management practices that can simultaneously maintain productivity and reduce emissions, particularly CH_4 and N_2O. Therefore, this study aims to determine optimal water management strategies with SRI that sustain yields while lowering greenhouse gas emissions including its analysis of water productivity and water use efficiency. These strategies will be developed by testing various irrigation scenarios at different growth stages of the crop.

2. Materials and Methods

2.1. Experimental setup

The study was conducted at Kinjiro Farm (6°35'35.36"S and 106°46'17.95" E) in Bogor, Indonesia, over three growing seasons from 2016 to 2018. The first growing season took place from April 14 to August 4, 2016, the second from April 8 to July 29, 2017, and the third from January 20 to May 12, 2018, with each rice cultivation cycle lasting 112 days. Elements of the System of Rice Intensification (SRI) were applied during cultivation, including single transplanting with young seedlings (14 days after sowing) at a spacing of 30 x 30 cm using the *Pertiwi* rice variety.

For fertilization, the soil was treated with urea, SP-36, and KCl fertilizers. Urea was applied at a rate of 100 kg/ha at 0–10 days after transplanting (DAT), 100 kg/ha at 20–30 DAT, and 75 kg/ha at 35–45 DAT. SP-36 was applied at 100 kg/ha at 0–10 DAT, while KCl was applied at 75 kg/ha at 0–10 DAT and 75 kg/ha at 35–45 DAT. Details of the soil's physical properties are presented in **Table 1**.

Table 1. Soil physics properties in the location.

Properties	Value
Particle density (g/cm³)	1.96
Total porosity (% volume)	65.3
Water content (% volume)	
pF 1	63.3
pF 2	46.9
pF 2.54 (Field capacity)	40.3
pF 4.2 (Permanent wilting point)	19.6
Permeability (cm/jam)	8.17
Soil texture (%)	
Sand	23
Silt	34
Clay	43

The irrigation patterns in this study were divided into three distinct water regimes: flooded (FL), WET, and DRY. The flooded (FL) regime was implemented as a conventional irrigation system, the WET regime represented a moderate water condition, and the DRY regime simulated a water-saving scenario under SRI rice cultivation. In the FL regime, the water level was maintained continuously at 2–5 cm above the soil surface. During the final growth stages, the water level was gradually reduced to the soil surface. In the WET regime, the water level was set at 1 cm above the soil surface during the first 20 days after transplantation (DAT). Afterward, it was maintained at 0 cm (soil surface level) until harvest. In the DRY regime, the water level was maintained at 1 cm above the soil surface for the first 20 days. It was then adjusted to 0 cm at 21–30 DAT and subsequently lowered to 5 cm below the soil surface until harvest (**Figure 1**).
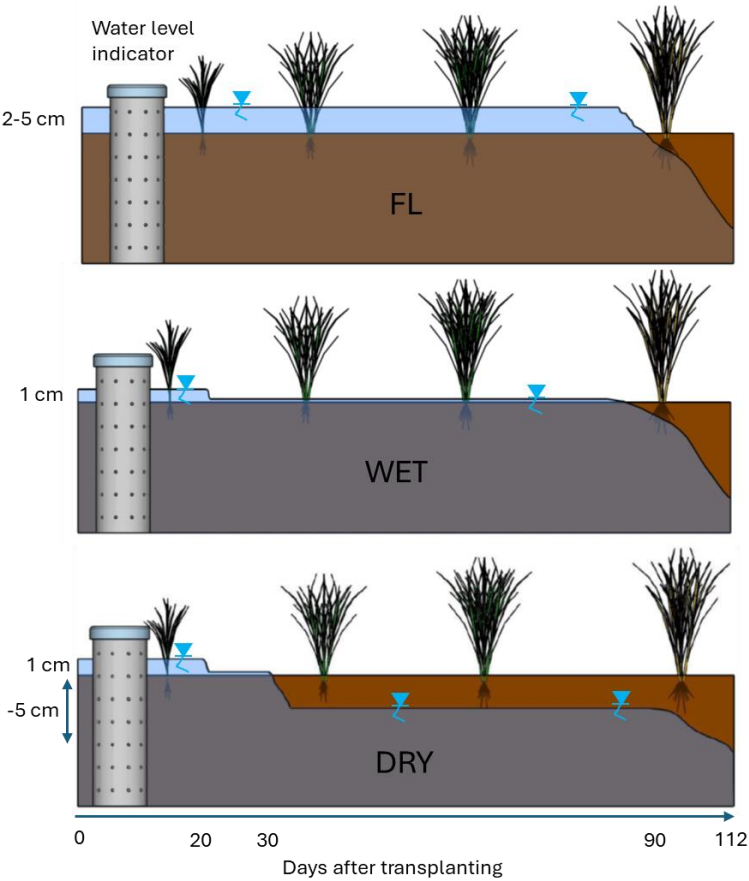

Figure 1. Water management of three irrigation regimes.

2.2. Greenhouse gas emission measurements and analysis

Measurements of greenhouse gas emissions, specifically methane (CH_4) and nitrous oxide (N_2O), were conducted weekly using a closed chamber system. The chamber measured 30 cm × 30 cm × 120 cm, accompanied by a chamber base of 30 cm × 30 cm × 20 cm, 200 ml tedlar bags, and 10 ml brown vials equipped with rubber stoppers. Prior to gas sampling, a fan inside the chamber was activated, and the chamber was securely placed on the chamber base. Transparent tubing connected to a three-way valve on the chamber facilitated sampling by attaching tedlar bags and syringes. Gas samples were collected at four times intervals—0, 10, 20, and 30 minutes. The sampled gas in the tedlar bags was transferred into 10 ml vials using syringes through the rubber stoppers for each time point. Subsequently, the gas samples were analyzed at the Greenhouse Gas Laboratory.

Gas analysis was conducted using a calibrated Gas Chromatography (GC) system. The analysis results provided gas concentration values in parts per million (ppm). The rate of change in gas concentration over time was used to determine the gas flux. Methane flux was calculated using Equation (1) [14]:

$$E = \frac{\delta C}{\delta t} \text{ x } \frac{V}{A} \text{ x } \frac{mW}{mV} \text{ x } \frac{273.2}{273.2+T} \quad (1)$$

where E is CH_4/N_2O gas flux (mg/m²/min), $\delta C/\delta t$ is change in CH_4/N_2O concentration over time (ppm/min), V is chamber volume (m³), A is chamber surface area (m²), mV is molar volume of gas (22.41 liters at standard temperature and pressure), mW is molecular weight of CH_4/N_2O gas and T is sampling temperature (°C). A positive CH_4/N_2O gas flux value indicates that the rice field emits methane gas, while a negative value indicates CH_4/N_2O absorption or uptake.

The total flux over a growing season was calculated by integrating the flux values using the numerical Simpson's Rule model, as expressed in Equation (2):

$$\int_a^b f(x)dx \approx \frac{b-a}{6}\left[f(a) + 4f\left(\frac{a+b}{2}\right) + f(b)\right] \qquad (2)$$

where a is measurement time point 'a', b is measurement time point 'b', f(a) is the greenhouse gas emission value at a time 'a' (mg/m²/d) and f(b) is the greenhouse gas emission value at time 'b' (mg/m²/d).

2.3. Water and weathers parameters measurements

The determination of water parameters is based on a water balance using the lysimeter principle, taking into account water inflow and outflow. Water inflow includes rainfall (P) and irrigation (I), while water outflow consists of actual evapotranspiration (ETa) and drainage/runoff (RO). The relationship is expressed by the following Equation (3):

$$WL_i = WL_{i-1} + P + I - (ET_a + RO) \qquad (3)$$

where WL represents the water level (mm), and i denotes time (days).

The observed weather parameters include air temperature, humidity, and solar radiation. We analyzed weather data to obtain max, min, and average of air temperatures. For humidity and solar radiation, we calculate the mean daily value. Daily reference evapotranspiration based on Penman-Monteith FAO was calculated using the available weather data over three cropping seasons.

2.4. Yield, water productivity, and water use efficiency

The grain yield of rice for each water regime is converted to tons per hectare (ton/ha) at harvest. Water productivity is calculated using the following Equations (4) and (5):

$$WP_{I+P} = \frac{Y}{I+P} \qquad (4)$$

$$WP_{ET} = \frac{Y}{ETa} \qquad (5)$$

where WP_{I+P} represents water productivity with respect to water inflow (kg/m³), WP_{ET} represents water productivity with respect to actual evapotranspiration (kg/m³), and Y is the total yield (ton/ha). Additionally, to evaluate water use efficiency, the water efficiency index is determined using the following Equation (6):

$$WUE = \frac{Y}{I} \tag{6}$$

where WUE is the water use efficiency index (kg/m³). Due to severe bird attack, the yield data for the 2017 season were not reliable. Estimations were made based on remaining unspoiled grain and supported by linear interpolation between 2016 and 2018 yields for each irrigation regime. A simple linear regression model using season and treatment as predictors was also applied to validate the estimates. These values were used in the analysis to ensure data consistency.

3. Results

3.1. Weather conditions among crop seasons

Table 2 provides weather data over three years of crop season, which includes parameters like air temperature, relative humidity, solar radiation, evapotranspiration, and precipitation. The weather conditions during the three growing seasons were relatively stable across all parameters, despite some fluctuations. Maximum air temperature remained constant at 35.9°C in 2016 and 2017 and slightly increased to 36.2°C in 2018. For average air temperature, a gradual decrease from 26.9°C in 2016 to 26.2°C in 2018 may reflect changes in growing conditions. For paddy, the ideal temperature range is 25-35°C; the values in the table are within this range, favoring growth. Meanwhile, the slight variations (20.4°C to 20.6°C) of minimum air temperature indicate stable nighttime temperatures, which are critical for crop respiration and avoiding cold stress.

Table 2. Weather conditions among crop seasons.

No	Parameters	Season			Unit
		2016	**2017**	**2018**	
1	Max air temperature	35.9	35.9	36.2	°C
2	Average air temperature	26.9	26.7	26.2	°C
3	Min air temperature	20.4	20.1	20.6	°C
4	Relative humidity	84.6	82.7	84.5	%
5	Average Solar radiation	13.0	12.9	12.1	MJ/m²/d
6	Average reference evapotranspiration	3.25	2.60	2.43	mm
7	Total Precipitation	1211	1414	1025	mm

Relative humidity (RH) ranged from 82.7% in 2017 to 84.6% in 2016. High humidity is generally favorable for paddy as it prevents excessive water loss through transpiration. However, excessive humidity can promote diseases such as pathogenic fungal infections (e.g., blast and sheath blight). The average solar radiation slightly declined from 13.0 MJ/m²/d in 2016 to 12.1 MJ/m²/d in 2018. Adequate sunlight is necessary for photosynthesis and crop yield. Reference evapotranspiration was in line with the solar radiation. A notable decrease in reference evapotranspiration values (from 3.25 mm in 2016 to 2.43 mm in 2018) suggests a reduction in water demand by the atmosphere. Meanwhile, precipitation varied significantly, with a peak in 2017 (1414 mm) and a decline in 2018 (1025 mm).

3.2. Seasonal CH_4 and N_2O emissions

Figure 2 shows the fluctuation of CH_4 emission during three crop seasons under three different regimes. CH_4 emissions vary significantly across the years, showing both positive and negative values. Significant emission peaks were observed in the FL regime, particularly in 2017 (e.g., 1184.2 mg/m² at DAT 28) and 2016 (e.g., 961.9 mg/m² at DAT 105). The positive correlation between flooding and CH_4 emissions supports the idea that standing water facilitates methane production as occurred

in the FL regime. Under the WET regime, the conditions show intermediate levels of methane emissions compared to flooded conditions. However, in some cases (e.g., DAT 28, 2017: 1044.4 mg/m²), emissions were nearly as high as under flooded conditions. In some instances (e.g., DAT 0 and DAT 35 in 2017), the WET regime shows CH_4 uptake (negative values), indicating methanotrophy might dominate temporarily. The data suggested that shifting from flooded to wet conditions could significantly reduce CH_4 emissions without entirely eliminating CH_4 release [15]. The DRY regime with the lowest water level shows that CH_4 emissions were typically the lowest or even negative (indicating uptake). Here, strong uptake was observed in 2016 (e.g., -155.2 mg/m² at DAT 0) and positive emissions were occasional and relatively low, and the peak were lowest than two other regimes (e.g., 250.4 mg/m² at DAT 21, 2018). Aerobic soil conditions under dry conditions favor methanotrophic bacteria that consume CH_4 [16].
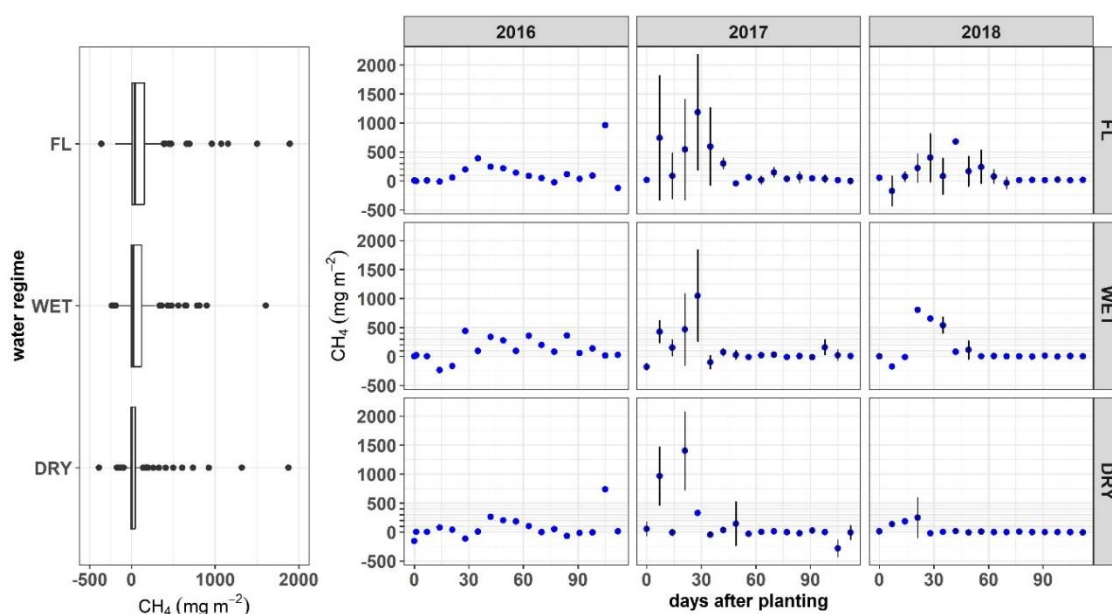

Figure 2. Seasonal CH_4 emissions among crop seasons in three irrigation regimes.

A different trend was observed in N_2O emissions, where the FL regime produced the lowest N_2O emissions compared to the other two irrigation systems (WET and DRY), particularly in 2018, as shown in **Figure 3**. N_2O emissions were relatively low under flooded conditions in the FL regime, consistent with reduced availability of oxygen in the soil. For instance, low emissions were observed in most years and dates (e.g., -0.7 mg/m² at DAT 91 in 2018 or 0.5 mg/m² at DAT 0 in 2016). Negative values (e.g., -18.0 mg/m² at DAT 112 in 2016) may indicate net consumption of N_2O, likely due to denitrification to N_2 [17]. Peaks were rare but occurred under specific conditions (e.g., 13.1 mg/m² at DAT 84 in 2016).

The WET regime shows moderate N_2O emissions, with occasional peaks, e.g., peaks of 14.5 mg/m² (DAT 35 in 2017) and 26.0 mg/m² (DAT 35 in 2018) that suggested transient periods of aerobic soil zones facilitating nitrification. On the other hand, negative values, as observed in 2016 and 2018 (e.g., -7.2 mg/m² at DAT 70 in 2016), indicate conditions favoring N_2O consumption, likely due to near-anaerobic soil environments. Under the DRY regime, N_2O emissions were highest, where aerobic environments enhance nitrification. According to Figure 2 high positive emissions were observed, such as 58.7 mg/m² (DAT 42 in 2018) and 25.2 mg/m² (DAT 49 in 2018). Lower negative values or near-neutral values (e.g., -0.3 mg/m² at DAT 63 in 2018) occur less frequently in dry conditions compared to FL and WET, suggesting limited denitrification.
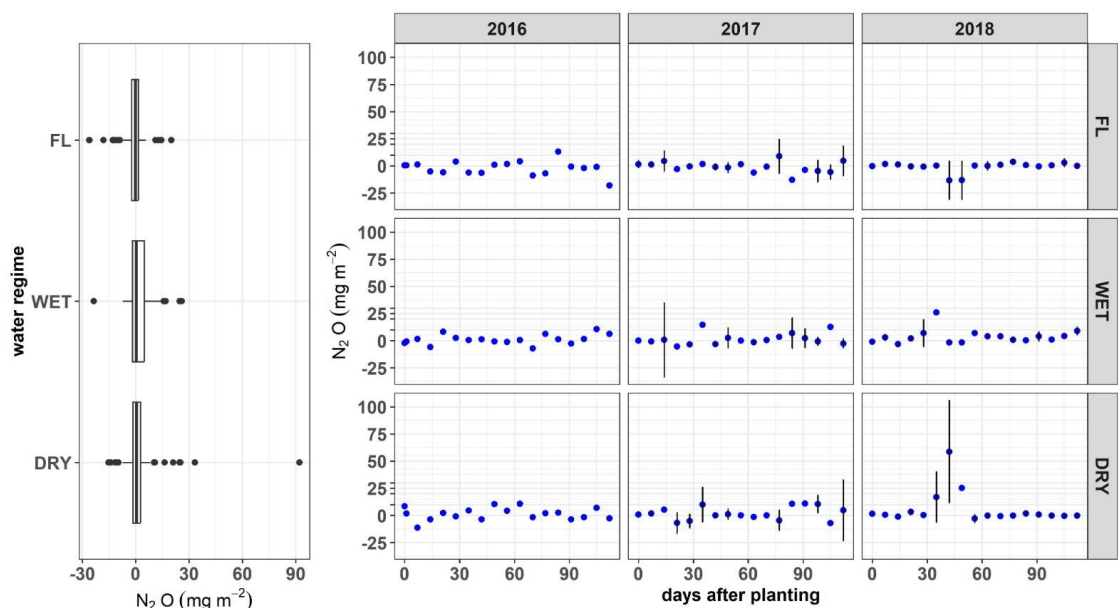
Figure 3. Seasonal N_2O emissions among crop seasons in three irrigation regimes.

Table 3 presents the total emissions of both CH_4 and N_2O across each irrigation regime among three seasons. The results highlight a consistent pattern between CH_4 and N_2O emissions. The FL irrigation treatment produced the highest CH_4 emissions but the lowest N_2O emissions. Conversely, the DRY irrigation treatment had the lowest CH_4 emissions but the highest cumulative N_2O emissions. FL regime as continuous flooding creates anaerobic conditions favorable for methanogenesis by microbes in which CH_4 emissions peaked in 2017 (267.0 kg/ha/season). The WET showed intermediate CH_4 emissions compared to FL and DRY. Wet irrigation, with intermittent drying, limits anaerobic conditions, reducing methanogenesis. Under the WET regime, CH_4 emissions were more stable across seasons, ranging from 124.0 to 153.3 kg/ha/season. The lowest water level in the DRY regime produced the lowest CH_4 emissions, particularly in 2018 (33.6 kg/ha/season) since dry conditions reduce anaerobic processes, significantly limiting CH_4 production. The average reduction in CH_4 emissions under the DRY regime is 42% and 57% compared to the WET and FL regimes, respectively.

Table 3. Total emission and global warming potential among regimes.

Season	Regime	Parameters			Unit
		CH_4	N_2O	GWP*	
	FL	173.6	-1.81	4,193	kg/ha/season
2016	WET	145.1	1.34	4,283	kg/ha/season
	DRY	100.7	1.33	3,082	kg/ha/season
	FL	267.0	0.45	7,332	kg/ha/season
2017	WET	153.3	-0.62	3,972	kg/ha/season
	DRY	118.0	0.33	3,275	kg/ha/season
	FL	130.2	-1.26	3,172	kg/ha/season
2018	WET	124.0	3.25	4,236	kg/ha/season
	DRY	33.6	6.36	2,644	kg/ha/season

*GWP: the global warming potentials at the 100-year time horizon of 27 and 273 for CH4 and N_2O, respectively (IPCC AR6).

On the other hand, N_2O emissions had negative values on the FL regime particularly in 2016 and 2018, possibly due to denitrification processes converting N_2O into N_2 gas under saturated conditions, while emissions were negligible in 2017 since the value close to zero (0.45 kg/ha/season). Meanwhile,

the WET regime consistently has higher N_2O emissions than FL, due to alternating wet-dry cycles that enhance nitrification-denitrification processes. Here, N_2O peaked in 2018 (3.25 kg/ha/season). Under the DRY regime, N_2O emissions were at the highest level, with a significant increase in 2018 (6.36 kg/ha/season). Aerobic soil conditions promote nitrification, while subsequent irrigation events enable N_2O release.

To assess the total emissions from a field, GWP is used to reflect the combined impact of CH_4 and N_2O emissions. Based on Table 2, the FL regime had the highest GWP in 2017 (7,332 kg CO_2-eq/ha/season), primarily driven by high CH_4 emissions. In 2018, the GWP (3,172 kg CO_2-eq/ha/season) of this regime was reduced, likely due to a significant drop in CH_4 emissions and negative N_2O emissions. The WET regime had consistently high GWP values, peaking in 2016 (4,283 kg CO_2-eq/ha/season). While CH_4 emissions were lower than FL, N_2O emissions under wet-dry conditions significantly contributed to GWP. DRY regime achieved the lowest GWP across all years, with the lowest value in 2018 (2,644 kg CO_2-eq/ha/season). This is due to the substantial reduction in CH_4 emissions, even though N_2O emissions were higher. The reduction in GWP under the DRY regime was recorded at 28% and 33% compared to the WET and FL regimes, respectively.

Therefore, the DRY regime is the most sustainable option for reducing GWP in paddy fields, but it requires careful management to control N_2O emissions. Flooded irrigation, while minimizing N_2O emissions, contributes significantly to global warming due to CH_4 emissions. Wet irrigation strikes a balance but still results in relatively high GWP due to intermediate levels of both CH_4 and N_2O. Future strategies should focus on integrating water management practices with emission mitigation techniques to enhance sustainability.

3.3. Water productivity and water use efficiency among regimes

Grain yield and water productivity varied significantly across the three irrigation regimes—Flooded (FL), Wet (WET), and Dry (DRY)—from 2016 to 2018 as shown in **Table 4**. The yield increased from the first season (2016) to the third season (2018). Between 2016 and 2018, yield under FL increased by **38.8%** (from 4.69 to 6.51 t/ha), and WET rose by **32.0%** (from 5.19 to 6.85 t/ha). In contrast, DRY showed only a **3.0%** increase, indicating that its yield potential had likely plateaued early. Comparison among irrigation regimes, DRY irrigation produced the highest yield, about **28% greater than FL** and **16% higher than WET** in 2016. By 2018, WET produced the highest yield (6.85 t/ha), exceeding FL by **5.2%,** while DRY fell slightly behind WET by **9.8%.** This suggests that although DRY had the early advantage, the WET regime offered more stable yield improvement over time. These findings are in line with Bouman et al. [18], who noted that intermittent irrigation (WET and DRY) can sustain high yields with reduced water input.

Table 4 also shows irrigation and water productivities among the regimes. The first season required the highest amount of irrigation water compared to the second and third seasons. This was primarily due to significant water loss through runoff, particularly rainwater that could not be effectively utilized. Improvements were made in the second and third seasons, resulting in reduced irrigation water requirements. Consequently, water productivity and efficiency in the third season were better than in the first season. When comparing the three irrigation regimes, the DRY regime required the least amount of irrigation water compared to the other two systems. The DRY system achieved water savings of 21–39% compared to the FL regime and 6–20% compared to the WET regime. The less water used in the DRY regime led to significant improvements in water productivity and water use efficiency, particularly during the first season. Water productivity increased by 16–31%, while water use efficiency improved by 31–53%. In the third season, water productivity across all three regimes was comparable, as the yields were relatively similar. However, the DRY regime demonstrated the highest water use efficiency among the three regimes, with an improvement of 11–29%.

Table 4. Yield, water productivity, and water use efficiency among regimes.

Season	Irrigation Regime	Yield (ton/ha)	Irrigation (mm)	ETa (mm)	WP_{I+P} (kg/m³)	WP_{ET} (kg/m³)	WUE (kg/m³)
	FL	4.69	498	461	0.27	1.02	0.94
2016	WET	5.19	378	421	0.33	1.23	1.37
	DRY	6.00	302	408	0.40	1.47	1.99
	FL	5.60	183	378	0.35	1.48	3.06
2017	WET	6.02	153	349	0.38	1.72	3.93
	DRY	6.09	145	338	0.39	1.80	4.20
	FL	6.51	136	310	0.56	2.10	4.78
2018	WET	6.85	114	295	0.60	2.32	5.99
	DRY	6.18	91	280	0.55	2.21	6.76

4. Discussion

The System of Rice Intensification (SRI), recognized as a water-saving rice cultivation method, demonstrated its effectiveness in the current experiment. Although there were variations in yields between the first, second and third planting seasons, the DRY regime consistently achieved consistent production outcomes with more efficient use of irrigation water (**Table 4**). The key to maintaining productivity in the DRY regime lies in its aerobic conditions, which ensure higher oxygen availability. This approach aligns with previous research indicating that rice plants can thrive in non-flooded and unsaturated soil conditions [19].

In SRI rice cultivation, strengthening the root system is a critical aspect, achieved in part by lowering water levels [20]. Reduced water levels encourage roots to grow vertically deeper into the soil to access water and nutrients as reported by previous studies [21–23]. The development of longer roots contributes to stronger rice plant growth under the SRI method with the DRY regime compared to the FL regime, thus, SRI performs better with intermittent irrigation than with continuous flooding [24]. Empirical evidence also showed that SRI combined with alternate wetting and drying irrigation (AWD) enhances crop standing until harvest [25]. Additionally, these results align with findings by Thakur et al., [26], who reported that the SRI method with water-saving irrigation not only improves root growth but also enhances nutrient uptake, thereby sustaining yields even under limited water availability.

The DRY regime enhanced water productivity, consistent with previous research that highlights the benefits of controlled water application in reducing non-productive water losses, such as minimizing evaporation and percolation losses [27] and balancing water use and maintaining adequate soil moisture [28]. Moreover, the DRY regime consistently achieved the highest water use efficiency, with improvements of 31–53% in the first season and 11–29% in the third season. These results align with findings from Geerts and Raes [29], who emphasized that deficit irrigation strategies like DRY can substantially increase water use efficiency without significantly compromising yield. The DRY regime's advantage in water use efficiency, even in later seasons, underscores its potential for long-term sustainability. Reduced water application not only conserves water resources but also improves the energy efficiency of irrigation practices, which is critical in regions facing water scarcity.

The DRY regime consistently reduced GWP over three planting seasons. The DRY regime's ability to achieve the lowest global warming potential (GWP)—45% and 46% lower than the WET and FL regimes, respectively—highlights its effectiveness in balancing these trade-offs. This finding aligns with the growing emphasis on water-saving irrigation techniques, such as alternate wetting and drying (AWD), as viable strategies for mitigating GHG emissions in rice cultivation [30]. The greatest contribution to the reduction in GWP was a significant decrease in CH_4 emissions, which aligns with prior research on aerobic soil conditions limiting methanogenesis [31]. However, this regime elevated N_2O emissions, a known trade-off when transitioning from anaerobic to aerobic soil conditions [32]. Conversely, the FL regime minimizes N_2O emissions but at the cost of higher CH_4

emissions due to prolonged flooding, which promotes the anaerobic decomposition of organic matter.

The DRY regime's ability to maintain yields while achieving the lowest GWP positions it as a sustainable water management practice for SRI. However, its success depends on careful implementation and monitoring to address the potential for increased N_2O emissions. Integrating complementary practices, such as precision nutrient management or the use of nitrification inhibitors, could further enhance its environmental and agronomic benefits [33].

5. Conclusions

The study demonstrated that DRY regime is the optimal water management strategy for the System of Rice Intensification (SRI) in Indonesia, effectively balancing greenhouse gas (GHG) emission mitigation and rice productivity. The DRY regime achieved the lowest methane ($CH4$) emissions and global warming potential (GWP), with GWP reductions of 45% and 46% compared to the WET and FL regimes, respectively. While nitrous oxide (N_2O) emissions were higher in the DRY regime compared to the FL regime, the overall GWP was minimized. Additionally, the DRY regime supported maintained rice yields, with productivity comparable to or exceeding other regimes during the three-year study. This makes the DRY regime an effective approach for sustainable rice cultivation under SRI.

Author Contributions: Conceptualization, C.A (Chusnul Arif); B.I.S and M.M.; methodology, C.A.; S.K.S; and B.I.S; data curation, C.A; S.K.S; B.D.A; original draft preparation, C.A; writing—review and editing, B.I.S, F.D; M.T; R.S.; visualization, C.A; M.T; supervision, B.I.S; M.M.; project administration, R.S.; funding acquisition, C.A; M.M. authors have read and agreed to the published version of the manuscript

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gangopadhyay, S.; Chowdhuri, I.; Das, N.; Pal, S.C.; Mandal, S. The Effects of No-Tillage and Conventional Tillage on Greenhouse Gas Emissions from Paddy Fields with Various Rice Varieties. *Soil and Tillage Research* **2023**, *232*, 105772, doi:10.1016/j.still.2023.105772.
2. Oo, A.Z.; Sudo, S.; Fumoto, T.; Inubushi, K.; Ono, K.; Yamamoto, A.; Bellingrath-Kimura, S.D.; Win, K.T.; Umamageswari, C.; Bama, K.S.; et al. Field Validation of the DNDC-Rice Model for Methane and Nitrous Oxide Emissions from Double-Cropping Paddy Rice under Different Irrigation Practices in Tamil Nadu, India. *Agriculture* **2020**, *10*, 355, doi:10.3390/agriculture10080355.
3. Bwire, D.; Saito, H.; Sidle, R.C.; Nishiwaki, J. Water Management and Hydrological Characteristics of Paddy-Rice Fields under Alternate Wetting and Drying Irrigation Practice as Climate Smart Practice: A Review. *Agronomy* **2024**, *14*, 1421, doi:10.3390/agronomy14071421.
4. Qian, H.; Zhu, X.; Huang, S.; Linquist, B.; Kuzyakov, Y.; Wassmann, R.; Minamikawa, K.; Martinez-Eixarch, M.; Yan, X.; Zhou, F.; et al. Greenhouse Gas Emissions and Mitigation in Rice Agriculture. *Nat Rev Earth Environ* **2023**, *4*, 716–732, doi:10.1038/s43017-023-00482-1.

5.   Dahlgreen, J.; Parr, A. Exploring the Impact of Alternate Wetting and Drying and the System of Rice Intensification on Greenhouse Gas Emissions: A Review of Rice Cultivation Practices. *Agronomy* **2024**, *14*, 378, doi:10.3390/agronomy14020378.

6.   Mallareddy, M.; Thirumalaikumar, R.; Balasubramanian, P.; Naseeruddin, R.; Nithya, N.; Mariadoss, A.; Eazhilkrishna, N.; Choudhary, A.K.; Deiveegan, M.; Subramanian, E.; et al. Maximizing Water Use Efficiency in Rice Farming: A Comprehensive Review of Innovative Irrigation Management Technologies. *Water* **2023**, *15*, 1802, doi:10.3390/w15101802.

7.   Uphoff, N.; Dazzo, F.B. Making Rice Production More Environmentally-Friendly. *Environments* **2016**, *3*, 12, doi:10.3390/environments3020012.

8.   Jain, N.; Dubey, R.; Dubey, D.S.; Singh, J.; Khanna, M.; Pathak, H.; Bhatia, A. Mitigation of Greenhouse Gas Emission with System of Rice Intensification in the Indo-Gangetic Plains. *Paddy Water Environ* **2014**, *12*, 355–363, doi:10.1007/s10333-013-0390-2.

9.   Choi, J.; Kim, G.; Park, W.; Shin, M.; Choi, Y.; Lee, S.; Kim, S.; Yun, D. Effect of SRI Water Management on Water Quality and Greenhouse Gas Emissions in Korea. *Irrigation and Drainage* **2014**, doi:10.1002/ird.1843.

10.   Uphoff, N.; Kassam, A.; Harwood, R. SRI as a Methodology for Raising Crop and Water Productivity: Productive Adaptations in Rice Agronomy and Irrigation Water Management. *Paddy Water Environ.* **2011**, *9 Sp. Iss. SI MAR*, 3–11, doi:10.1007/s10333-010-0224-4.

11.   Arif, C.; Toriyama, K.; Nugroho, B.D.A.; Mizoguchi, M. Crop Coefficient and Water Productivity in Conventional and System of Rice Intensification (SRI) Irrigation Regimes of Terrace Rice Fields in Indonesia. *Jurnal Teknologi* **2015**, *76*, doi:10.11113/jt.v76.5958.

12.   Nugroho, B.D.A.; Toriyama, K.; Kobayashi, K.; Arif, C.; Yokoyama, S.; Mizoguchi, M. Effect of Intermittent Irrigation Following the System of Rice Intensification (SRI) on Rice Yield in a Famer's Paddy Fields in Indonesia. *Paddy Water Environ* **2018**, 1–9, doi:10.1007/s10333-018-0663-x.

13.   Sato, S.; Yamaji, E.; Kuroda, T. Strategies and Engineering Adaptions to Disseminate SRI Methods in Large-Scale Irrigation Systems in Eastern Indonesia. *Paddy Water Environ* **2011**, *9*, 79–88, doi:10.1007/s10333-010-0242-2.

14.   IAEA *Manual on Measurement of Methane and Nitrous Oxide Emissions from Agricultural*; International Atomic Energy Agency: Vienna, Austria, 1993;

15.   Sha, C.; Wang, Q.; Wu, J.; Hu, W.; Shen, C.; Zhang, B.; Wang, M. Regulation of Methane Emissions in a Constructed Wetland by Water Table Changes. *Sustainability* **2023**, *15*, 1536, doi:10.3390/su15021536.

16.   Lim, J.; Wehmeyer, H.; Heffner, T.; Aeppli, M.; Gu, W.; Kim, P.J.; Horn, M.A.; Ho, A. Resilience of Aerobic Methanotrophs in Soils; Spotlight on the Methane Sink under Agriculture. *FEMS Microbiol Ecol* **2024**, *100*, fiae008, doi:10.1093/femsec/fiae008.

17.   Ishii, S.; Ohno, H.; Tsuboi, M.; Otsuka, S.; Senoo, K. Identification and Isolation of Active N2O Reducers in Rice Paddy Soil. *ISME J* **2011**, *5*, 1936–1945, doi:10.1038/ismej.2011.69.

18.   Bouman, B.A.M. *Water Management in Irrigated Rice: Coping with Water Scarcity*; Int. Rice Res. Inst., 2007; ISBN 978-971-22-0219-3.

19.   Bouman, B.A.M.; Peng, S.; Castañeda, A.R.; Visperas, R.M. Yield and Water Use of Irrigated Tropical Aerobic Rice Systems. *Agricultural Water Management* **2005**, *74*, 87–105, doi:10.1016/j.agwat.2004.11.007.

20.   Doni, F.; Safitri, R.; Suhaimi, N.S.M.; Miranti, M.; Rossiana, N.; Mispan, M.S.; Anhar, A.; Uphoff, N. Evaluating the Underlying Physiological and Molecular Mechanisms in the System of Rice Intensification Performance with Trichoderma-Rice Plant Symbiosis as a Model System. *Front. Plant Sci.* **2023**, *14*, doi:10.3389/fpls.2023.1214213.

21.   Setiawan, B.I.; Imansyah, A.; Arif, C.; Watanabe, T.; Mizoguchi, M.; Kato, H. SRI Paddy Growth and GHG Emissions at Various Groundwater Levels. *Irrigation and Drainage* **2014**, *63*, 612–620, doi:10.1002/ird.1866.

22.   Aziez, A.; Hanudin, E.; Harieni, S. Impact of Water Management on Root Morphology, Growth and Yield Component of Lowland Rice Varieties under the Organic System of Rice Intensification. *Journal of Degraded and Mining Lands Management* **2018**, *5*, 1035–1045, doi:10.15243/jdmlm.2018.052.1035.

23.   Arif, C.; Saptomo, S.K.; Setiawan, B.I.; Taufik, M.; Suwarno, W.B.; Mizoguchi, M. A Model of Evapotranspirative Irrigation to Manage the Various Water Levels in the System of Rice Intensification (SRI) and Its Effect on Crop and Water Productivities. *Water* **2022**, *14*, 170, doi:10.3390/w14020170.

24. Thakur, A.K.; Mandal, K.G.; Mohanty, R.K.; Ambast, S.K. Rice Root Growth, Photosynthesis, Yield and Water Productivity Improvements through Modifying Cultivation Practices and Water Management. *Agricultural Water Management* **2018**, *206*, 67–77, doi:10.1016/j.agwat.2018.04.027.

25. Chapagain, T.; Yamaji, E. The Effects of Irrigation Method, Age of Seedling and Spacing on Crop Performance, Productivity and Water-Wise Rice Production in Japan. *Paddy Water Environ* **2010**, *8*, 81–90, doi:10.1007/s10333-009-0187-5.

26. Thakur, A.K.; Rath, S.; Patil, D.U.; Kumar, A. Effects on Rice Plant Morphology and Physiology of Water and Associated Management Practices of the System of Rice Intensification and Their Implications for Crop Performance. *Paddy and Water Environment 9* **2011**, 13-24 Sp. Iss. SI MAR, doi:10.1007/s10333-010-0236-0.

27. Zwart, S.J.; Bastiaanssen, W.G.M. Review of Measured Crop Water Productivity Values for Irrigated Wheat, Rice, Cotton and Maize. *Agricultural Water Management* **2004**, *69*, 115–133, doi:10.1016/j.agwat.2004.04.007.

28. Bouman, B.A.M.; Humphreys, E.; Tuong, T.P.; Barker, R. Rice and Water. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press, 2007; Vol. 92, pp. 187–237.

29. Geerts, S.; Raes, D. Deficit Irrigation as an On-Farm Strategy to Maximize Crop Water Productivity in Dry Areas. *Agricultural Water Management* **2009**, *96*, 1275–1284, doi:10.1016/j.agwat.2009.04.009.

30. Sander, B.O.; Samson, M.; Buresh, R.J. Methane and Nitrous Oxide Emissions from Flooded Rice Fields as Affected by Water and Straw Management between Rice Crops. *Geoderma* **2014**, *235–236*, 355–362, doi:10.1016/j.geoderma.2014.07.020.

31. Linquist, B.; van Groenigen, K.J.; Adviento-Borbe, M.A.; Pittelkow, C.; van Kessel, C. An Agronomic Assessment of Greenhouse Gas Emissions from Major Cereal Crops. *Global Change Biology* **2012**, *18*, 194–209, doi:10.1111/j.1365-2486.2011.02502.x.

32. Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H. Emissions of N2O and NO from Fertilized Fields: Summary of Available Measurement Data. *Global Biogeochemical Cycles* **2002**, *16*, 6-1-6–13, doi:10.1029/2001GB001811.

33. Pathak, H.; Tewari, A.N.; Sankhyan, S.; Dubey, D.S.; Mina, U.; Singh, V.K. Direct-Seeded Rice: Potential, Performance and Problems - a Review. *Current Advances in Agricultural Sciences* **2014**, *6*, 77–88.