

Optimized irrigation regimes in system of rice intensification paddy systems for lower global warming potential and stable yield

Chusnul Arif^{1*}, Satyanto Krido Saptomo¹, Budi Indra Setiawan¹, Muh Taufik², Bayu Dwi Apri Nugroho³, Febri Doni⁴, Reskiana Saefuddin⁵, Masaru Mizoguchi⁶

¹ Division of Sustainable Infrastructure Engineering, Faculty of Engineering and Technology, IPB University, Jl. Raya Dramaga, Kampus IPB Dramaga, Bogor, Indonesia

² Department of Geophysics and Meteorology, Faculty of Mathematics and Natural Sciences, IPB University, Jl. Raya Dramaga, Kampus IPB Dramaga, Bogor, Indonesia

³ Department of Agricultural Engineering and Biosystem, Faculty of Agricultural Technology, Gadjah Mada University, Jl. Flora Bulaksumur No.1, Kocoran, Yogyakarta, Indonesia

⁴ Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Jalan Raya Bandung Sumedang Km 21, Bandung, Indonesia

⁵ Research Center for Limnology and Water Resources, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor km 46, Cibinong, Indonesia

⁶ Department of Biological and Environmental Engineering, Graduate School of Agricultural and Life Sciences, the University of Tokyo, 1-1-1 Yayoi Bunkyo-ku, Tokyo, Japan

* Corresponding author's e-mail: chusnul_arif@apps.ipb.ac.id

ABSTRACT

Mitigating greenhouse gas (GHG) emissions from irrigated rice while maintaining productivity remains a major challenge in sustainable water management. This study aimed to identify an optimized irrigation regime within the system of rice intensification (SRI) by reducing greenhouse gas emission and maintain grain yield as well as increasing water-use efficiency (WUE) across three crop seasons in Bogor, Indonesia. Three irrigation regimes were applied with different water levels, i.e., flooded with water depth in between 2–5 cm (FL), wet with 0–1 cm water depth, and dry with -5 cm below the soil surface. Methane (CH₄) and nitrous oxide (N₂O) fluxes were measured weekly using a closed chamber method, and seasonal GWP was calculated to assess total GHG emissions. As results, a clear trade-off between CH₄ and N₂O emissions in total was observed across regimes due to differences in water status. The dry regime significantly reduced CH₄ emissions and has the lowest overall GWP, which was approximately 28% lower than the wet regime and 39% lower than the FL regime. Although the dry regime released N₂O emissions slightly higher than the FL regime, it has significantly lower impact on climate due to the reduction in CH₄ emissions. Among the regimes, grain yield was not differed significantly, with mean yields ranging from 6.05 to 6.39 t ha⁻¹ across the seasons. Moreover, the dry regime was saving more irrigation water and gained the highest water-use efficiency, by 31–53% in the first season and 11–29% in the third season. These demonstrate that controlled water levels under the dry scenario within SRI systems can simultaneously maintain rice productivity, enhance water-use efficiency, and reduce GHG emissions.

Keywords: climate-smart rice cultivation, intermittent irrigation, methane - nitrous oxide trade-off, system of rice intensification, water productivity.

INTRODUCTION

Rice paddies sustain more than half of the global population, yet rice production remains one of the most water-intensive agricultural systems. Conventional continuous flooding (CF)

irrigation dominates lowland rice cultivation, particularly in Indonesia, due to its effectiveness in weed suppression and yield stabilization (Zarwazi et al., 2016). However, prolonged soil submergence creates strongly anaerobic conditions that stimulate methanogenic archaea,

resulting in substantial methane (CH_4) emissions. Consequently, rice cultivation is recognized as a major anthropogenic source of CH_4 , contributing significantly to global greenhouse gas emissions (Qian et al., 2023).

From an environmental engineering perspective, a key challenge is to redesign irrigation regimes that regulate soil redox dynamics to reduce emissions while maintaining yield stability. Rice cultivation is a major anthropogenic source of methane (CH_4), contributing approximately 8–12% of global CH_4 emissions, highlighting the importance of improving water management practices in paddy systems. Global CH_4 emissions from rice fields have been estimated to range from 18.3 ± 0.1 to $38.8 \pm 1.0 \text{ Tg CH}_4 \text{ yr}^{-1}$, depending on irrigation system and managements (Zhang et al., 2016).

In addition CH_4 , irrigation management strongly influences nitrous oxide (N_2O) emissions through shifts between aerobic and anaerobic soil condition that regulate nitrification–denitrification processes (Kong et al., 2024). Water-saving irrigation strategies such as alternate wetting and drying (AWD) can substantially reduce CH_4 emissions but may simultaneously increase N_2O fluxes, creating a well-documented trade-off (Jiang et al., 2019; Qian et al., 2023). This trade-off complicates the evaluation of mitigation strategies when individual gases are considered in isolation.

Therefore, an integrated assessment using global warming potential (GWP), following IPCC conversion factors (Masson-Delmotte et al., 2021), is required to quantify the net climatic impact of irrigation regimes. Previous meta-analyses indicate that water-saving irrigation generally reduces overall GWP, although the magnitude of this benefit depends on site-specific conditions and management practices (Tan et al., 2025). For example, AWD has been reported to reduce GWP by approximately 20–45% compared to CF, primarily due to substantial reductions in CH_4 emissions despite a potential increase in N_2O emissions (Jiang et al., 2019; Linqvist et al., 2015; Sander et al., 2014; Tan et al., 2025). In addition, irrigation regimes significantly influence water productivity and water-use efficiency (WUE). Water-saving irrigation strategies have been shown to enhance WUE while reducing greenhouse gas emissions, suggesting a potential ‘win–win’ pathway under increasing water scarcity (Wang et al., 2020).

In Indonesia, CF remains widely practiced because it effectively suppresses weed growth by

limiting oxygen availability and resource competition. However, this approach is associated with excessive water consumption and significant losses through percolation, runoff, and evaporation (Bouman and Tuong, 2001). Under increasing climate variability and water scarcity, such inefficiencies are becoming progressively unsustainable. At the same time, continuously reduced soil conditions under CF promote methanogenesis, resulting in higher CH_4 emissions compared with water-saving irrigation strategies (Dahlgreen and Parr, 2024). Meta-analyses have shown that AWD can reduce CH_4 emissions by approximately 40–70% relative to CF, depending on site conditions and management practices (Lee et al., 2023; Rafy et al., 2025; Zhao et al., 2024).

Water-saving irrigation approaches, including intermittent irrigation and AWD, have been proposed as alternatives that reduce water use and mitigate CH_4 emissions. Among these, the System of Rice Intensification (SRI) has emerged as a management framework that combines controlled irrigation, improved soil aeration, and adaptive crop practices. Previous studies suggest that SRI can reduce irrigation water inputs and enhance productivity while lowering methane emissions relative to conventional flooded systems (Materu, 2025). However, existing studies often focus on short-term observations or emphasize CH_4 mitigation without systematically integrating N_2O emissions, GWP, and WUE into a unified assessment. For example, Sander et al., (2014) primarily assessed CH_4 emission reductions under water-saving irrigation without fully integrating crop productivity metrics, and meta-analyses such as Liu et al., (2019) assess CH_4 , N_2O , and GWP responses to water management, but provide limited integration with WUE and irrigation performance. Similarly, several field-scale SRI studies have reported yield improvements and water savings but lack a comprehensive multi-season assessment that simultaneously integrates CH_4 , N_2O , GWP, and WUE under controlled irrigation conditions (for example e.g., Gangopadhyay et al., 2022; Hasanah et al., 2019; Jain et al., 2014).

Although SRI has been introduced in Indonesia since 1999 and several studies have examined its agronomic performance (Arif et al., 2015; Nugroho et al., 2018; Sato et al., 2011), robust field-based evidence quantifying its climatic and hydrological performance remains limited. In particular, there is a lack of multi-seasonal studies that simultaneously evaluate CH_4 and N_2O emissions,

seasonal GWP, yield stability, and water-use efficiency under tropical conditions. This knowledge gap limits the ability to design irrigation regimes that are both climate-efficient and agronomically reliable, contributing to the continued preference for CF among farmers due to concerns over yield reduction and increased weed pressure. Previous studies indicate that water-saving irrigation may increase weed growth and crop–weed competition due to reduced flooding, which otherwise suppresses weed emergence and establishment (Bouman and Tuong, 2001; Brim-DeForest et al., 2017; Dossou-Yovo and Saito, 2021).

Accordingly, this study aims to experimentally evaluate and optimize irrigation regimes within SRI-based paddy systems under tropical field conditions in Indonesia. By integrating multi-season measurements of CH₄ and N₂O fluxes, GWP, grain yield, and water-use efficiency (WUE), this study seeks to identify irrigation strategies that minimize net greenhouse gas emissions without compromising productivity. We hypothesize that (i) optimized intermittent irrigation within SRI systems can significantly reduce CH₄ emissions compared with CF, (ii) increases in N₂O emissions under such regimes do not offset the overall reduction in GWP, and (iii) yield and WUE can be maintained or improved under optimized water management.

MATERIALS AND METHODS

Experimental setup

The experiment was carried out at Kinjiro Farm (6°35'35.36" S; 106°46'17.95" E) in Bogor, Indonesia, across three growing seasons between 2016 and 2018. The first season spanned from April 14 to August 4, 2016, followed by the second from April 8 to July 29, 2017, and the third from January 20 to May 12, 2018. Each cultivation cycle lasted 112 days. The site is characterized by a humid tropical climate, classified as Af (tropical rainforest climate) according to the Köppen–Geiger system, with an average annual precipitation of approximately 3500–4000 mm and a mean annual temperature of around 26–27 °C.

The experiment was established using controlled field-based paddy plots (2 × 2 m, soil depth 30 cm). Each plot was hydraulically isolated by an impermeable bottom layer constructed using a cement–sand mixture and surrounded by brick walls coated with fine cement–sand plaster to a

height of approximately 50 cm to prevent seepage and inter-plot water exchange. This design allowed precise control of irrigation regimes while maintaining near-field hydrological conditions. The experimental design followed a completely randomized design (CRD) with two replicates per treatment (CF, wet, and dry) due to the controlled experimental setup and high level of environmental uniformity across plots. Treatments were randomly assigned to plots to minimize spatial bias. The schematic layout of the experimental plots is presented in Figure 1.

Rice was cultivated following SRI principles, including transplanting single seedlings (14 days after sowing) at 30 × 30 cm spacing using the Peritiwi variety, a widely cultivated Indonesian lowland rice cultivar characterized by medium growth duration (±110–115 days), good tillering capacity, and moderate yield potential under irrigated conditions. Soil physicochemical properties were analyzed prior to the experiment (Table 1). The soil at the experimental site was classified as clay loam, consisting of 23% sand, 34% silt, and 43% clay. It exhibited a slightly acidic to neutral pH (6.7), with relatively high organic carbon content (3.84%) and moderate total nitrogen (0.20%), resulting in a C/N ratio of 19. The soil had a bulk density of 0.68 g cm⁻³ and a particle density of 1.96 g cm⁻³, indicating a relatively well-structured soil condition. The volumetric soil moisture content at field condition was approximately 0.60 m³ m⁻³.

Fertilizer applications were standardized across all treatments. Urea was applied at rates of 100 kg ha⁻¹ during 0–10 DAT, 100 kg ha⁻¹ during 20–30 DAT, and 75 kg ha⁻¹ during 35–45 DAT. SP-36 was applied at 100 kg ha⁻¹ during 0–10 DAT, while KCl was applied at 75 kg ha⁻¹ during both 0–10 DAT and 35–45 DAT. All fertilizers were applied manually by surface broadcasting and lightly incorporated into the topsoil (0–5 cm) to reduce nutrient losses and improve availability under varying soil moisture conditions.

Three irrigation treatments were implemented: flooded (FL), wet, and dry. Under the FL regime, a water layer of 2–5 cm above the soil surface was maintained for most of the growing period. In the wet regime, the water level was kept at 1 cm flooded until 20 days after transplanting (DAT) and subsequently maintained at the soil surface (0 cm). In the dry regime, water depth was maintained at 1 cm until 20 DAT, followed by 0 cm from 21 to 30 DAT, and then lowered to –5 cm below the soil surface until harvest. Water

Table 1. Physicochemical properties of soil at the location

Soil parameters	Value
Soil texture	
Sand	23%
Silt	34%
Clay	43%
Soil pH	6.7
Soil organic carbon	3.84%
Total nitrogen	0.20%
Bulk density	0.68 g/cm ³
Particle density	1.96 g/cm ³
Soil moisture	0.600 m ³ /m ³
C/N ratio	19

levels were monitored using eTape-water level sensors that attached in the perforated PVC tubes (field water tubes) inserted vertically into the soil to a depth of approximately 30 cm, with graduated scale markings to indicate water depth relative to the soil surface. Water depth was measured daily, and irrigation or drainage was adjusted manually to maintain target water levels for each treatment. A schematic representation is provided in Figure 1, whereas Figure 2 presents representative field conditions, highlighting contrasts in

standing water depth and soil surface exposure among treatments.

Sampling and analysis of greenhouse gas fluxes

Methane (CH₄) and nitrous oxide (N₂O) fluxes were measured using the closed static chamber method. Chambers (30 × 30 × 120 cm) were installed on permanent base frames (30 × 30 × 20 cm), which were inserted into the soil to ensure an airtight seal (Figure 3). Gas sampling was conducted weekly between 11:00 a.m. to and 01:00 p.m. to minimize diurnal variability. During each sampling event, gas samples were collected at 0, 10, 20, and 30 minutes after chamber closure. Head-space air was mixed using an internal fan prior to sampling to ensure homogeneous gas distribution.

Gas samples were collected into 200 mL Tedlar bags and subsequently transferred into 10 mL pre-evacuated glass vials using gas-tight syringes. Gas concentrations were analyzed using a gas chromatograph (GC) equipped with a flame ionization detector (FID) for CH₄ and an electron capture detector (ECD) for N₂O and fitted with a stainless-steel packed column. The GC system was calibrated using certified standard gases with known concentrations, and calibration was

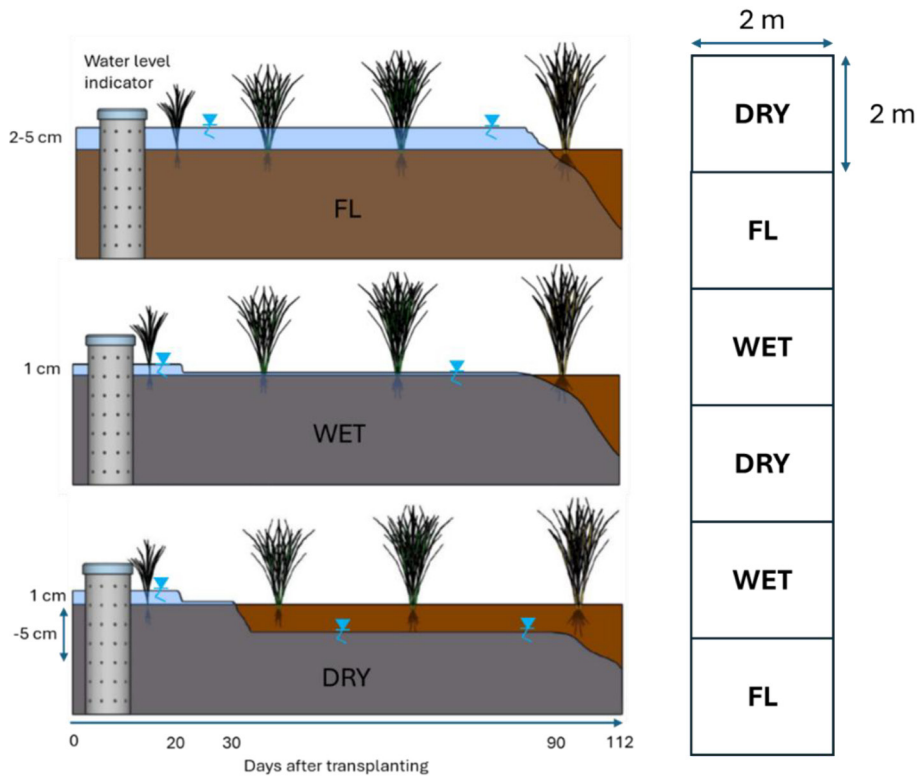


Figure 1. Schematic representation of water level regulation under three irrigation regimes (FL, wet, and dry)

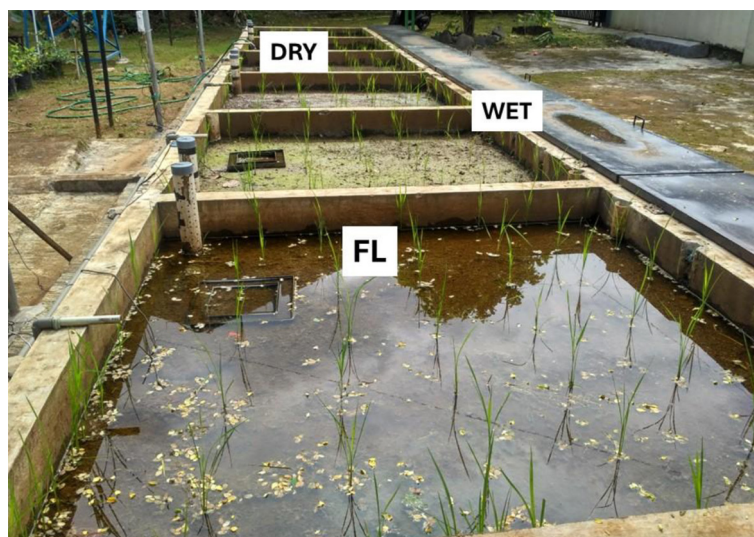


Figure 2. Surface water status under contrasting irrigation thresholds (FL, wet, and dry) in SRI-managed rice plots



Figure 3. In situ greenhouse gas sampling using the closed static chamber method in experimental paddy plots

performed before each measurement batch to ensure analytical accuracy

Gas fluxes were calculated from the linear change in gas concentration over time (ppm min^{-1}), following the equation (Equation 1) (IAEA, 1993), and adjusted for chamber volume, surface area, air temperature, and atmospheric pressure.

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

where: E represents the gas flux ($\text{mg m}^{-2} \text{min}^{-1}$), $\delta C/\delta t$ denotes the rate of change in gas

concentration over time (ppm min^{-1}), V is the chamber volume (m^3), A is the chamber surface area (m^2), mV is the molar volume of the gas (22.41 L at standard temperature and pressure), mW is the molecular weight of the respective gas, and T is the sampling temperature ($^{\circ}\text{C}$).

Positive flux values indicate net emissions, whereas negative values represent gas uptake. Only fluxes showing a consistent and physically meaningful change in gas concentration over

time were included in the analysis. While many measurements exhibited strong linearity, some flux estimates showed lower R^2 values, particularly under low emission conditions or minimal concentration gradients. These data were retained when the concentration changes remained monotonic and consistent with expected emission behaviour. The variability in R^2 reflects natural field conditions and is commonly reported in chamber-based GHG measurements.

Figure 4 provides representative regression examples of CH_4 and N_2O concentrations over time, indicating acceptable linearity under field conditions ($R^2 > 0.80$). The corresponding fluxes derived from these regressions were $8.11 \text{ mg/m}^2/\text{day}$ for CH_4 and $4.24 \text{ mg/m}^2/\text{day}$ for N_2O , illustrating the reliability of the flux estimation approach.

Seasonal cumulative emissions were estimated by integrating discrete flux measurements over time using Simpson’s numerical integration method with a 7-day time step corresponding to the weekly sampling interval. The integration was applied between consecutive measurement points, as expressed in Equation 2.

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

where: a and b represent consecutive sampling times, and $f(a)$ and $f(b)$ are the corresponding greenhouse gas fluxes ($\text{mg/m}^2/\text{day}$) at times a and b , respectively.

Hydrological and meteorological measurements and analysis

Water balance was estimated using a simplified lysimeter-based approach, accounting for inflows (precipitation, P ; irrigation, I) and outflows

(actual evapotranspiration, ET_a ; runoff/drainage, RO), expressed by Equation 3.

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

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

Precipitation was measured using an ECRN-100 precipitation sensor, while irrigation inflow was quantified using a water flow meter installed on the inlet pipe. Runoff/drainage were controlled manually using an outlet valve (tap) installed on each plot. When the water level exceeded the target threshold, the valve was opened to release excess water, which was collected in a container and measured volumetrically to quantify drainage.

Weather data, including solar radiation, air temperature, relative humidity, and wind speed, were measured using an integrated sensor system consisting of a PYR solar radiation sensor, EHT RH/temperature sensor, and anemometer. All sensors were connected to an EM50 data logger, which automatically recorded measurements at regular intervals throughout the experimental period. Reference evapotranspiration (ET_o) was calculated using the FAO Penman–Monteith equation (Allen et al., 1998). Actual evapotranspiration (ET_a) was estimated as the residual term of the water balance equation, assuming negligible capillary rise and deep percolation due to the impermeable plot boundaries, and no lateral water exchange between plots.

Assessment of grain yield and water productivity metrics

Grain yield was determined for each irrigation regime at harvest and expressed in tons per hectare (t ha^{-1}). Although grain moisture content

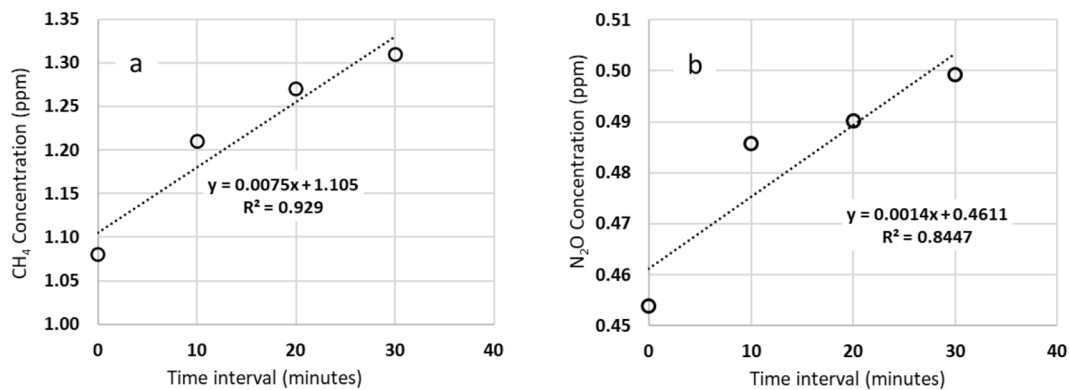


Figure 4. Regression examples of CH_4 and N_2O concentrations over time

was not directly measured, harvesting was conducted under consistent field conditions and at the same timing across all treatments, thereby minimizing variability in grain moisture content. Consequently, yield comparisons are considered reliable for evaluating relative treatment effects.

Water productivity was evaluated using two approaches, based on total water input and actual evapotranspiration. Water productivity with respect to total water inflow (WP_{I+P}) was calculated as the ratio between grain yield (Y) and the sum of irrigation (I) and precipitation (P), while water productivity based on actual evapotranspiration (WP_{ET}) was calculated as the ratio between yield and ET_a , as shown in Equations 4 and 5.

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

$$WP_{ET} = \frac{Y}{ET_a} \quad (5)$$

In addition, water use efficiency (WUE) was calculated to assess the efficiency of irrigation water use, defined as the ratio between grain yield and irrigation input, as expressed in Equation 6.

$$WUE = \frac{Y}{I} \quad (6)$$

where: WUE is expressed in kg m^{-3} .

Statistical analysis and the limitation of study

Statistical analyses were conducted to evaluate the effects of irrigation regimes on CH_4 and N_2O emissions, GWP, grain yield, and water use indicators. Due to the limited number of replicates within individual seasons, data were pooled across years to assess overall treatment responses and improve analytical robustness. All statistical analyses were performed using R statistical software. Analysis of variance (ANOVA) was applied, followed by least significant difference (LSD) tests at a significance level of $p < 0.05$ to compare water regime treatment means. Given the limited replication, the statistical results should be interpreted with caution and are intended to reflect general trends rather than precise effect sizes.

Emission measurements in 2016 were conducted without replication and are therefore presented descriptively. In 2017 and 2018, measurements were conducted with two replicates per treatment. While this level of replication is below the conventional standard, such constraints are not uncommon in controlled field-based

environmental experiments due to logistical and instrumentation limitations.

Grain yield for 2017 was approximated using a linear regression model due to severe bird damage prior to harvest based on the relationship between productive tiller number and observed yield data from 2016 and 2018. However, the derived model ($\text{Yield} = 6.09 + 0.020 \times \text{tiller number}$) showed a low coefficient of determination ($R^2 = 0.23$), indicating limited predictive accuracy and substantial unexplained variability. Therefore, the estimated 2017 yield values are used only as indicative estimates and were not employed as the primary basis for statistical inference.

To account for these limitations, the study emphasizes the consistency of observed patterns across seasons and variables rather than relying solely on statistical significance. Excluding the estimated 2017 data does not alter the overall trends among irrigation treatments, supporting the robustness of the study conclusions. This approach is consistent with previous experimental studies dealing with heterogeneous datasets and limited replication, where statistical analysis is used primarily to support pattern identification rather than strict inference (Vambol and Borowski, 2026).

RESULTS

Meteorological conditions across cropping seasons

Figure 5 summarizes the meteorological conditions recorded during the three cropping seasons, including air temperature, relative humidity, solar radiation, reference evapotranspiration (ET_0), and precipitation. Overall, the observed weather conditions exhibited moderate interannual variability rather than complete uniformity. Maximum air temperature remained nearly constant at 35.9°C in 2016 and 2017 and slightly increased to 36.2°C in 2018. In contrast, mean air temperature showed a gradual decline from 26.9°C in 2016 to 26.2°C in 2018. Minimum air temperature varied only slightly ($20.1\text{--}20.6^\circ\text{C}$), indicating relatively consistent nighttime thermal conditions. These temperature ranges fall within the generally optimal range for rice cultivation ($25\text{--}35^\circ\text{C}$), suggesting that thermal conditions were suitable for crop growth throughout the study period.

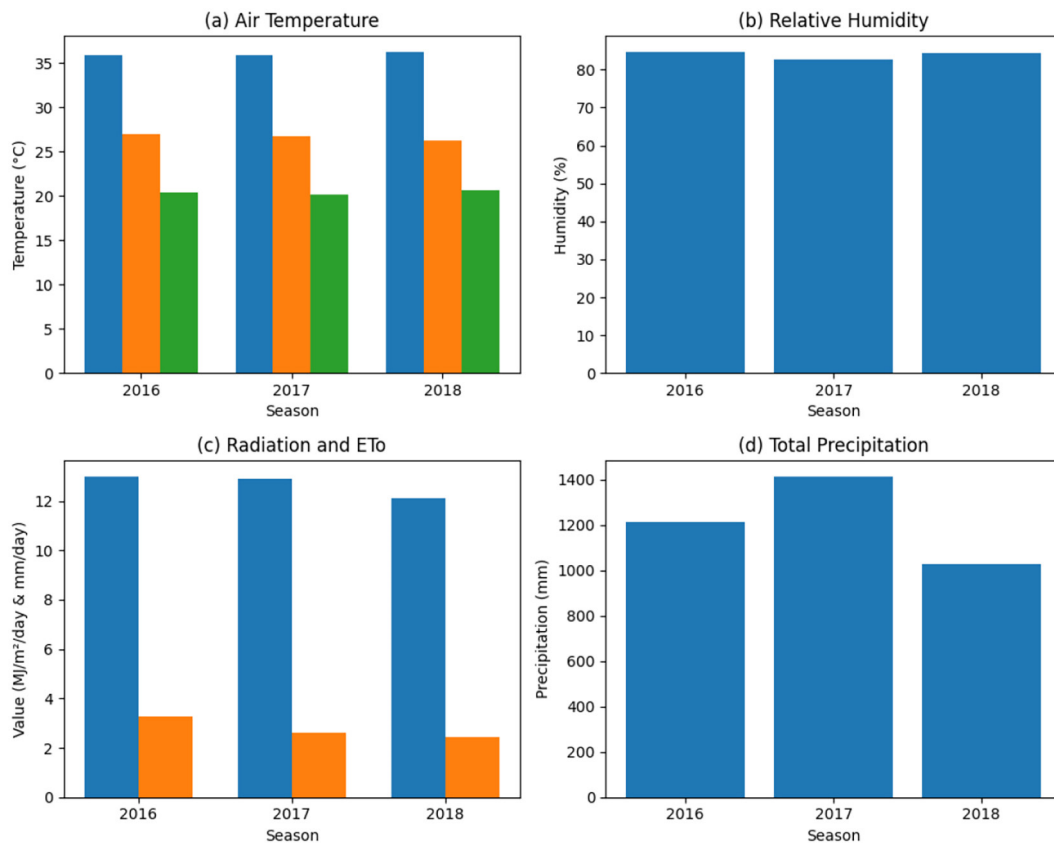


Figure 5. The meteorological conditions recorded during the three cropping seasons

Relative humidity ranged from 82.7% to 84.6%, indicating consistently high atmospheric moisture conditions across seasons. While such conditions are generally favourable for rice growth by reducing evaporative demand, they may also increase the risk of disease incidence under prolonged exposure. Solar radiation showed a slight decreasing trend from 13.0 MJ/m²/d in 2016 to 12.1 MJ/m²/d in 2018. A similar declining pattern was observed in reference evapotranspiration, which decreased from 3.25 mm/d to 2.43 mm/d, reflecting reduced atmospheric evaporative demand over time.

In contrast to other parameters, precipitation exhibited substantial variability among seasons, ranging from 1025 mm in 2018 to 1414 mm in 2017, representing a difference of approximately 38%. This variation suggests that rainfall distribution may have contributed to differences in water availability and potentially influenced emission dynamics and crop performance across seasons.

Seasonal CH₄ and N₂O emissions

Figure 6 illustrates the temporal dynamics of CH₄ fluxes across three cropping seasons under

different irrigation regimes. Overall, CH₄ fluxes exhibited considerable variability over time and between seasons, with both positive and negative values observed. The highest CH₄ fluxes were generally recorded under the flooded (FL) regime. For example, peak emissions reached 1184.2 mg/m²/day at 28 DAT in 2017 and 961.9 mg/m²/day at 105 DAT in 2016. On average, CH₄ fluxes were highest under FL (155.8 mg/m²/day), followed by the WET regime (119.9 mg/m²/day) and the DRY regime (68.8 mg/m²/day) as presented in Figure 6. This pattern indicates that prolonged inundation tends to promote higher methane emissions.

Under the wet regime, CH₄ fluxes were generally lower than those observed under continuous flooding, although relatively high values were occasionally recorded. For instance, CH₄ flux reached 1044.4 mg/m²/day at 28 DAT in 2017, approaching the levels observed under the FL regime. In several cases (e.g., early growth stages in 2017), negative CH₄ fluxes were observed. These values may indicate temporary net methane uptake or reflect low concentration gradients and measurement uncertainty under field conditions and therefore should be interpreted with caution. The dry regime consistently showed the lowest

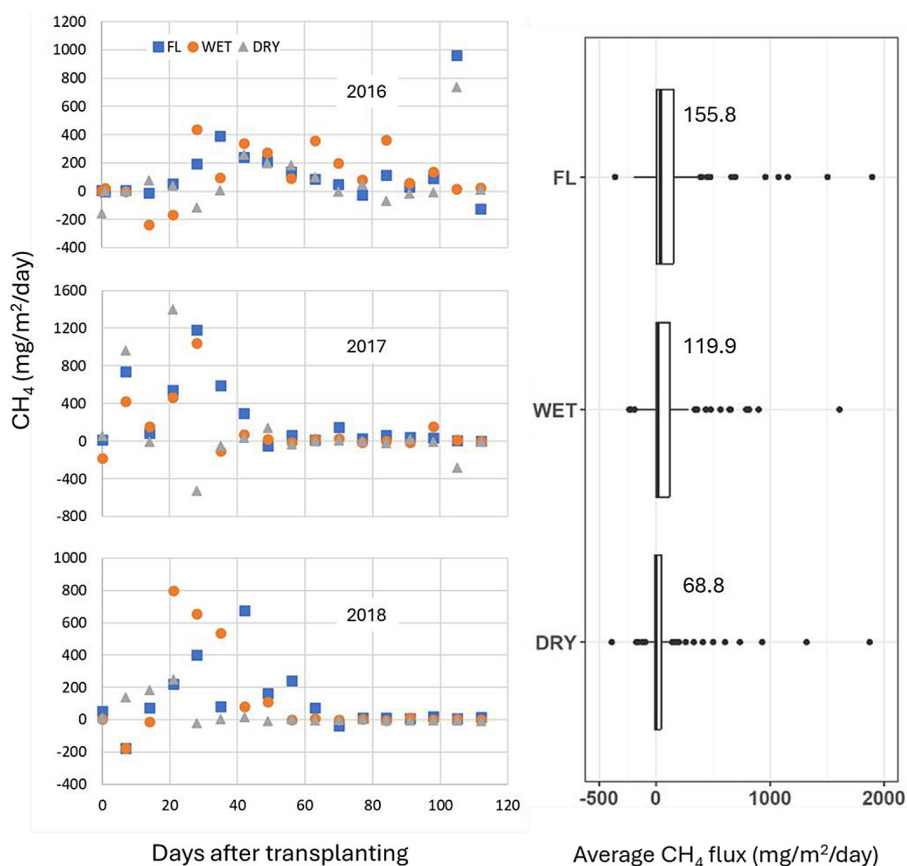


Figure 6. Seasonal CH₄ fluxes under three irrigation regimes with mean values per treatment

CH₄ fluxes among treatments. Negative fluxes were frequently observed, particularly at early stages (e.g., -155.2 mg/m²/day at 0 DAT in 2016), while positive emissions were generally lower and less pronounced compared to the FL and wet regimes (e.g., 250.4 mg/m²/day at 21 DAT in 2018). Across all seasons, a general pattern was observed in which higher water levels tended to be associated with higher CH₄ emissions, while reduced water levels were associated with lower or occasionally negative fluxes. This trend is consistent with previous studies indicating that water management plays an important role in regulating methane dynamics in paddy systems (Sha et al., 2023; Lim et al., 2024).

A contrasting pattern was observed for N₂O fluxes compared to CH₄, with the FL regime generally showing the lowest N₂O fluxes among water regimes, particularly in 2018 (Figure 7). Overall, N₂O fluxes under FL remained low throughout most observation periods (e.g., 0.5 mg/m²/day at 0 DAT in 2016 and -0.7 mg/m²/day at 91 DAT in 2018). On average, N₂O fluxes were lowest under FL (-1.3 mg/m²/day), followed by wet (2.1 mg/m²/day) and dry (3.0 mg/m²/day) as presented in Figure 7, indicating a tendency for

higher emissions under reduced water levels. These low values under FL are consistent with reduced oxygen availability in flooded soils. Negative N₂O fluxes were occasionally observed (e.g., -18.0 mg/m²/day at 112 DAT in 2016). Such values may indicate temporary net N₂O uptake, potentially associated with the reduction of N₂O to N₂ during denitrification processes (Ishii et al., 2011). However, these values may also reflect low concentration gradients and measure uncertainty under field conditions and should therefore be interpreted with caution.

Under the wet regime, N₂O fluxes showed intermediate behaviour, with generally low background values and occasional emission peaks. For example, elevated fluxes were observed at 14.5 mg/m²/day (35 DAT in 2017) and 26.0 mg/m²/day (35 DAT in 2018). These episodic increases suggest the presence of transient soil conditions that may favour N₂O production. Negative fluxes were also observed in some cases (e.g., -7.2 mg/m²/day at 70 DAT in 2016), indicating periods of low emissions or possible net uptake, although such values should be interpreted cautiously. The dry regime generally exhibited higher N₂O fluxes compared to FL and wet. Pronounced emission

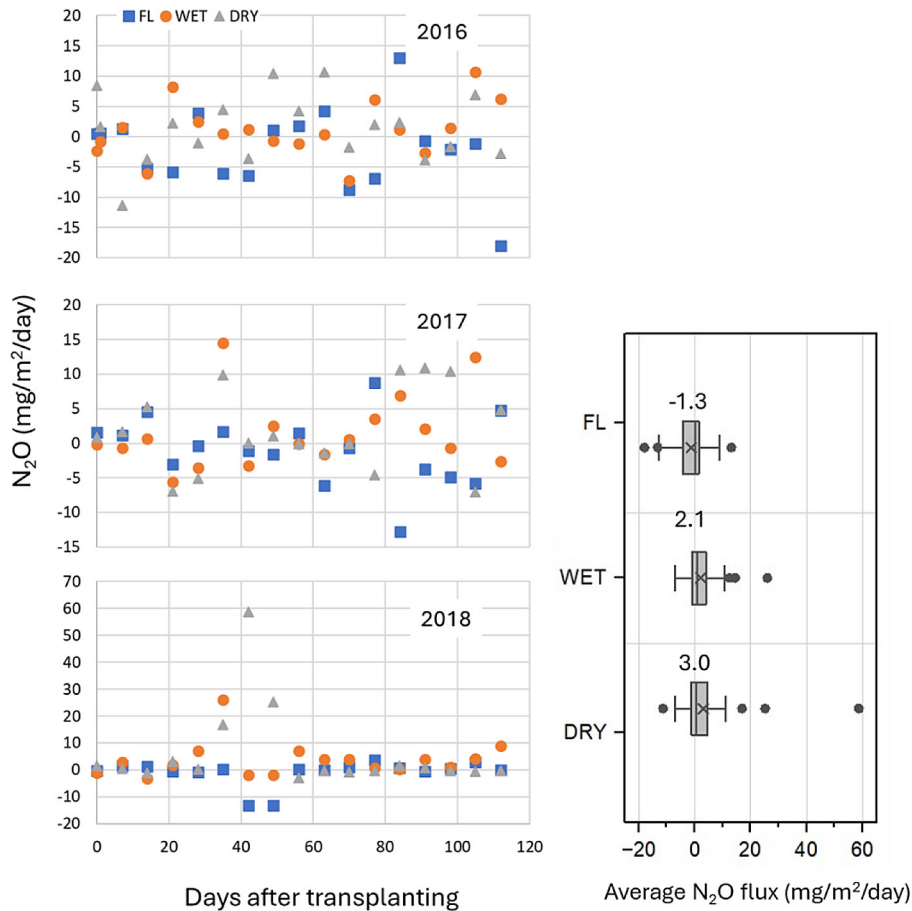


Figure 7. Seasonal N₂O fluxes under three irrigation regimes with mean values per regime

peaks were observed, particularly in 2018 (e.g., 58.7 mg/m²/day at 42 DAT and 25.2 mg/m²/day at 49 DAT). Negative or near-zero fluxes (e.g., -0.3 mg/m²/day at 63 DAT in 2018) occurred less frequently under DRY conditions.

Across all seasons, a general tendency was observed in which lower water levels were associated with higher N₂O fluxes, while continuously flooded conditions were associated with lower emissions. However, given the variability in the data and the presence of negative flux values, these patterns should be interpreted as indicative trends rather than definitive relationships.

Table 2 summarizes the cumulative CH₄ and N₂O emissions under different irrigation regimes across three cropping seasons, along with their mean values. CH₄ emissions exhibited clear differences among irrigation regimes. The FL regime produced the highest mean CH₄ emissions (190.3 kg ha⁻¹ season⁻¹), whereas the DRY regime showed the lowest values (84.1 kg ha⁻¹ season⁻¹), corresponding to an approximate reduction of 56% relative to the FL. The WET regime

displayed intermediate emissions (140.8 kg ha⁻¹ season⁻¹). Overall, CH₄ emissions tended to decrease with decreasing water levels. Statistical analysis suggested differences among irrigation regimes ($p \approx 0.066$); however, given the limited replication across seasons, these results should be interpreted cautiously and are considered indicative of general trends rather than definitive statistical significance.

In contrast to CH₄, N₂O emissions showed an opposite tendency. The DRY regime resulted in the highest mean N₂O emissions (2.67 kg ha⁻¹ season⁻¹), followed by the wet regime (1.32 kg ha⁻¹ season⁻¹), while the lowest values were observed under the FL regime (-0.87 kg ha⁻¹ season⁻¹). This pattern suggests that lower water levels may promote conditions favourable for N₂O production. Despite the increase in N₂O emissions under drier conditions, the overall climate impact was primarily driven by CH₄ emissions. The FL regime produced the highest global warming potential (GWP) (4.899 kg CO₂-eq ha⁻¹ season⁻¹), whereas the DRY regime resulted in the lowest

Table 2. Cumulative GHG emissions and global warming potential across regimes

Season	Regime	Parameters		
		CH ₄ (kg ha ⁻¹ season ⁻¹)	N ₂ O (kg ha ⁻¹ season ⁻¹)	GWP* (kg CO ₂ -eq ha ⁻¹ season ⁻¹)
2016	FL	173.6	-1.81	4,193
	WET	145.1	1.34	4,283
	DRY	100.7	1.33	3,082
2017	FL	267.0	0.45	7,332
	WET	153.3	-0.62	3,972
	DRY	118	0.33	3,275
2018	FL	130.2	-1.26	3,172
	WET	124.0	3.25	4,236
	DRY	33.6	6.36	2,644
Average	FL	190.3 ± 69.2a**	-0.87 ± 1.15a**	4899 ± 2112a**
	WET	140.8 ± 15.1ab**	1.32 ± 1.94a**	4164 ± 167a**
	DRY	84.1 ± 44.8b**	2.67 ± 3.23a**	3000 ± 321b**
LSD (0.05)		93	3.89	1760

Note: *GWP: the global warming potentials at the 100-year time horizon of 27 and 273 for CH₄ and N₂O, respectively (IPCC AR6), **Values are presented as mean ± standard deviation (n = 3 seasons). Different letters within a column indicate significant differences at $p < 0.05$ according to the LSD test.

GWP (3.000 kg CO₂-eq ha⁻¹ season⁻¹), representing a reduction of approximately 39%. The wet regime showed intermediate values (4.164 kg CO₂-eq ha⁻¹ season⁻¹). Overall, these results indicate a trade-off between CH₄ and N₂O emissions under different irrigation regimes. While water-saving irrigation may increase N₂O emissions, the substantial reduction in CH₄ emissions tends to result in a lower overall global warming potential.

Water use performance across irrigation regimes

Grain yield and water productivity under the three irrigation regimes are summarized in Table 3. Averaged across the three growing seasons, mean grain yield ranged from 6.05 ± 1.20 t ha⁻¹ under the FL regime to 6.39 ± 0.53 t ha⁻¹ under the dry regime, while the wet regime produced 6.34 ± 1.00 t ha⁻¹. Statistical analysis did not indicate significant differences among irrigation regimes ($p > 0.05$), suggesting that reduced irrigation intensity did not adversely affect rice productivity.

Despite the absence of statistically significant differences, a consistent pattern was observed in which the dry and wet regimes tended to produce slightly higher yields than the continuously flooded system. In the first season (2016), the dry regime achieved the highest yield (6.00 t ha⁻¹), while in the third season (2018), the wet regime

recorded the highest yield (6.85 t ha⁻¹). These observations indicate that intermittent irrigation can maintain rice yields comparable to those under continuous flooding. This finding is in line with previous studies showing that water-saving irrigation practices can sustain crop productivity while reducing water inputs (Bouman et al., 2007).

Table 3 also presents irrigation water input and associated water productivity indicators. Across the three seasons, the dry regime consistently required the lowest irrigation input, ranging from 91 to 302 mm, compared with 136–498 mm under the FL regime and 114–378 mm under the wet regime. On average, irrigation water use under the dry regime was reduced by approximately 21–39% relative to FL and 6–20% relative to the wet. The reduced irrigation input under the dry regime was associated with improved water productivity. Averaged across seasons, water productivity based on irrigation plus precipitation (WP_{I+P}) reached 0.47 ± 0.08 kg m⁻³ under the dry, slightly higher than 0.46 ± 0.14 kg m⁻³ under the wet and 0.42 ± 0.15 kg m⁻³ under the FL. Similarly, water productivity based on evapotranspiration (WP_{ET}) increased from 1.65 ± 0.56 kg m⁻³ under the FL to 1.92 ± 0.39 kg m⁻³ under the dry. A more pronounced difference was observed in water use efficiency (WUE), where the dry regime achieved the highest mean value (4.52 ± 2.40 kg m⁻³), followed by the WET (3.98 ± 2.37

Table 3. Grain yield and water use efficiency metrics across irrigation regimes

Season	Regimes	Yield (t ha ⁻¹)	Irrigation (mm)	ETa (mm)	WP _{I+P} (kg m ⁻³)	WP _{ET} (kg m ⁻³)	WUE (kg m ⁻³)
2016	FL	4.69	498	461	0.27	1.02	0.94
	WET	5.19	378	421	0.33	1.23	1.37
	DRY	6.00	302	408	0.40	1.47	1.99
2017	FL	6.95*	183	378	0.44	1.84	3.80
	WET	6.99*	153	349	0.45	2.00	4.57
	DRY	6.99*	145	338	0.45	2.07	4.82
2018	FL	6.51	136	310	0.56	2.10	4.78
	WET	6.85	114	295	0.60	2.32	5.99
	DRY	6.18	91	280	0.55	2.21	6.76
Average	FL	6.05 ± 1.20a	272 ± 195a	383 ± 76a	0.42 ± 0.15a	1.65 ± 0.56a	3.17 ± 2.00a
	WET	6.34 ± 1.00a	215 ± 145a	355 ± 64a	0.46 ± 0.14a	1.85 ± 0.56a	3.98 ± 2.37a
	DRY	6.39 ± 0.53a	179 ± 110a	342 ± 64a	0.47 ± 0.08a	1.92 ± 0.39a	4.52 ± 2.40a

Note: *Estimated using a linear regression model developed from the relationship between productive tiller number and observed yield in 2016 and 2018.

kg m⁻³) and the FL (3.17 ± 2.00 kg m⁻³). Overall, these results suggest that water-saving irrigation enhances water productivity and efficiency while maintaining comparable grain yields.

DISCUSSION

The system of rice intensification (SRI), especially implemented through the dry regime in this study, demonstrated its effectiveness in improving water-use performance without compromising yield. As shown in Table 3, the dry regime maintained comparable grain yield (6.39 t ha⁻¹) relative to the wet (6.34 t ha⁻¹) and the FL (6.05 t ha⁻¹), despite substantially lower irrigation input. Although these differences were not statistically significant, the consistency of this pattern across seasons suggests that reduced irrigation intensity can sustain rice productivity under SRI-based management.

The ability of the dry regime to maintain yield is closely related to improved soil aeration conditions. Intermittent drying enhances oxygen availability in the root zone, which supports root development and nutrient uptake. In the current study, this is reflected in the stable yields observed under reduced water input (Table 3). In SRI rice cultivation, improved root development is associated with water management practices that avoid prolonged soil flooding and promote better soil aeration (Doni et al., 2023) Reduced water levels encourage roots to grow deeper into the soil profile in search of water and nutrients, as reported in previous studies (Arif et al., 2022; Aziez et al., 2018;

Setiawan et al., 2014). This mechanism is consistent with the performance of the dry regime in this study, where comparable yields were maintained despite lower irrigation input, suggesting effective root functioning under intermittent soil moisture conditions. Similar mechanisms have been reported in previous studies, where non-flooded or intermittently irrigated conditions promoted deeper and more active root systems (Bouman et al., 2005; Thakur et al., 2018). Thus, the results of this study reinforce the role of controlled soil aeration as a key factor in sustaining productivity under water-saving irrigation.

In addition to maintaining yield, the dry regime substantially improved water-use performance. As indicated in Table 3, the dry treatment consistently required the lowest irrigation input (91–302 mm), resulting in higher water productivity and efficiency. Water use efficiency (WUE) reached 4.52 kg m⁻³ under the dry, compared with 3.98 kg m⁻³ under the WET and 3.17 kg m⁻³ under the FL. This improvement in WUE directly reflects the more efficient conversion of water into grain yield under limited water supply. Similar trends have been reported in deficit irrigation studies, where reduced water input leads to lower non-productive losses such as evaporation and percolation (Geerts and Raes, 2009). Therefore, the present results confirm that water-saving irrigation enhances water productivity primarily through improved water allocation efficiency.

Importantly, the benefits of the dry regime extend beyond water productivity to climate impact mitigation. As shown in Table 2, the dry regime

produced the lowest global warming potential (3000 kg CO₂-eq ha⁻¹ season⁻¹), compared with 4164 kg CO₂-eq ha⁻¹ under the wet and 4.899 kg CO₂-eq ha⁻¹ under the FL. This corresponds to a reduction of approximately 39% relative to the FL, indicating a substantial mitigation potential. The reduction in GWP is primarily driven by the decrease in CH₄ emissions under drier soil conditions, as previously presented in Table 2. Aerobic soil environments suppress methanogenesis while promoting methane oxidation, thereby lowering overall CH₄ emissions (Linguist et al., 2012).

However, this mitigation benefit is accompanied by a trade-off in N₂O emissions. As indicated in Table 2, N₂O emissions increased under the dry regime compared to the FL, reflecting enhanced nitrification - denitrification processes under alternating aerobic - anaerobic conditions. Despite this increase, the contribution of N₂O to total GWP remained relatively small compared to the CH₄, resulting in a net reduction in overall climate impact. This trade-off between CH₄ and N₂O emissions is well documented in rice systems (Bouwman et al., 2002), and the present study confirms that CH₄ reduction generally outweighs the increase in N₂O under water-saving irrigation.

Overall, the results demonstrate that integrating SRI management with water-saving irrigation provides multiple benefits. The dry regime consistently maintained yield (Table 2), improved water use efficiency (Table 3), and reduced global warming potential (Table 2), primarily through substantial reductions in CH₄ emissions (Table 2). These findings highlight the potential of controlled irrigation strategies to simultaneously address water scarcity and climate change mitigation in rice production systems. Such approaches are particularly relevant in regions facing increasing pressure on water resources and the need to reduce agricultural greenhouse gas emissions.

CONCLUSIONS

The results of this study demonstrate that water-saving irrigation within the SRI can effectively reduce greenhouse gas emissions while maintaining rice productivity. Among the tested irrigation regimes, the dry regime consistently produced the lowest methane (CH₄) emissions and the lowest GWP. Averaged across the three growing seasons, the GWP under the dry regime was approximately 28% lower than the wet regime and 39% lower

than the FL regime. Although nitrous oxide (N₂O) emissions were slightly higher under the dry regime compared with the continuously flooded treatment, the overall climate impact remained substantially lower due to the large reduction in CH₄ emissions. In terms of agronomic performance, grain yield among irrigation regimes was statistically comparable across seasons, with average yields ranging from 6.05 to 6.39 t ha⁻¹. Despite using less irrigation water, the dry regime maintained similar yield levels while achieving the highest water use efficiency among the treatments. These findings indicate that controlled water-saving irrigation under SRI can simultaneously maintain rice productivity, improve water-use efficiency, and reduce the climate footprint of rice cultivation. Therefore, the dry irrigation regime represents a promising strategy for sustainable rice production in water-limited rice-growing regions.

Acknowledgements

The authors would like to express their sincere gratitude to the Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology, for providing financial support through the Regular Fundamental Research (PFR) scheme under the project titled “Integrated Model of Artificial Intelligence–Based Water and Environment Management for Sustainable Rice Farming (IMAIWEM-SRF)” with contract number 22999/IT3.D10/PT.01.03/P/B/2025. The authors also extend their appreciation to all collaborators and field partners whose contributions and assistance greatly supported the completion of this research.

REFERENCES

- Allen, R., Pereira, L., Raes, D., Smith, M. (1998). *FAO Irrigation and Drainage Paper No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements)*. Food and Agriculture Organisation of the United Nations.
- Arif, C., Saptomo, S. K., Setiawan, B. I., Taufik, M., Suwarno, W. B., Mizoguchi, M. (2022). 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*, 14(2), 170. <https://doi.org/10.3390/w14020170>
- Arif, C., Toriyama, K., Nugroho, B. D. A., Mizoguchi, M. (2015). Crop coefficient and water

- productivity in conventional and system of rice intensification (SRI) irrigation regimes of terrace rice fields in Indonesia. *Jurnal Teknologi*, 76(15), Article 15. <https://doi.org/10.11113/jt.v76.5958>
4. Aziez, A. F., Hanudin, E., Harieni, S. (2018). 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*, 5(2), 1035–1045. <https://doi.org/10.15243/jdmlm.2018.052.1035>
 5. Bouman, B. A. M., Humphreys, E., Tuong, T. P., Barker, R. (2007). Rice and water. In D. L. Sparks (Ed.), *Advances in Agronomy* 92, 187–237. Academic Press. [https://doi.org/10.1016/S0065-2113\(04\)92004-4](https://doi.org/10.1016/S0065-2113(04)92004-4)
 6. Bouman, B. A. M., Peng, S., Castañeda, A. R., Visperas, R. M. (2005). Yield and water use of irrigated tropical aerobic rice systems. *Agricultural Water Management*, 74(2), 87–105. <https://doi.org/10.1016/j.agwat.2004.11.007>
 7. Bouman, B. A. M., Tuong, T. P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, 49(1), 11–30. [https://doi.org/10.1016/S0378-3774\(00\)00128-1](https://doi.org/10.1016/S0378-3774(00)00128-1)
 8. Bouwman, A. F., Boumans, L. J. M., Batjes, N. H. (2002). Emissions of N₂O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*, 16(4), 6-1-6–13. <https://doi.org/10.1029/2001GB001811>
 9. Brim-DeForest, W. B., Al-Khatib, K., Linqvist, B. A., Fischer, A. J. (2017). Weed community dynamics and system productivity in alternative irrigation systems in California rice. *Weed Science*, 65(1), 177–188. <https://doi.org/10.1614/WS-D-16-00064.1>
 10. Dahlgreen, J., Parr, A. (2024). 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*, 14(2), 378. <https://doi.org/10.3390/agronomy14020378>
 11. Doni, F., Safitri, R., Suhaimi, N. S. M., Miranti, M., Rossiana, N., Mispan, M. S., Anhar, A., Uphoff, N. (2023). Evaluating the underlying physiological and molecular mechanisms in the system of rice intensification performance with Trichoderma-rice plant symbiosis as a model system. *Frontiers in Plant Science*, 14. <https://doi.org/10.3389/fpls.2023.1214213>
 12. Dossou-Yovo, E. R., Saito, K. (2021). Impact of management practices on weed infestation, water productivity, rice yield and grain quality in irrigated systems in Côte d'Ivoire. *Field Crops Research*, 270, 108209. <https://doi.org/10.1016/j.fcr.2021.108209>
 13. Gangopadhyay, S., Banerjee, R., Batabyal, S., Das, N., Mondal, A., Pal, S. C., Mandal, S. (2022). Carbon sequestration and greenhouse gas emissions for different rice cultivation practices. *Sustainable Production and Consumption*, 34, 90–104. <https://doi.org/10.1016/j.spc.2022.09.001>
 14. Geerts, S., Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, 96(9), 1275–1284. <https://doi.org/10.1016/j.agwat.2009.04.009>
 15. Hasanah, N. A. I., Setiawan, B. I., Arif, C., Widodo, S., Uphoff, N. (2019). Optimizing rice paddies' lower greenhouse gas emissions and higher yield with SRI management under varying water table levels. *Paddy and Water Environment*, 17(3), 485–495. <https://doi.org/10.1007/s10333-019-00744-z>
 16. IAEA. (1993). *Manual on Measurement of Methane and Nitrous Oxide Emissions from Agricultural*. International Atomic Energy Agency.
 17. Ishii, S., Ohno, H., Tsuboi, M., Otsuka, S., Senoo, K. (2011). Identification and isolation of active N₂O reducers in rice paddy soil. *The ISME Journal*, 5(12), 1936–1945. <https://doi.org/10.1038/ismej.2011.69>
 18. Jain, N., Dubey, R., Dubey, D. S., Singh, J., Khanna, M., Pathak, H., Bhatia, A. (2014). Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. *Paddy and Water Environment*, 12(3), 355–363. <https://doi.org/10.1007/s10333-013-0390-2>
 19. Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., van Groenigen, K. J., Linqvist, B. (2019). Water management to mitigate the global warming potential of rice systems: A global meta-analysis. *Field Crops Research*, 234, 47–54. <https://doi.org/10.1016/j.fcr.2019.02.010>
 20. Kong, D., Zhang, X., Yu, Q., Jin, Y., Jiang, P., Wu, S., Liu, S., Zou, J. (2024). Mitigation of N₂O emissions in water-saving paddy fields: Evaluating organic fertilizer substitution and microbial mechanisms. *Journal of Integrative Agriculture*, 23(9), 3159–3173. <https://doi.org/10.1016/j.jia.2024.03.047>
 21. Lee, J.-M., Jeong, H.-C., Lee, H.-S., Park, H.-R., Kim, G.-S., Lee, S.-I. (2023). Effects of water management practices on methane emissions and rice yields in east Asian paddy fields: a regional-scale meta-analysis. *Korean Journal of Soil Science and Fertilizer*, 56(4), 313–324. <https://doi.org/10.7745/KJSSF.2023.56.4.313>
 22. Linqvist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., van Groenigen, K. J. (2012). Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135, 10–21. <https://doi.org/10.1016/j.fcr.2012.06.007>
 23. Linqvist, B. A., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., da Rosa, E. F.

- F., van Kessel, C. (2015). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, 21(1), 407–417. <https://doi.org/10.1111/gcb.12701>
24. Liu, X., Zhou, T., Liu, Y., Zhang, X., Li, L., Pan, G. (2019). Effect of mid-season drainage on CH₄ and N₂O emission and grain yield in rice ecosystem: A meta-analysis. *Agricultural Water Management*, 213(C), 1028–1035.
25. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., Zhou, B. (Eds.). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
26. Materu, S. T. (2025). Comprehensive review of the system of rice intensification to enhance productivity and environmental sustainability in major rice-producing countries. *Discover Food*, 5(1), 358. <https://doi.org/10.1007/s44187-025-00648-4>
27. Nugroho, B. D. A., Toriyama, K., Kobayashi, K., Arif, C., Yokoyama, S., Mizoguchi, M. (2018). Effect of intermittent irrigation following the system of rice intensification (SRI) on rice yield in a farmer's paddy fields in Indonesia. *Paddy and Water Environment*, 1–9. <https://doi.org/10.1007/s10333-018-0663-x>
28. Qian, H., Zhu, X., Huang, S., Linqvist, B., Kuzya-kov, Y., Wassmann, R., Minamikawa, K., Martinez-Eixarch, M., Yan, X., Zhou, F., Sander, B. O., Zhang, W., Shang, Z., Zou, J., Zheng, X., Li, G., Liu, Z., Wang, S., Ding, Y., ... Jiang, Y. (2023). Greenhouse gas emissions and mitigation in rice agriculture. *Nature Reviews Earth & Environment*, 4(10), 716–732. <https://doi.org/10.1038/s43017-023-00482-1>
29. Rafy, A. U., Hannan, M., Mohammed, M., Khan, N. (2025). Meta-analysis of alternate wetting and drying (AWD) irrigation effects on methane and nitrous oxide emissions across different climates and soil types. *European Journal of Ecology, Biology and Agriculture*, 2(5), 181–200. [https://doi.org/10.59324/ejeba.2025.2\(5\).13](https://doi.org/10.59324/ejeba.2025.2(5).13)
30. Sander, B. O., Samson, M., Buresh, R. J. (2014). Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma*, 235–236, 355–362. <https://doi.org/10.1016/j.geoderma.2014.07.020>
31. Sato, S., Yamaji, E., Kuroda, T. (2011). Strategies and engineering adaptations to disseminate SRI methods in large-scale irrigation systems in Eastern Indonesia. *Paddy and Water Environment*, 9(1), 79–88. <https://doi.org/10.1007/s10333-010-0242-2>
32. Setiawan, B. I., Imansyah, A., Arif, C., Watanabe, T., Mizoguchi, M., Kato, H. (2014). SRI paddy growth and GHG emissions at various groundwater levels. *Irrigation and Drainage*, 63, 612–620. <https://doi.org/10.1002/ird.1866>
33. Tan, M., Cui, N., Jiang, S., Xing, L., Wen, S., Liu, Q., Li, W., Yan, S., Wang, Y., Jin, H., Wang, Z. (2025). Effect of practicing water-saving irrigation on greenhouse gas emissions and crop productivity: A global meta-analysis. *Agricultural Water Management*, 308, 109300. <https://doi.org/10.1016/j.agwat.2025.109300>
34. Thakur, A. K., Mandal, K. G., Mohanty, R. K., Ambast, S. K. (2018). Rice root growth, photosynthesis, yield and water productivity improvements through modifying cultivation practices and water management. *Agricultural Water Management*, 206, 67–77. <https://doi.org/10.1016/j.agwat.2018.04.027>
35. Thakur, A. K., Rath, S., Patil, D. U., Kumar, A. (2011). 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, (1), 13–24 Sp. Iss. SI MAR. <https://doi.org/10.1007/s10333-010-0236-0>
36. Vambol, V., Borowski, G. (2026). *Studying the heterogeneity of woody biomass: An experimental and statistical approach*. 27(1), 434–444.
37. Wang, H., Zhang, Y., Zhang, Y., McDaniel, M. D., Sun, L., Su, W., Fan, X., Liu, S., Xiao, X. (2020). Water-saving irrigation is a ‘win-win’ management strategy in rice paddies – With both reduced greenhouse gas emissions and enhanced water use efficiency. *Agricultural Water Management*, 228, 105889. <https://doi.org/10.1016/j.agwat.2019.105889>
38. Zarwazi, L. M., Chozin, M. A., Guntoro, D. (2016). Potensi gangguan gulma pada tiga sistem budidaya padi sawah., 44(2), 147–153. *Indonesian Journal of Agronomy*, 44(2), 147–153.
39. Zhang, B., Tian, H., Ren, W., Tao, B., Lu, C., Yang, J., Banger, K., Pan, S. (2016). Methane emissions from global rice fields: Magnitude, spatiotemporal patterns, and environmental controls. *Global Biogeochemical Cycles*, 30(9), 1246–1263. <https://doi.org/10.1002/2016GB005381>
40. Zhao, C., Qiu, R., Zhang, T., Luo, Y., Agathokleous, E. (2024). Effects of alternate wetting and drying irrigation on methane and nitrous oxide emissions from rice fields: A meta-analysis. *Global Change Biology*, 30(12), e17581. <https://doi.org/10.1111/gcb.17581>