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Article

Impact of Water Management on Methane Emission Dynamics in Sri Lankan Paddy Ecosystems

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Abstract: Paddy ecosystems constitute a dominant source of greenhouse gases, particularly of methane (CH_4), due to the continuous flooding (CF) practiced under conventional paddy cultivation. A new management method, namely alternative wetting and draining (AWD) (i.e., flooding whenever surface water levels decline to 15 cm below the soil surface), is an emerging practice developed to mitigate CH_4 emissions while providing an optimal solution for freshwater scarcity. Despite extensive paddy cultivation in Sri Lanka, no systematic research study has been conducted to investigate CH_4 emissions under different water management practices. Thus, field experiments were conducted in Sri Lanka to investigate the feedback of controlled water management on seasonal and diel variation of CH_4 emission, water consumption, and crop productivity. Adopting the same rice variety, two water management methods, continuous flooding (CF) and alternative wetting and draining (AWD), were compared with plants (W/P) and without plants (N/P) present. The emission of CH_4 was measured using the static closed chamber method. The results show a 32% reduction in cumulative CH_4 emission, on average, under AWD when compared to CF. The yield under the AWD was slightly higher than that of CF. Although it was not statistically significant ($p > 0.05$) there was not any reduction in yield in AWD than in CF. The total water saving under AWD ranged between 27–35% when compared to CF. Thus, the results support (without considering the effect of nitrous oxide) AWD as a promising method for mitigating CH_4 emissions while preserving freshwater and maintaining grain yield in paddy systems.

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1. Introduction

Agricultural ecosystems are responsible for approximately 89% of AFOLU (agriculture forestry and other land use) CH_4 emissions between 1990 and 2019, a highly potent greenhouse gas having a global warming potential (GWP) 25-fold higher than that of CO_2 over a 100-year time horizon [1]. Among different agroecological systems, paddy ecosystems constitute a distinct anthropogenic CH_4 footprint responsible for approximately 20% of total anthropogenic emissions. Of the different rice ecotypes, irrigated rice paddies are the most prominent source of CH_4 emissions, contributing to approximately 70–80% of total paddy emissions, followed by rain-fed rice (~15%) and deep-water rice (~10%), respectively.

Despite continuing worldwide efforts to control climate warming, the global annual mean temperature continues to rise. There is more than a 50% probability that the mean global temperature rise will surpass 1.5 °C between 2021 and 2040 [2]. To remain below 1.5 °C global warming, as per the Paris agreement [3], global greenhouse gas emissions essentially need to be reduced by 50% by the year 2030. Understanding and characterizing the major sources of greenhouse gases and the accurate quantification of emissions are essential prerequisites to mitigating GHG emissions.

Rice is one of the essential cereal crops for more than half of the world's population. Asia, in particular, depends strongly on rice as a staple food and accounts for 90% of global rice production and consumption [4]. Since rice is an extremely water-sensitive plant, conventional Asian paddy ecosystems broadly exhibit a strong hydrological coexistence. However, Asian water resources are depleting at an alarming rate due to unprecedented climate change in recent decades with only 15–54% of water resources estimated to be available by 2025, relative to 1990, in many Asian countries [5]. Therefore, to cater to the increasing demand for rice production under the intense pressure on water availability, Asian countries have been compelled to explore more efficient water management strategies in paddy cultivation without compromising crop productivity. As a potential initiative, the alternative wetting and draining (AWD) method was developed by the international rice research institute and its partners as a novel strategy for the optimal use of fresh water [6]. Notably, AWD is a water-saving technique in which irrigation water is supplied to the field until the water reaches a typical depth of X cm whereupon the water level is allowed to subsequently subside through evapotranspiration and percolation until it is 15 cm below the soil surface, followed by reflooding. This method contrasts the conventional water management strategy where the paddy is completely flooded (CF) with this regime maintained throughout the rice growth cycle.

Due to the strong nexus between the water cycle and the terrestrial carbon cycle, the two water management methods, conventional CF and AWD, inevitably have different feedback on carbon emissions from paddy systems. Conventional CF results in anaerobic conditions suitable for methanogenesis [7]. In contrast, draining the paddy systems can effectively reduce CH_4 emissions [8]. Decreases in net GHG production is dominated by the decrease in CH_4 emissions because N_2O emissions changes are minimal between CF and AWD [8]. AWD has been shown to potentially reduce the net GHG production of CH_4 and N_2O emissions by 45–90% [9] while the consumption of irrigated water can be reduced by 15–35% without sacrificing the rice production [10]. Furthermore, studies have also shown increased yields following the adoption of AWD; for instance, a 13–38% increase equal to 0.4–1.0 t ha^{-1} [11]. However, with AWD, a discernible increase in N_2O emission has also been observed (even as bursts) as compared to continuous inundation in several studies [12,13]. In general, cumulative N_2O emissions throughout a paddy season are less than that of total CH_4 emissions as CO_2-eq, despite the presence of contradictory scenarios in the literature [14,15].

Of the total agricultural land in Sri Lanka, 17.6% is occupied by rice [16], which is the staple food of the Sri Lankan population. Paddy soils are cultivated twice per year, namely during the country's 'Dry (October to January)' and 'Wet (March to June)' seasons. Paddy cultivation in Sri Lanka has been practiced for centuries under characteristically waterlogged conditions while alternative strategies, such as AWD, are still at incipient research stages. Systematic studies conducted in Sri Lanka to investigate CH_4 emissions from paddy systems under conventional waterlogged conditions are too sparse to be enumerated while such studies for AWD have not been undertaken. This, in turn, adds novelty to this study as an initiative to provide CH_4 emission measurements from two complete paddy cycles under conventional and water-controlled conditions. Despite the availability of detailed studies on CH_4 emissions in other Asian countries under waterlogged and AWD conditions, methane emissions from Sri Lankan paddy systems are, in general, largely underrepresented in the global agricultural CH_4 budget.

As a part of the regional research initiative directed by the Asia-Pacific Network for global change research on CH_4 emissions from paddy ecosystems under waterlogged and differently managed water conditions, this study examined CH_4 emissions from Sri Lankan paddy sites. The main objective of this study was to investigate CH_4 emissions from Sri Lankan paddy sites under continuously flooded (CF) and AWD water management conditions as well as the potential of AWD as an emerging technique for mitigating GHG emission and for conserving water, without compromising the crop yield. Notably, this study did not alter any other conventional practices in the country, for instance, the fertilizer management in paddy cultivation, which is beyond the scope of this research. In consequence, the integrated feedback of such changes, combined with water management changes studied in this research, is not represented in the results of this study.

2. Materials and Methods

2.1. Experimental Site and Design

The field study was conducted at an experimental paddy site (7.5255° N, 80.4390° E), at the Rice Research Development Institute (RRDI), Bathalegoda, where farmers practice intensive farming. The climate in the area is that of a tropical monsoon with a mean annual temperature of 27 °C and mean annual precipitation of 1649 mm. The experimental site is located 161 m above the mean sea level and the topsoil layer thickness is 20 cm. According to the world reference base for soil resources, the soil can be designated as an anthrosol due to significant remodeling as a consequence of extensive agricultural interference. The details of soil properties are given in Table 1.

Table 1. Soil properties of the experimental site.

Property	
Texture	Loamy sand
Clay (%)	9.75
Sand (%)	85.00
Silt (%)	5.25
Total carbon (g/cm^3)	2.53
Total nitrogen (g/cm^3)	0.28
C:N ratio	9.04
Organic matter content (%)	2.66
Particle density (g cm^{-3})	2.58
Bulk density (g cm^{-3})	1.22
Dry density (g cm^{-3})	1.18
Total porosity (cm^3 cm^{-3})	0.54
Soil gas diffusion coefficient at dry condition (cm^2 s^{-1})	0.142

The experiment was conducted in each 3.5 m × 3.0 m three replicate plots for each treatment in randomized block design during the wet season. The experimental site was divided into 12 plots under CF and AWD treatments and each plot was subdivided into two parts with plants and without plants. The field was ploughed and puddled up to the topsoil layer and leveled prior to transplanting. Rice seedlings of BG 300 (midterm variety), which were grown in a nursery, were pulled and transplanted into the puddled and leveled plots. The general characteristics of the locally-developed rice variety BG 300 have been detailed in many previous studies [17–19]. Transplanting was performed manually to achieve a 15 cm uniform distance between plants in straight rows to maintain equal plant density in the chambers. Four treatments were adopted in this study: completely flooded (CF) (continuously flooded by maintaining 3–5 cm water level above the soil surface) and alternate wetting and draining (AWD) (flooding whenever surface water levels decline to 15 cm below the soil surface) with paddy plants (P) and without paddy plants (NP) using the same rice variety. Plot beds under completely flooded conditions were surrounded with a polythene sheet (250 microns) to avoid water seepage. Though it was planned to maintain a continuously flooded condition from 0 to 13 days after transplanting (DAT), it was unable due to a technical problem with the irrigation for 8 days. All plots were allowed to drain from 77 DAT for harvesting. The AWD period commenced from 13 DAT whereas AWD plots were maintained under completely flooded conditions during the flowering period of the rice growing cycle. With the raised water table due to the southwest monsoon, maintaining AWD conditions was strenuous; however, two AWD periods were achieved. Fertilizer was applied equally for all treatments according to conventional farming practices. Table 2 shows the cultivation practice calendar together with the detailed timing.

Table 2. Rice cropping calendar during the wet season.

Practice	
Cropping period	9 June–28 September 2022
Crop duration	119 days
Ploughing	−14 DAT
Transplanting	0 DAT (22 June 2022)
Pesticide application ((Carbosulfan 200 g/SC L—640 mL/ha)	54 DAT
Pesticide application (Chlorantraniliprole 100 g/ha)	58 DAT and 68 DAT
1st fertilization (TSP 35 kg/ha)	0 DAT
2nd fertilization (Urea 30 kg/ha)	13 DAT
3rd fertilization (Urea 75 kg/ha + MOP 75 kg/ha)	47 DAT
1st AWD cycle	13–23 DAT
2nd AWD cycle	23–47 DAT
Harvesting	98 DAT

Note(s): DAT: days after transplant, TSP: Triple Superphosphate, MOP: Muriate of Potash.

2.2. Measurements and Calculations

Gas samples were collected for evaluating both seasonal and diel variations. The closed chamber technique was used to collect the gas samples. Since the transplanting method was selected for planting at the paddy site, rectangular chambers were used in such a way that the chamber covered an area equal to the area occupied by ten rice plants following the guidelines outlined by Minamikawa et al. [20]. Chambers (35 cm wide × 75 cm length) were made with acrylic and transparent polythene with three different height stages (250 cm, 500 cm, and 950 cm) in order to approximately maintain the same head space between the plant and the chamber top to avoid the suppression of rice growth. A battery-driven small fan was fixed inside the chamber top for mixing the headspace gases thoroughly to maintain a uniform target gas concentration [21]. Also, the chamber was equipped with a separate gas sampling port and a vent hole with a rubber stopper to avoid pressure changes that could be caused by the chamber deployment. Chamber bases were permanently inserted 10 cm into the soil at each experimental plot throughout the whole paddy season. Gas samples were collected by placing the chamber on the base and ensuring a gas-tight closure with a water seal. Gas sampling was commenced on 6 DAT and conducted once every week with additional measurements where necessary and with particular focus on the N fertilizer event and the transition of the AWD period. Minamikawa et al. [22] recommended that in temperate parts of Asia, daily mean CH_4 flux estimates can be attained with once per day sampling during the mid-morning, approximately 10:00 (09:00–11:00), resulting in acceptable estimates (i.e., ±10%). They further noted that the emission rate observed during this period was considered to be representative of the average rate over the whole day, which is used to estimate the total cumulative emissions for the whole season [23,24]. Hence, gas samples were collected between 9 and 11 am local time at 0, 15, and 30 min intervals with the aid of a 60 mL syringe, fitted with a stopcock valve, and stored in 6 mL evacuated glass vials under pressure. On each gas sampling day, the water depth inside the base and base height above the soil surface were recorded. The fluctuation in the water table was instrumental in maintaining the AWD treatment. In this study, the water depth in the AWD method was ensured through piezometers which were made using PVC pipes via installation at each plot. The soil redox potential was recorded regularly at a 5 cm depth, representing the rhizosphere depth of paddy plants. An integrated sensor network with a data logger (ZL6 Advanced cloud data logger, METER Group Inc., USA) was installed at the experimental site (0–5 cm depth) to obtain field parameter variations of soil moisture, soil temperature, air temperature, and relative humidity. Daily maximum, minimum air temperature, and rainfall data were collected from the RRDI weather station. Grain yield was measured at the harvest stage. Measurements of gas samples were analyzed for CH_4 concentrations using a gas chromatograph (GC-2014: capillary and packed gas chromatograph-SHIMADZU) equipped with a thermal conductivity detector (TCD) and SHINCARBON ST column (50/80 mesh 2.0 m × 3.0 mm I.D.) using helium as the carrier gas at a flow rate of 50 mL/min. The temperatures of the column, injector, and detector were maintained at 150 °C, 210 °C, and 210 °C, respectively, during measurements.

The CH_4 fluxes were calculated based on the ideal gas law and the method for estimating the magnitude of flux underestimation arising from chamber deployment [25]. Further, cumulative emissions of CH_4 were calculated by integrating the area under the curve of adjacent measurement points as mentioned in Ly et al. [26].

2.3. Statistical Analysis and Data Visualization

The emission values expressed in the study are the means of triplicates plus or minus the standard deviation. All statistical analyses were performed using Minitab® 17.1.0. One-way analysis of variance (ANOVA) and paired t-tests were used to analyze the statistical significance in seasonal CH_4 emissions and grain yield, respectively. To test differences among treatments, a Tukey's HSD (honest significant difference) test was performed with a significance level of 0.05. Pearson correlation analysis was performed to assess the relationships between CH_4 flux and temperature.

For data visualization, both Microsoft Excel 2016 and the Tecplot 360 2023 R1 software were used.

3. Results and Discussion

3.1. Weather Data and Water Usage

Figure 1 shows the daily rainfall (Figure 1a) and air temperature (Figure 1b) ranges throughout the paddy season at the experiment site.

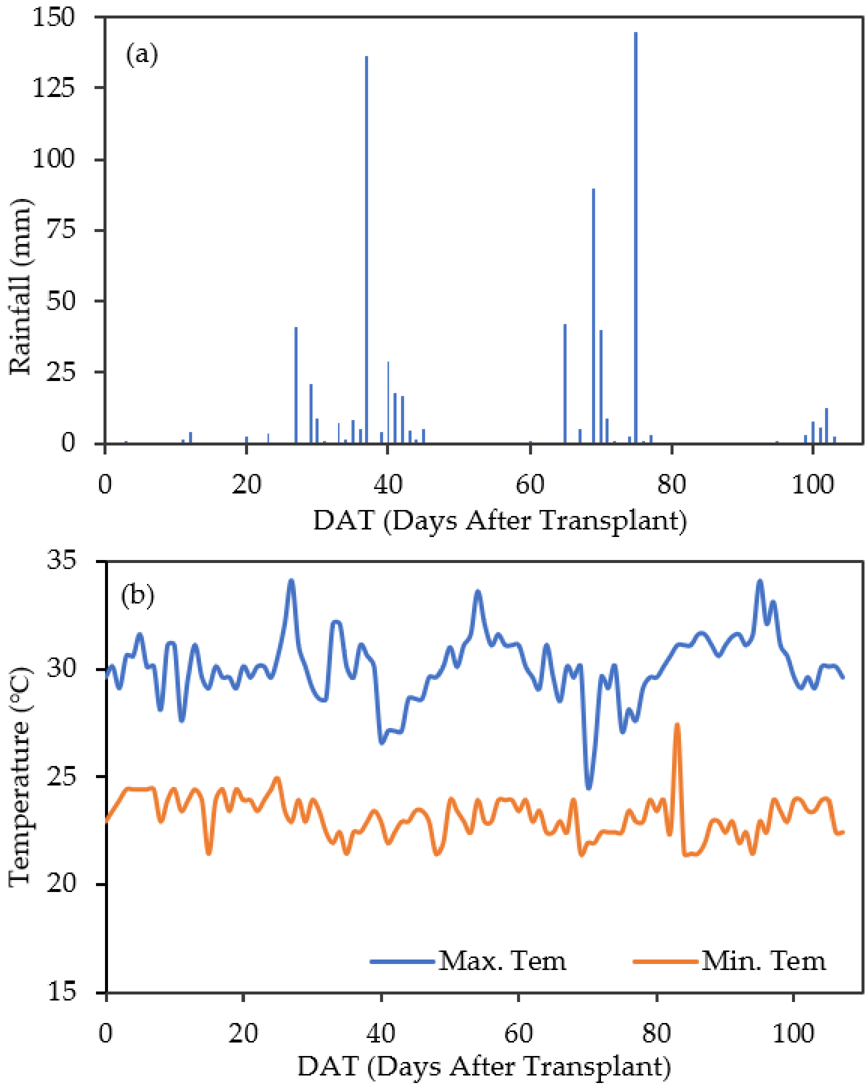

Figure 1. (**a**) Seasonal variation in daily rainfall and (**b**) the daily maximum and minimum air temperature.

A total precipitation of 691 mm was recorded for the paddy season (wet season) while the maximum amount of accumulated monthly rainfall was 252 mm in August. The maximum and minimum air temperatures were 30 °C and 23 °C, respectively. Water table variation of the two treatments, CF and AWD, with and without plants are shown in Figure 2a. Although it was planned to maintain fully flooded conditions for all plots at the beginning of the rice season (from 0–13 DAT), the water level fluctuated due to a technical problem associated with irrigation scheduling. At 13 DAT, the AWD treatment was commenced, intentionally, and lasted (water level < 0 cm) for 34 days. With the onset of the southwestern monsoon rainfall (Figure 1a), it was very difficult to maintain a −15 cm water depth (below the ground level) due to the saturated soil conditions and because the water depth varied between −10 to −15 cm. The reduction in seasonal water usage under the AWD condition was 27–35% as compared to the CF. It was consistent with the results of meta-analysis conducted by Mao [27] and Carrijo et al. [28] who documented the water saving of AWD as 20–35% and 25.7%, respectively, compared with the conventional method.

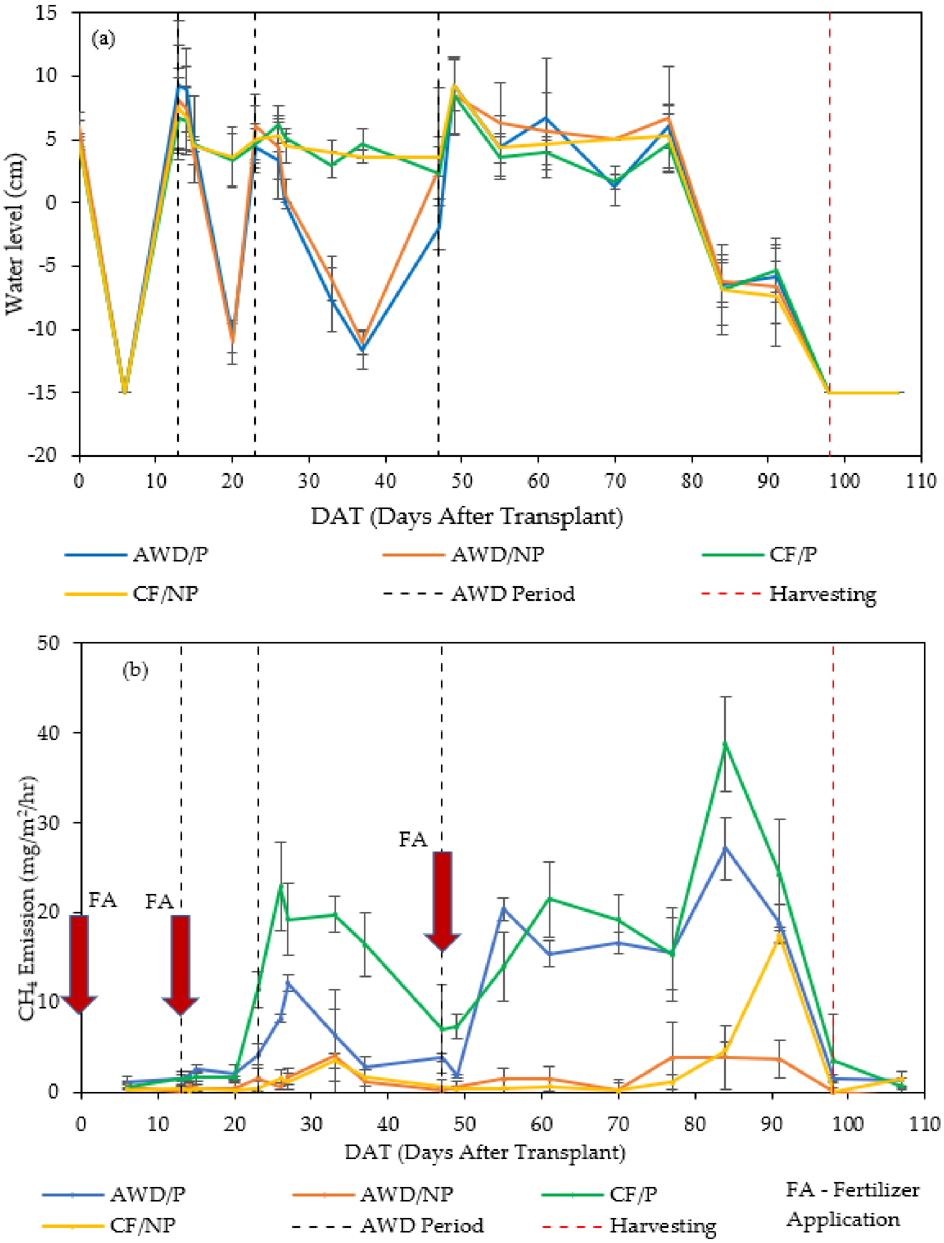

Figure 2. (**a**) Seasonal variation in the daily mean surface water level and (**b**) seasonal variation in CH_4 flux during the wet rice growing season. Error bars for CH_4 fluxes indicate the standard error ($n = 3$). Vertical black colour dash lines indicate the alternative wetting and draining periods while the red colour represents harvesting days. AWD/P: Alternative wetting and draining with plants; AWD/NP: Alternative wetting and draining without plants; CF/P: continuous flooding with plants; CF/NP: continuous flooding without plants.

3.2. CH_4 Gas Emission

3.2.1. Seasonal Dynamics of CH_4

Methane fluxes are the net balance of CH_4 formation, oxidation, and transport mechanisms. All these processes are controlled and depend on various biotic and abiotic factors such as carbon source, temperature, soil redox potential, soil microbial function, and properties of the plant [29]. The seasonal variation of CH_4 emission is shown in Figure 2b.

Generally, in paddy systems, transportation and atmospheric emission of CH_4 occurs mainly via three channels: diffusion of dissolved gas through water–air and soil–water interfaces, ebullition as gas bubbles, and plant transport. As expected, emission rates from the CF/P treatment were higher than those of AWD/P. Fluxes varied spatially as indicated by the large error bars. The highest emissions were observed at the start of the drainage period for the harvesting. Throughout the entire season, three peaks were observed under treatments with plants (P) as also discussed by Pandey et al. [30] and Oo et al. [31]. In the beginning, CH_4 fluxes were considerably lower with little difference across CF and AWD plots since all the plots were maintained under the same water conditions. The first CH_4 measurement at 6 DAT was almost zero since, unexpectedly, there was a −15 cm water level in all plots. After that, with the increasing water level, small but almost similar fluxes were observed across all the plots.

Methane fluxes initially peaked four weeks after transplantation in the vegetation growth phase for with-plant (P) treatments. It can be seen that the emission peak of the AWD/P combination was less than that of CF/P during the same period due to the drainage of water. Generally, high CH_4 flux is attributable to the strict absence of free oxygen and carbon availability in the paddy soil. During the flooded conditions, O_2 transportation into the soil is prevented and trapped O_2 in the soil is rapidly consumed due to soil microbial respiration [32]. Organic matter available in the flooded soils causes a further reduction in O_2 by supplying electron donors, leading to a potentially anaerobic environment [33,34]. In the absence of O_2, soil anaerobiosis decreased sharply via biochemical reactions as denoted by the soil redox potential (Eh). Notably, Eh ranged from −100 to −200 mV during the CF period, as also evidenced by Yagi and Minami [35] and Wang et al. [36] who reported that the production of CH_4 starts at a redox potential of –150 to −160 mV. Moreover, Inubushi et al. [37] mentioned that conditions of soil submersion favor the growth of rice plants which can be responsible for >90% of CH_4 transport from soil to the atmosphere.

In the AWD treatment, however, drainage of water exposed the soil to the atmosphere and resulted in an increase in the soil redox potential [24]. Lower CH_4 emissions under drainage have been consistently reported in many past studies indicating a negative correlation between CH_4 emission and soil Eh [38–40]. In this study, we also observed a reduction in CH_4 emission under AWD with Eh ranging between (−125) mV and (+510) mV. The soils with high redox values favor methanotrophs who oxidize CH_4 while suppressing methanogenic activities as discussed by Woese et al. [41]. Hence, with the onset of AWD cycle, AWD/P showed consistently low emissions compared to CF/P from 23 to 47 DAT (Figure 2b).

After the first flush (26 DAT), CH_4 emissions in both combinations declined, likely due to the limited labile/reactive soil carbon. The decreasing trend continued until 50 DAT which also coincided with an event of fertilizer application. As mentioned by Schimel [42] and Dannenberg and Conrad [43], N fertilizer application promotes the formation of CH_4 by increasing the rice plant growth, thus increasing the carbon supply for methanogenic bacteria under flooded condition. Therefore, with the stable low soil redox potential (−150 to −200 mV) and optimal soil pH (6 to 8), the release of more plant-borne carbon sources and the increased capacity of plant-mediated methane emission increase methane formation and release to the atmosphere [44]. Therefore, both fluxes in CF/P and AWD/P peaked for a second time at the flowering phase, as also evidenced in the literature [29,33]. During the flowering period of rice plants, all plots were maintained under continuously flooded conditions to avoid impacts on the crop yield. Following the initial decline in CH_4 flux, a transition from aerobic to anaerobic conditions occurred due to the cessation of the AWD episode; subsequently, a rapid increase in CH_4 emission was detected under the AWD/P combination. As emphasized by Hou et al. [45], soil geochemical conditions can be strongly transformed from aerobic to hypoxic and anaerobic conditions within 15 days of reflooding after drainage. A higher amount of carbon substrate is also available for methanogens even at the later growing stage due to the increase in decaying plant tissue and root exudates for both treatments [46] with the greatly reduced condition of soils due to anaerobic status. This explains the observed increase in CH_4 fluxes. Although CH_4 emissions under both combinations (CF/P and AWD/P) should theoretically remain almost identical under similar prevailing flooding conditions, which were maintained during the flowering stage, the observed slight decrease in CH_4 emission from the AWD/P treatment was likely the result of less developed aerenchyma of rice plants in the AWD treatment relative to the CF treatment [47].

The third peak in flux occurred at the ripening stage with the commencement of drainage for harvesting (84 DAT). Bujun [48] reported that it is possible for methane emissions to decline during ripening and maturity, provided carbon becomes limited and root porosity and root transport capacities decline, due to root aging and degradation. However, high CH_4 fluxes may continue, or even increase, until the end of the season, provided that root exudation continues at high levels or decaying roots enhance CH_4 production. According to Bubier and Moore [49], a large burst of CH_4 emission from soil pores (i.e., trapped methane) may also take place due to the decline of the water table. The results reported in Figure 2a revealed that CH_4 emission could trigger at the ripening under the controls of balance between root exudation, root porosity, and root oxidation power as supported by the hypothesis of Bujun [50] and the water table effect [50]. Furthermore, the less developed arenchymatous tissues of rice plants that have undergone former drainage under AWD treatments stood as a reason for the low transportation and emission by AWD plots than CF [47].

The transport of CH_4 from paddy soil to the atmosphere occurs via the diffusion of dissolved gas, ebullition as gas bubbles, and plant transport (diffusion of CH_4 in the aerenchyma and cortex) [34,51]. Literature studies have concluded that more than 90% of CH_4 produced in paddy soil is emitted through rice plants [52]. In this study, it is clearly noticeable that fluxes from treatments with rice plants (CF/P and AWD/P) were significantly higher than without plants. Throughout the whole season, CF/NP and AWD/NP of both treatments showed relatively low emissions, around 15% lower in comparison to CF/P and AWD/P (see Table 3). This is primarily due to the fact that CH_4 tends to oxidize at the interface between oxic and anoxic regimes where the concentration gradients of CH_4 and oxygen essentially overlap; for instance, at the surface of flooded rice soils and in the rhizosphere of rice plants. Therefore, as reported in many studies [37,53], 65–80% of generated CH_4 becomes oxidized in no-plant plots.

In the literature, the reduction in CH_4 emissions due to the water-saving strategy was reported to be up to 90% [8,15,33]. In this study, the seasonal CH_4 emissions from rice plants under CF and AWD were 517.0 and 349.6 kg CH_4 ha^{-1}, respectively, while the corresponding figures from bare land were 57.0 (CF) and 36.1 kg CH_4 ha^{-1} (AWD) (Table 3).

Table 3. Statistical analysis results of seasonal CH_4 emission and grain yield under different treatments.

Treatment	CF/P	AWD/P	CF/NP	AWD/NP
Seasonal CH_4 emission (kg/ha)	517.0 A *	349.6 AB *	57.0 B *	36.1 B *
Yield (Mg/ha)	3.7 **	3.8 **	NA	NA

Note(s): CF/P, continuous flooding with plants; AWD/P, alternative wetting and draining with plants; CF/NP, continuous flooding without plants; AWD/NP, alternative wetting and draining without plants. NA, Not Applicable. The asterisks * and ** represent 'significant at $p < 0.05$' and 'not significant at $p < 0.05$' respectively.

Considering the CF method as the local conventional practice, this study revealed that the AWD treatment yielded a 32% mean reduction in seasonal cumulative CH_4 emissions compared to the conventional method. Along the same line, Zheng et al. [54] and Towprayoon et al. [55] observed a 27.5% and 26–46% reduction in CH_4 emissions due to the mid-season drainage application, respectively. Also, Tirol-Padre et al. [56] reported a 29% mean reduction in CH_4 emission under AWD over three seasons. Thus, the results of this study corroborate the findings of the literature, suggesting the AWD as a promising water-management strategy to reduce CH_4 emissions.

3.2.2. Diell Variation of CH_4 fluxes under Submerged Conditions

On 70 DAT, samples were collected at 2 h intervals over a 24 h period to investigate the diell variation of the CF/P treatment. Daily CH_4 emissions ranged from 14.63–22.85 mg/m²/hr (Figure 3) while showing a positive correlation with air temperature ($r = 0.686$, $p = 0.041 < 0.05$).

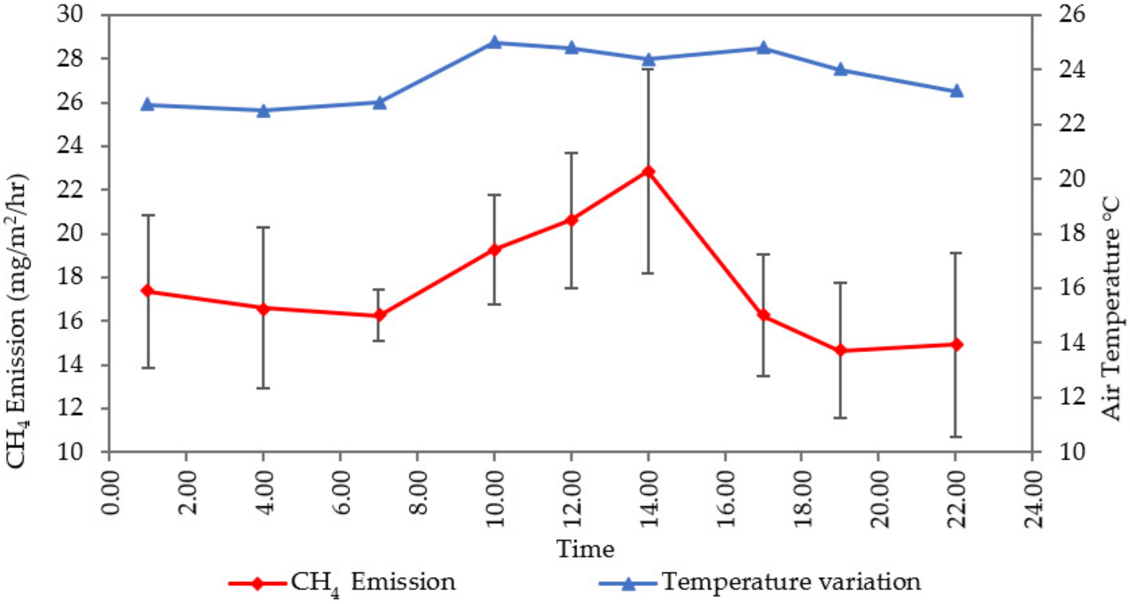

Figure 3. Diel variation of CH_4 flux under conventional farming practice.

The highest CH_4 emission was reported at 2.00 pm during the afternoon, which is consistent with the literature observations [22,57]. Although transpiration, stomatal conductance, and temperature are among the key parameters driving CH_4 transport and subsequent emissions, diel variation, in general, depends primarily on temperature [57].

Subsurface gas transport and emissions are predominantly a diffusion-controlled process characterized by gas diffusivity where the mass flow occurs along a concentration gradient. This implies that diel variations in gas flux are caused by changes in concentration gradients and gas diffusivity. Wang and Shangguan. [58] concluded that the key factor which affects diel CH_4 emission is the efficiency of gas transport to the atmosphere and its effect on physical processes (evaporation and respiration) and the diel variation of meteorological parameters (air temperature, radiation) but not CH_4 production in the soil. With an increasing temperature, Nouchi et al. [59] documented that the conductance of aerenchyma in rice plants increases while Goodroad and Keeney [60] and Dunfield et al. [61] reported that the solubility of CH_4 in soil–water decreases. Although the effect of soil temperature is instrumental in CH_4 production, Wang and Shangguan [58] and Smith et al. [62] reported a lag period between the change in soil temperature and the change in gas production. Corroborating this, Pandey et al. [30] reported that there is a lagging process for reducing the impact of soil temperature changes on CH_4 production. Hence, the CH_4 emission peaked around early noon in diel variation after 4 h of the highest recorded temperature.

Figure 4 shows an integrated three-dimensional graphical representation of diel and seasonal variation of methane emissions throughout the paddy cycle which was produced using Tecplot 360 2020 R2 software. Notably, the diel variation is illustrated using color contours representing 11 different emission ranges.

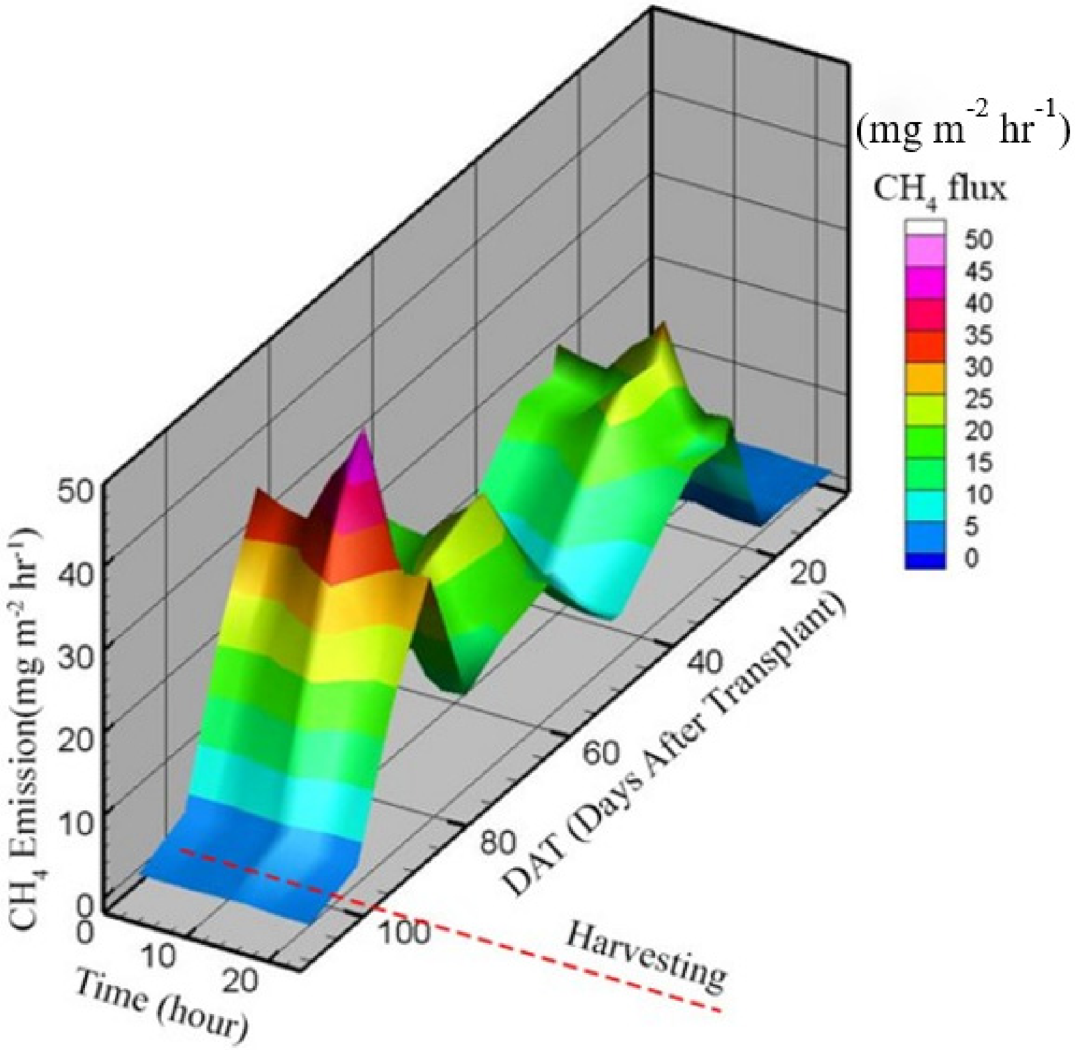

Figure 4. Diel variation of CH_4 emission (z−axis) at days after transplant (DAT) (x−axis) (flooded color variation under 11 different emission ranges).

Here, the diel measurements at 70 DAT were linearly scaled to other DAT measurements using a reference measurement on each day. Figure 4 thus provides a useful graphical insight into the overall CH_4 emissions from the paddy system under submerged conditions.

3.3. Rice Productivity

Essentially, AWD management aims to mitigate CH_4 emissions while conserving water usage and, importantly, without compromising rice productivity. As documented by Lampayan et al. [6], water at 15 cm below the paddy surface may not induce any effect on the yield reduction because the soil remains saturated enough to supply the water to the roots of rice plants. The literature reports both increases and decreases in yield with AWD management [55,63–65]. In the current study, no statistically significant difference in the crop yield (Table 3, $p > 0.05$) occurred due to AWD treatment [AWD (3.79 Mg ha^{-1}) than that under CF (3.71 Mg ha^{-1})]. Therefore, our results support AWD management as a promising strategy to be applied in paddy systems with no negative impact on rice yield.

The data presented herein are limited to two complete paddy cycles as the field measurements made in the preceding cycles were affected by mobility restrictions during the COVID-19 pandemic period. The continuation of this study for further paddy cycles will provide a better description of results over a larger temporal span. We further note some other variables that may affect seasonal and/or diel CH_4 dynamics in paddy ecosystems which were beyond the scope of this study. We did not particularly investigate the effect of N fertilizer application in paddy systems on CH_4 emission. The literature reports that nitrogen fertilizers may potentially promote CH_4 production in the first 22 days and then depress the production in 45 days, resulting in no net cumulative CH_4 production under the urea treatment [23]. In contrast, the negative and positive effects of ammonium-based fertilizers on CH_4 emissions have been reported in the literature [66,67]. In this study, we did not measure N_2O fluxes despite N_2O emissions being reported as associated with drainage [12]. The study was limited to one soil type, one rice variety, and selected AWD windows which may induce considerable impact on CH_4 emissions. Additional studies with further emphasis on the effect of climatic factors, soil geochemical properties, soil management (e.g., tillage), straw management, other amendments (e.g., biochar), and different rice cultivar also need to be considered to derive more conclusive estimates on the impact of different water managements on CH_4 emission. Consequently, additional measurements are urgently needed before recommendations from this study can be applied more widely, in particular N_2O fluxes to allow a total net greenhouse gas budget to be developed.

4. Conclusions

This study examined alternative wetting and draining (AWD) (i.e., flooding whenever the surface water level declined to 15 cm below the soil surface) as a promising water-saving strategy to make a trade-off between reducing CH_4 emissions and sustaining the rice yield in comparison to the conventional completely flooded (CF) paddy cultivation practiced in Sri Lanka. Results show that of the two water treatment methods, AWD reduced water usage by 27–35% compared to CF. Owing to the periodic aerobic conditions introduced by two episodes of AWD in mid-season during the rice growing season, CH_4 emission was suppressed by about 32%, without a significant statistical contrast ($p > 0.05$) in the crop yield. Thus, the results demonstrated the AWD as a promising water management strategy to control paddy-derived methane emissions while sustaining crop productivity. Further studies with a focus on additional variables include the soil type, rice variety, optimum window of AWD, and impact of nitrogen fertilizer (and N_2O fluxes) are needed to further demonstrate the applicability of AWD to control methane emissions from paddy ecosystems.

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References

1. Nabuurs, G.-J.; Mrabet, R.; Hatab, A.A.; Bustamante, M.; Clark, H.; Havlík, P.; House, J.; Mbow, C.; Ninan, K.N.; Popp, A.; et al. Agriculture, Forestry and Other Land Uses (AFOLU). In *Climate Change 2022—Mitigation of Climate Change*; Intergovernmental Panel on Climate Change (IPCC), Ed.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 747–860. https://doi.org/10.1017/9781009157926.009.
2. IPCC. Summary for Policymakers. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.
3. United Nations (UN). Paris agreement. In *Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris)*; UN: Geneva, Switzerland, 2015; Volume 4, p. 2017.
4. Bandumula, N. Rice Production in Asia: Key to Global Food Security. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2018**, *88*, 1323–1328. https://doi.org/10.1007/s40011-017-0867-7.
5. Gleick, P. (Ed.) *Water in Crisis: A Guide to the World's Fresh Water Resources*; Oxford University Press: New York, NY, USA, 1993.
6. Lampayan, R.; Palis, F.; Flor, R.J.; Bouman, B.; Quicho, E.; De Dios, J.L.; Espiritu, A.; Sibayan, E.; Vicmudo, V.R.; Lactaoen, A.T.; et al. Adoption and dissemination of "safe alternate wetting and drying" in pump irrigated areas in the Philippines. In Proceedings of the 60th International Executive Council Meeting of the International Commission on Irrigation and Drainage (ICID), 5th Regional Conference, New Delhi, India, 6–12 December 2009.
7. Qiu, J. China cuts methane emissions from rice fields. *Nat. News* **2009**. https://doi.org/10.1038/news.2009.833.
8. Yan, X.; Ohara, T.; Akimoto, H. Development of region-specific emission factors and estimation of methane emission from rice fields in the East, Southeast and South Asian countries. *Glob. Chang. Biol.* **2003**, *9*, 237–254. https://doi.org/10.1046/j.1365-2486.2003.00564.x.
9. Linquist, B.A.; Anders, M.M.; Adviento-Borbe, M.A.A.; Chaney, R.L.; Nalley, L.L.; Da Rosa, E.F.F.; Van Kessel, C. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Glob. Chang. Biol.* **2015**, *21*, 407–417. https://doi.org/10.1111/gcb.12701.
10. Siopongco, J.; Wassmann, R.; Sander, B. *Alternate Wetting and Drying in Philippine Rice Production: Feasibility Study for a Clean Development Mechanism*; International Rice Research Institute: Metro Manila, Philippines, 2013.
11. Lampayan, R.M.; Rejesus, R.M.; Singleton, G.R.; Bouman, B.A.M. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Res.* **2015**, *170*, 95–108. https://doi.org/10.1016/j.fcr.2014.10.013.
12. Wu, L.; Tang, S.; Hu, R.; Wang, J.; Duan, P.; Xu, C.; Zhang, W.; Xu, M. Increased N_2O emission due to paddy soil drainage is regulated by carbon and nitrogen availability. *Geoderma* **2023**, *432*, 116422. https://doi.org/10.1016/j.geoderma.2023.116422.
13. Toma, Y.; Takechi, Y.; Inoue, A.; Nakaya, N.; Hosoya, K.; Yamashita, Y.; Adachi, M.; Kono, T.; Hideto, U. Early mid-season drainage can mitigate greenhouse gas emission from organic rice farming with green manure application. *Soil Sci. Plant Nutr.* **2021**, *67*, 482–492. https://doi.org/10.1080/00380768.2021.1927832.
14. Linquist, B.A.; Adviento-Borbe, M.A.; Pittelkow, C.M.; Van Kessel, C.; Van Groenigen, K.J. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Res.* **2012**, *135*, 10–21. https://doi.org/10.1016/j.fcr.2012.06.007.
15. Feng, J.; Chen, C.; Zhang, Y.; Song, Z.; Deng, A.; Zheng, C.; Zhang, W. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *164*, 220–228. https://doi.org/10.1016/j.agee.2012.10.009.
16. Minamikawa, K.; Tokida, T.; Sudo, S.; Padre, A.; Yagi, K. *Guidelines for Measuring CH_4 and N_2O Emissions from Rice Paddies by a Manually Operated Closed Chamber Method*; National Institute for Agro-Environmental Sciences: Tsukuba, Japan, 2015.
17. Marambe, B. Weedy rice—Evolution, threats, and management. *Trop. Agric.* **2009**, *157*, 43–64.
18. Liyanage, G.L.V.M.; Pathirana, S.P.G.S.; Rankoth, L.M.; Wickramasinghe, H.K.J.P. Evaluation of growth, yield and nutritional characterisitics of selected rice (*Oryza sativa* L.) varieties under organic farming conditions. In Proceedings of the 15th Agricultural Research Symposium, Kuliyapitiya, Sri Lanka, 28–29 June 2016.
19. Sinthuja, R.; Prasantha, B.D.R.; Hettiarachchi, A. Comparative study of grain quality characteristics of some selected traditional and improved rice varieties in Sri Lanka: A review. *Sri Lanka J. Food Agric.* **2021**, *7*, 13–30. https://doi.org/10.4038/sljfa.v7i1.91.
20. Prinn, R.G.; Pszenny, A.A.P. (Eds.) International Global Atmospheric Chemistry (IGAC) Project: The Operational Plan. In *International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions*; IGBP: Stockholm, Sweden, 1994.
21. Wijesinghe, R.; Pushpakumari, P. *AgStat: Pocket Book of Agricultural Statistics*; Socio Economics and Planning Centre, Department of Agriculture: Peradeniya, Sri Lanka, 2008.
22. Minamikawa, K.; Yagi, K.; Tokida, T.; Sander, B.O.; Wassmann, R. Appropriate frequency and time of day to measure methane emissions from an irrigated rice paddy in Japan using the manual closed chamber method. *Greenh. Gas Meas. Manag.* **2012**, *2*, 118–128. https://doi.org/10.1080/20430779.2012.729988.

23. Cai, Z.; Xing, G.; Yan, X.; Xu, H.; Tsuruta, H.; Yagi, K.; Minami, K. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. *Plant Soil* **1997**, *196*, 7–14. https://doi.org/10.1023/A:1004263405020.
24. Zou, J.; Huang, Y.; Jiang, J.; Zheng, X.; Sass, R.L. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application: Effects of agricultural management on China. *Glob. Biogeochem. Cycles* **2005**, 19, 2004GB002401. https://doi.org/10.1029/2004GB002401.
25. Venterea, R.T. Simplified Method for Quantifying Theoretical Underestimation of Chamber-Based Trace Gas Fluxes. *J. Environ. Qual.* **2010**, *39*, 126–135. https://doi.org/10.2134/jeq2009.0231.
26. Ly, P.; Jensen, L.S.; Bruun, T.B.; De Neergaard, A. Methane (CH_4) and nitrous oxide (N_2O) emissions from the system of rice intensification (SRI) under a rain-fed lowland rice ecosystem in Cambodia. *Nutr. Cycl. Agroecosyst.* **2013**, *97*, 13–27. https://doi.org/10.1007/s10705-013-9588-3.
27. Mao, Z. Environmental impact of water-saving irrigation for rice. In *Irrigation Scheduling: From Theory to Practice, Proceedings of the ICID/FAO Workshop on Irrigation Scheduling, Rome, Italy, 12–13 September 1995*; FAO: Rome, Italy, 1996.
28. Carrijo, D.R.; Lundy, M.E.; Linquist, B.A. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Res.* **2017**, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002.
29. Gon, H.A.C.; Neue, H.U.; Lantin, R.S.; Wassmann, R.; Alberto, M.C.; Aduna, J.B.; Tan, M.J.P. Controlling factors of methane emission from rice fields. In *World Inventory of Soil Emission Potentials*; Batjes, N.H., Bridges, E.M., Eds.; International Soil Reference and Information Centre: Wageningen, The Netherlands, 1992; pp. 81–92.
30. Pandey, A.; Mai, V.T.; Vu, D.Q.; Bui, T.P.L.; Mai, T.L.A.; Jensen, L.S.; De Neergaard, A. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agric. Ecosyst. Environ.* **2014**, *196*, 137–146. https://doi.org/10.1016/j.agee.2014.06.010.
31. Oo, A.Z.; Sudo, S.; Inubushi, K.; Mano, M.; Yamamoto, A.; Ono, K.; Osawa, T.; Hayashida, S.; Patra, P.K.; Terao, Y.; et al. Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India. *Agric. Ecosyst. Environ.* **2018**, *252*, 148–158. https://doi.org/10.1016/j.agee.2017.10.014.
32. Gupta, K.; Kumar, R.; Baruah, K.K.; Hazarika, S.; Karmakar, S.; Bordoloi, N. Greenhouse gas emission from rice fields: A review from Indian context. *Environ. Sci. Pollut. Res.* **2021**, *28*, 30551–30572. https://doi.org/10.1007/s11356-021-13935-1.
33. Wassmann, R.; Aulakh, M.S. The role of rice plants in regulating mechanisms of methane missions. *Biol. Fertil. Soils* **2000**, *31*, 20–29. https://doi.org/10.1007/s003740050619.
34. Le Mer, J.; Roger, P. Production, oxidation, emission and consumption of methane by soils: A review. *Eur. J. Soil Biol.* **2001**, *37*, 25–50. https://doi.org/10.1016/S1164-5563(01)01067-6.
35. Yagi, K.; Minami, K. Effects of organic matter application on methane emission from Japanese paddy fields. In *Soil and the Greenhouse Effects*; Bouwman, A.F., Ed.; John Wiley: Hoboken, NJ, USA, 1990; pp. 467–473.
36. Wang, C.; Lai, D.Y.F.; Sardans, J.; Wang, W.; Zeng, C.; Peñuelas, J. Factors Related with CH_4 and N_2O Emissions from a Paddy Field: Clues for Management implications. *PLoS ONE* **2017**, *12*, e0169254. https://doi.org/10.1371/journal.pone.0169254.
37. Inubushi, K.; Muramatsu, Y.; Umerayasi, M. Influence of Percolation on Methane Emission from Flooded Paddy Soil. *Jpn. J. Soil Sci. Plant Nutr.* **1992**, *63*, 184–189. https://doi.org/10.20710/dojo.63.2_184.
38. Corton, T.M.; Bajita, J.B.; Grospe, F.S.; Pamplona, R.R.; Assis, C.A.; Wassmann, R.; Lantin, R.S.; Buendia, L.V. Methane Emission from Irrigated and Intensively Managed Rice Fields in Central Luzon (Philippines). *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 37–53. https://doi.org/10.1023/A:1009826131741.
39. Wassmann, R.; Lantin, R.; Neue, H.-U.; Buendia, L.; Corton, T.M.; Lu, Y. Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs. *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 23–36. https://doi.org/10.1023/A:1009874014903.
40. Wang, Z.Y.; Xu, Y.C.; Li, Z.; Guo, Y.X.; Wassmann, R.; Neue, H.U.; Lantin, R.S.; Buendia, L.V.; Ding, Y.P.; Wang, Z.Z. A Four-Year Record of Methane Emissions from Irrigated Rice Fields in the Beijing Region of China. *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 55–63. https://doi.org/10.1023/A:1009878115811.
41. Woese, C.R.; Magrum, L.J.; Fox, G.E. Archaebacteria. *J. Mol. Evol.* **1978**, *11*, 245–252. https://doi.org/10.1007/BF01734485.
42. Dannenberg, S.; Conrad, R. Effect of rice plants on methane production and rhizospheric metabolism in paddy soil. *Biogeochemistry* **1999**, *45*, 53–71.
43. Schimel, J. Global change: Rice, microbes and methane. *Nature* **2000**, *403*, 375–377.
44. Neue, H.U.; Wassmann, R.; Kludze, H.K.; Bujun, W.; Lantin, R.S. Factors and processes controlling methane emissions from rice fields. *Nutr. Cycl. Agroecosyst.* **1997**, *49*, 111–117. https://doi.org/10.1023/A:1009714526204.
45. Hou, A.X.; Chen, G.X.; Wang, Z.P.; Van Cleemput, O.; Patrick, W.H. Methane and Nitrous Oxide Emissions from a Rice Field in Relation to Soil Redox and Microbiological Processes. *Soil Sci. Soc. Am. J.* **2000**, *64*, 2180–2186. https://doi.org/10.2136/sssaj2000.6462180x.
46. Watanabe, A.; Yoshida, M.; Kimura, M. Contribution of rice straw carbon to CH_4 emission from rice paddies using ^{13}C-enriched rice straw. *J. Geophys. Res.* **1998**, *103*, 8237–8242. https://doi.org/10.1029/97JD03460.
47. Kludze, H.K.; DeLaune, R.D.; Patrick, W.H. Aerenchyma Formation and Methane and Oxygen Exchange in Rice. *Soil Sci. Soc. Am. J.* **1993**, *57*, 386–391. https://doi.org/10.2136/sssaj1993.03615995005700020017x.
48. Bujun, W. Effects of rice cultivars on diel and seasonal methane emission. Ph.D. Thesis, University of the Philippines, Los Banos, Philippines, 1995; 130 p.

49. Bubier, J.L.; Moore, T.R. An ecological perspective on methane emissions from northern wetlands. *Trends Ecol. Evol.* **1994**, *9*, 460–464. https://doi.org/10.1016/0169-5347(94)90309-3.
50. Christensen, T.R.; Ekberg, A.; Ström, L.; Mastepanov, M.; Panikov, N.; Öquist, M.; Svensson, B.H.; Nykänen, H.; Martikainen, P.J.; Oskarsson, H. Factors controlling large scale variations in methane emissions from wetlands. *Geophys. Res. Lett.* **2003**, *30*. https://doi.org/10.1029/2002GL016848.
51. Davamani, V.; Parameswari, E.; Arulmani, S. Mitigation of methane gas emissions in flooded paddy soil through the utilization of methanotrophs. *Sci. Total Environ.* **2020**, *726*, 138570. https://doi.org/10.1016/j.scitotenv.2020.138570.
52. Xie, J.F.; Li, Y.E. A review of studies on mechanism of greenhouse gas (GHG) emission and its affecting factors in arable soils. *Chin. J. Agrometeorol.* **2002**, *23*, 47–52.
53. Conrad, R.; Rothfuss, F. Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. *Biol. Fertil. Soils* **1991**, *12*, 28–32. https://doi.org/10.1007/BF00369384.
54. Xunhua, Z.; Mingxing, W.; Yuesi, W.; Renxing, S.; Jing, L.; Heyer, J.; Koegge, M.; Papen, H.; Jisheng, J.; Laotu, L. Mitigation options for methane, nitrous oxide and nitric oxide emissions from agricultural ecosystems. *Adv. Atmos. Sci.* **2000**, *17*, 83–92. https://doi.org/10.1007/s00376-000-0045-2.
55. Towprayoon, S.; Smakgahn, K.; Poonkaew, S. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. *Chemosphere* **2005**, *59*, 1547–1556. https://doi.org/10.1016/j.chemosphere.2005.02.009.
56. Tirol-Padre, A.; Tran, D.H.; Hoang, T.N.; Hau, D.V.; Ngan, T.T.; An, L.V.; Minh, N.D.; Wassmann, R.; Sander, B.O. Measuring GHG Emissions from Rice Production in Quang Nam Province (Central Vietnam): Emission Factors for Different Landscapes and Water Management Practices. In *Land Use and Climate Change Interactions in Central Vietnam, Water Resources Development and Management*; Nauditt, A., Ribbe, L., Eds.; Springer: Singapore, 2017; pp. 103–121. https://doi.org/10.1007/978-981-10-2624-9_7.
57. Chanton, J.P.; Whiting, G.J.; Blair, N.E.; Lindau, C.W.; Bollich, P.K. Methane emission from rice: Stable isotopes, diurnal variations, and CO_2 exchange. *Glob. Biogeochem. Cycles* **1997**, *11*, 15–27. https://doi.org/10.1029/96GB03761.
58. Wang, M.-X.; Shangguan, X.-J. CH_4 emission from various rice fields in P.R. China. *Theor. Appl. Climatol.* **1996**, *55*, 129–138. https://doi.org/10.1007/BF00864708.
59. Nouchi, I.; Hosono, T.; Aoki, K.; Minami, K. Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature, and its modelling. *Plant Soil* **1994**, *161*, 195–208. https://doi.org/10.1007/BF00046390.
60. Goodroad, L.L.; Keeney, D.R. Nitrous oxide production in aerobic soils under varying pH, temperature and water content. Soil *Biol. Biochem.* **1984**, *16*, 39–43. https://doi.org/10.1016/0038-0717(84)90123-8.
61. Dunfield, P.; Knowles, R.; Dumont, R.; Moore, T. Methane production and consumption in temperate and subarctic peat soils: Response to temperature and pH. *Soil Biol. Biochem.* **1993**, *25*, 321–326. https://doi.org/10.1016/0038-0717(93)90130-4.
62. Smith, K.A.; Thomson, P.E.; Clayton, H.; Mctaggart, I.P.; Conen, F. Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. *Atmos. Environ.* **1998**, *32*, 3301–3309. https://doi.org/10.1016/S1352-2310(97)00492-5.
63. Wassmann, R.; Neue, H.U.; Lantin, R.S.; Javellana, M.J.; Diego, R.; Hoffmann, H.; Papen, H.; Rennenberg, H. Methane emissions from rainfed rice fields, In *Fragile Lives in Fragile Ecosystems: Proceedings of the International Rice Research Conference*; International Rice Research Institute: Los Baños, Philippines, 1995; pp. 217–225.
64. Zhang, H.; Zhang, S.; Yang, J.; Zhang, J.; Wang, Z. Postanthesis Moderate Wetting Drying Improves Both Quality and Quantity of Rice Yield. *Agron. J.* **2008**, *100*, 726–734. https://doi.org/10.2134/agronj2007.0169.
65. Minamikawa, K.; Sakai, N. The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan. *Agric. Ecosyst. Environ.* **2006**, *116*, 181–188.
66. Bodelier, P.L.E.; Roslev, P.; Henckel, T.; Frenzel, P. Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. *Nature* **2000**, *403*, 421–424. https://doi.org/10.1038/35000193.
67. Ji, Y.; Liu, G.; Ma, J.; Zhang, G.-B.; Xu, H. Effects of Urea and Controlled Release Urea Fertilizers on Methane Emission from Paddy Fields: A Multi-Year Field Study. *Pedosphere* **2014**, *24*, 662–673. https://doi.org/10.1016/S1002-0160(14)60052-7.