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Special Issue

Assessing the benefits of alternating wet and dry (AWD) irrigation of rice fields on greenhouse gas emissions in central Taiwan

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ABSTRACT: Alternate Wetting and Drying irrigation (AWD) is a water-saving method that involves periodic drainage and re-flooding of rice paddies. This technique has been shown to significantly reduce water usage while mitigating greenhouse gas emissions (GHGs), particularly methane (CH_4). Our study evaluates the effects of AWD irrigation in central Taiwan, focusing on its effects on greenhouse gas emissions in rice paddies. In 2023, the AWD system decreased CH_4 emissions by 41.97% during the first crop and 31.98% in the second season, leading to an annual reduction of 34.29% (3,891.45 kg-CO_2e ha^{-1}). In 2024, this system achieved an overall CH_4 reduction of 17.91% (842.0 kg-CO_2e ha^{-1}). For N_2O, eco-friendly practices resulted in an annual decrease of 60.21% (2,193.0 kg-CO_2e ha^{-1}). A global warming potential (GWP) analysis for the second crop in 2024 showed a 64% reduction (3,970.0 kg-CO_2e ha^{-1}) when water-saving techniques were used compared to conventional methods. These findings highlight the potential of AWD and reduced fertilization strategies to lower global warming potential (GWP), thereby supporting sustainable rice production and GHGs mitigation. Correlations indicated that CH_4 emissions were strongly associated with soil temperature and moisture, while N_2O emissions were highly correlated with soil moisture. Given the limited studies on AWD under non-continuous flooding conditions in Taiwan, this research provided critical insights for optimizing water and nutrient management in rice cultivation and enhancing GHG mitigation efforts.

KEY WORDS: Greenhouse gas emissions, Methane, nitrous oxide, Global Warming Potential.

INTRODUCTION

Global warming is a pressing global challenge driving ongoing climate change, necessitating concrete actions to mitigate its acceleration. Without intervention, Earth is projected to risk a temperature increase of 2°C by 2040 (IPCC, 2019), a scenario largely attributed to rising greenhouse gas emissions from human activities (Purnamasari *et al*., 2019). Among various mitigation options, reducing methane (CH_4) emissions is considered one of the most cost-effective and immediate strategies to rapidly slow global warming, aligning with the climate target of limiting global temperature rise to 1.5°C (United Nations Environment Programme and Climate and Clean Air Coalition, 2021). The agricultural sector contributes primarily through emissions of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). As the second most abundant greenhouse gas after CO_2, methane is particularly significant in emissions from rice paddies, which are among the largest global sources of CH_4, accounting for approximately 8% of human-induced methane emissions. Asia, with the largest rice cultivation areas, is a major contributor to this total (Zhang *et al*., 2018; Ouyang *et al*., 2023). Research by Liping and Erda (2001) indicates that the prolonged irrigation common in rice cultivation fosters an anaerobic soil environment, which encourages methane-producing microbes to break down organic matter, resulting in methane production and release (Wang *et al*., 2018). Additionally, methane emissions during rice cultivation are influenced by various factors, including fertilizer type and application timing (Kajiura and Tokida, 2024), soil moisture levels, water management practices (Chidthaisong *et al*., 2018; Lakshani *et al*., 2023), and temperature fluctuations (Pereira *et al*., 2013; Li *et al*., 2024a).

Chapter 7 of the IPCC's Sixth Assessment Report (AR6 WGIII), published in February 2022, identifies rice cultivation as a major methane emission source in Asia. Specifically, within Southeast Asia, where Taiwan is located, methane emissions from rice paddies constitute over half of the region's total, positioning it as the largest global contributor to methane emissions from rice cultivation (Nabuurs *et al*., 2023). These findings highlight the importance of reducing methane emissions from rice paddies as a critical strategy in global greenhouse gas mitigation. Traditional continuous flooding (CF) practices create anaerobic soil conditions conducive to methane production (Qiu, 2009; Zheng *et al*., 2024). In contrast, water-saving irrigation methods such as Alternate Wetting and Drying (AWD) and Intermittent Irrigation have been effective in reducing methane emissions from rice fields while conserving water (Bouman and Tuong, 2001; LaHue *et al*., 2016; Lakshani *et al*., 2023). Lakshani *et al*. (2023) found that AWD reduces cumulative CH_4 emissions by 32% compared to CF, with water savings ranging from 27–35%. Further studies on AWD report methane reductions of 29% (Pramono *et al*., 2024), 37% (Matsuda *et al*., 2023), 49% (Chidthaisong *et al*., 2018), 52–55% (Anapalli *et al*., 2023), 77% (Echegaray-Cabrera *et al*., 2024), and 72–100% (Loaiza *et al*., 2024). Although reductions vary, AWD consistently demonstrates substantial effectiveness in methane mitigation. In Taiwan, rice cultivation accounts for about 38% of the nation's total water use, requiring 6,282 million m^3 over two growing crops (Irrigation Agency, 2020). Reducing the water demand of rice cultivation or reallocating water-intensive rice production could ease competition for water resources between agricultural and industrial sectors.

However, this reduction in methane emissions may be partially offset by an increase in N_2O emissions (in terms of GWP) (Cheng *et al*., 2022; Liang *et al*., 2023), as some studies suggest that extending aerobic phases in rice paddies enhances N_2O emissions through nitrification and denitrification processes (Ariani *et al*., 2022; Gaihre *et al*., 2023; Pramono *et al*., 2024), modulating microbial communities through the application of probiotics has shown potential to mitigate GHG emissions while enhancing rice yield. Probiotic treatments in rice paddies reduced CO_2 emissions by 47.58%, CH_4 emissions by 21.53%, and N_2O emissions by 88.50%, coupled with a 27.75% increase in rice yield (Pao *et al*., 2025), though other studies aim to minimize N_2O emissions (Loaiza *et al*., 2024). Given the unclear net effect of AWD on combined methane and nitrous oxide emissions, this study examines CH_4 and N_2O emissions from rice paddies in central Taiwan (Wufeng). The primary objectives are to investigate methane and nitrous oxide emissions under continuous flooding (CF) and AWD water management in rice paddies, assess AWD's potential as an emerging technique for GHG mitigation and water savings, and develop sustainable contract farming models to support pathways for sustainable agricultural production.

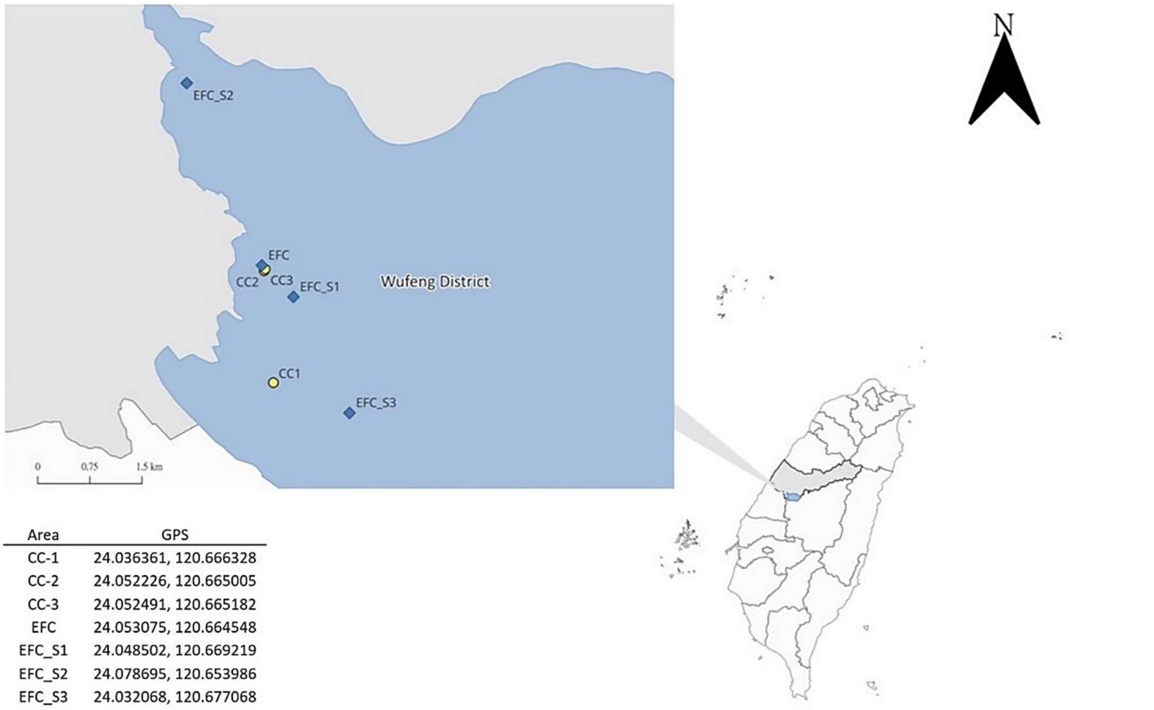
MATERIALS AND METHODS

Experimental site and planting design

From 2023 to 2024, three fields in the Wufeng area were selected for traditional irrigation, while an additional three fields were managed with AWD irrigation. Detailed locations and areas are provided in Table 1 and Fig 1. Under traditional irrigation, fields are kept flooded except during the peak tillering stage when drying is applied; irrigation resumes once the water level drops to 0 cm. Alternate Wetting and Drying (AWD) irrigation begins one week after transplanting, where fields are irrigated to a 10 cm depth and allowed to dry until the water level reaches the soil surface (0 cm), at which point irrigation is resumed. This cycle continues until the peak tillering stage, after which fields are dried for 7–10 days. During the heading to dough stages, AWD is halted, and a minimum water level of 5 cm is maintained. AWD resumes after this stage and continues until one week before harvest, when all irrigation is stopped to allow the fields to dry completely. Water levels are monitored using a sensor-equipped water level gauge (Argi Microclimate Soil Sensor), which was installed in both water-saving and conventional fields three days after transplanting. Soil temperature was recorded at 10 cm depth using soil temperature probes (Model: FD-v7, Manufacturer: Impact Power, Inc., contry: Taiwan). Measurements were taken daily to capture diurnal variations. Moisture Content: Soil moisture was determined using the gravimetric method, wherein soil samples were collected at 10–15 cm depth, oven-dried at 105°C for 24 hours, and reweighed to calculate moisture loss. Additional Parameters: The environmental conditions near the experimental site are recorded by the nearby meteorological station (Central Weather Bureau), including rainfall, air temperature, and relative humidity. These measurements followed the protocols outlined by Pao *et al*. (2025) and provided essential data for contextualizing greenhouse gas emissions.

The growth period of rice cultivation is divided into the seedling stage, establishment phase, tillering, heading, milk-ripe, and yellow-ripe stages, spanning approximately 120 days in total. During the seedling stage, land preparation includes plowing, leveling, sowing, and seedling nurturing (cultivar Tainung 71). Five to seven days prior to transplanting, fields are irrigated to a depth of 1–2 cm. Three days before transplanting, base fertilizer (N: P_2O_5: K_2O, 6:3:3; Yang Tian Pure-De 633, Taiwan) is applied using water-saving methods, followed by fine tilling. Transplanting occurs roughly 20 days after sowing, at a density of approximately 220–250 seedling trays per hectare. Transplanting is done by machine, with 3–5 seedlings per hill, and a water depth of 3–5 cm is maintained post-transplant.

In the water-saving treatment, irrigation is withheld about two weeks after transplanting, allowing the field to dry to a 0 cm water level before re-irrigating to 3–5 cm. This cycle continues until the heading stage. Conventional irrigation, however, maintains a water depth of 3–5 cm without interruption. In conventional fields, fertilizers (N: P_2O_5: K_2O, 12:18:12; Fertilizer Efficiency-39, Taiwan) are applied around the 15th and 30th days post-transplant as the first and second fertilization. In contrast, the water-saving approach only applies supplemental fertilizer N: P_2O_5: K_2O, 6:3:3; Yang



Area	GPS
CC-1	24.036361, 120.666328
CC-2	24.052226, 120.665005
CC-3	24.052491, 120.665182
EFC	24.053075, 120.664548
EFC_S1	24.048502, 120.669219
EFC_S2	24.078695, 120.653986
EFC_S3	24.032068, 120.677068

Fig 1. Rice field location map and coordinates in central Taiwan (Wufeng).

Table 1. Rice field plots and cultivated areas in central Taiwan (Wufeng)

Plot		Cultivated area (ha)
Eco-friendly culture	saving irrigation-I	0.5186
	saving irrigation-II	0.1986
	saving irrigation-III	0.1976
	Non saving	0.12268
conventional culture	convention-I	0.1899
	convention-II	1.01224
	convention-III	0.1448

Tian Pure-De 633, Taiwan) around the 15th day. The period from transplanting to heading lasts about 50 days, with heading spanning approximately 30 days.

During the heading stage, both conventional and water-saving methods involve a panicle fertilizer application, as grain development requires substantial water supply. A water depth of 5–10 cm is maintained, re-irrigating when levels drop to 3 cm. In the late milk-ripe and yellow-ripe stages, water is sustained at a 3 cm depth for photosynthesis until five to seven days before harvest, when fields are drained to prevent grain overfilling but incomplete development (Lampayan *et al.*, 2015). The yellow-ripe stage lasts approximately 30 days, concluding a full rice growth period.

Measurement method

Greenhouse gas monitoring for CH_4 and N_2O was conducted at each stage of rice growth, with measurements taken before transplanting, post-transplant, after the first and second fertilizations, post-panicle fertilization, pre-harvest, and post-harvest. The closed chamber method was employed for GHG flux measurements, linking a CH_4 analyzer (LI-7810) and an N_2O analyzer (LI-7820) to record data, with each device using standard data loggers. Our research team developed a chamber with a semi-circular transparent acrylic upper section and a 20 cm high, 30 cm diameter circular steel ring as the lower section, with larger acrylic chambers available for use depending on plant size. During measurements, the steel ring was inserted into the soil and tightly sealed with the acrylic cover using clamps to ensure airtightness. Gas from within the chamber was then pumped through plastic tubing to the analyzers. For taller plants, a larger closed chamber system (24 × 24 × 50 cm or larger) was employed to capture GHG emissions. The ideal gas law was used to calculate greenhouse gas flux from field data, with the calculation formula provided as follows (Migné *et al.*, 2002)：

$$\text{Flux}= (S\times V\times tc\times M)/((RT\times 1000\times A))$$

F: Greenhouse gas flux (mg m^{-2} $hour^{-1}$);
S: Linear slope of greenhouse gas concentration (ppm) with data recording frequency (CH_4: 20 s; N_2O: 20 s);
V: Volume of the closed chamber (L);
tc: Time conversion constant, where for CH_4 and N_2O: 180 = (1 h × (60 min/h) × (60 s/min)/20 s);
M: Molecular weight (g/mol);
R: Ideal gas constant = 0.082;
T: Absolute temperature (K);
1000: Mass conversion constant (1 mg = 1000 μg);
A: Area of the chamber base (m^2)

Additionally, the water level gauge simultaneously records soil temperature, soil moisture content, water depth,

Table 2. The total emission of greenhouse gas in two crop seasons from 2023 to 2024 in central Taiwan (Wufeng).

		Plot	CH_4(kg ha^{-1})	N_2O(kg ha^{-1})	GWP(CH_4+N_2O) (kg CO2e ha^{-1})	Yield(t/ha)	GHGI(t CO_2 e/t yield)
2023	First Crop	CC	90.60*	-	2527.74*	10.35*	0.24*
		EFC-S	52.57	-	1466.70	6.66	0.22
	Second Crop	CC	316.08*	-	8818.63*	7.09*	1.24*
		EFC-S	214.99	-	5998.22	5.62	1.06
2024	First Crop	CC	29.82^c	8.40^a	3124.71^c	9.39^a	0.33^c
		EFC	163.53^a	1.72^b	5033.21^a	5.67^c	0.88^a
		EFC-S	116.80^b	2.60^b	3967.22^b	6.88^b	0.57^b
	Second Crop	CC	348.67^a	4.94^a	11077.49^a	8.88^a	1.25^a
		EFC	147.16^b	3.39^b	5032.15^b	6.01^b	0.89^b
		EFC-S	112.97^c	3.00^b	3969.98^c	6.14^b	0.65^c

CC=Conventional culture; EFC= Eco-friendly culture; EFC-S=Eco-friendly culture with saving irrigation.
*=Indicates significant differences ($p < 0.05$) between the two field treatments (2023) in T-test analysis.
Different letters indicate significant differences ($p < 0.05$) in Tukey HSD analysis among the three field treatments (2024).

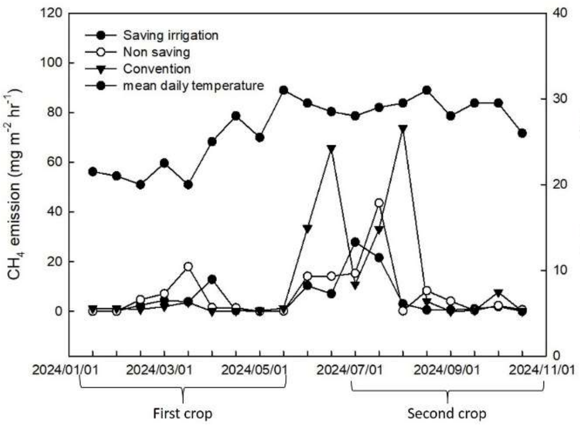


Fig 2. CH_4 emissions from rice and temperature changes of Wufeng in 2024.

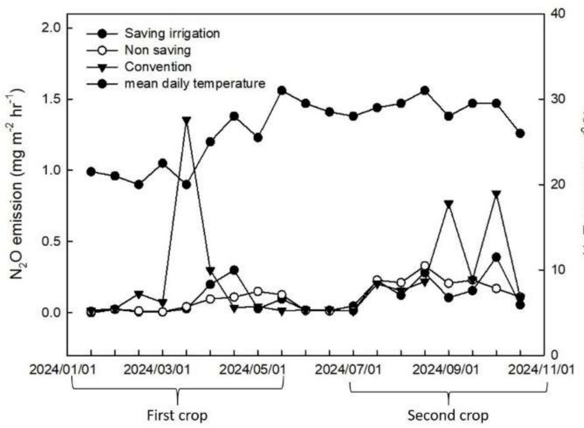


Fig 3. N_2O emissions from rice and temperature changes of Wufeng in 2024.

and soil electrical conductivity, with data logged at an hourly interval.

Greenhouse gas intensity (GHGI) was calculated as the total greenhouse gas emissions per unit of crop yield (in tons). This metric was determined by dividing the net GWP by the total crop yield. Crop yield was measured as dry weight per unit area, and this value was used in combination with the GWP for the specified period to compute the GHGI. The formula used for this calculation is:

GHGI (t CO_2 e / t yield) = GWP (t CO_2 e / ha) / crop yield (t yield / ha)

Statistical analysis

Data organization and plotting were performed using SigmaPlot software. Pearson correlation analysis between CH_4 and N_2O emissions and environmental factors was conducted with SPSS 20 statistical software. A significance level of $p < 0.05$ was set for all statistical tests.

RESULTS

Monitoring of CH4 and N2O emissions

Table 2 presents the total greenhouse gas emissions for each rice-growing season in Wufeng for 2023 and 2024, with emissions converted to CO_2 equivalents (CO_2e) according to AR6 GWP factors (CH_4:28, N_2O:273). The data show that emissions were consistently higher during the second crop than the first. Except for the 2024 first crop, emissions from conventional plots exceeded those from eco-friendly plots. This increase is likely due to the higher average temperatures recorded during the second crop (Figs 2 and Table 2), which may have contributed to the elevated greenhouse gas emissions.

In 2023, conventional culture produced CH_4 emissions of 2,527.7 kg CO_2e ha^{-1} for the first crop and 8,818.6 kg CO_2e ha^{-1} for the second. In contrast, the eco-friendly culture with water-saving practices recorded CH_4 emissions of 1,466.7 kg CO_2e ha^{-1} for the first crop and 5,998.2 kg CO_2e ha^{-1} for the second, marking a reduction of 41.97% for the first crop and 31.98% for the second, with an overall annual reduction of 34.29% (Fig 2, Tab 2). In 2024, CH_4 emissions for the conventional culture's first crop reached 835.0 kg CO_2e ha^{-1}, while the second crop rose to 9,762.8 kg CO_2e ha^{-1}. Comparatively, the eco-friendly culture achieved CH_4 emissions reductions to 4,578.8 kg CO_2e ha^{-1} for the first crop and 4,120.5 kg CO_2e ha^{-1} for the second, resulting in an annual reduction of 17.91% (Fig 2, Table 2).

Table 3. Pearson correlation analysis of CH_4 emissions and environmental factors.

	CH_4 emission	soil moisture content	soil temperature	water depth
CH_4 emission	1	.112	**.372****	**.426****
Soil moisture content	-	1	.007	**.344***
Soil temperature	-	-	1	.140
Water level	-	-	-	1

** indicates a significant level <0.01; * indicates a significant level <0.05 (n=51)

Table 4. Pearson correlation analysis of N_2O emissions and environmental factors

	N_2O emission	Soil moisture	Soil Temp.	Water level
N_2O emission	1	.075	-.246	-.125
Soil moisture content	-	1	.006	**.343***
Soil temperature	-	-	1	.141
Water level	-	-	-	1

** indicates a significant level <0.01，；* indicates a significant level <0.05 (n=51)

To assess the effect of AWD implementation on N_2O emissions, we monitored both CH_4 and N_2O emissions in 2024. The results revealed that N_2O emissions for the conventional system's first crop reached 2,293.2 kg CO_2e ha^{-1}, while the second crop produced 1,348.9 kg CO_2e ha^{-1}. In contrast, the eco-friendly system with water-saving practices recorded significantly lower N_2O emissions of 496.6 kg CO_2e ha^{-1} for the first crop and 952.5 kg CO_2e ha^{-1} for the second crop, indicating an overall annual reduction of 60.21% (Fig 3, Table 2).

In the first rice season of 2024, CH_4 and N_2O emissions were recorded with conventional plots serving as the baseline. The conventional plots had a GWP of 3,125 kg CO_2e ha^{-1} (Table 2), while the eco-friendly water-saving plot showed 3,967 kg CO_2e ha^{-1}, marking a 26% increase compared to the conventional plot, but the non-water-saving plot, which reached 5,033 kg CO_2e ha^{-1}—61% higher than the conventional level. In the second rice crop of 2024, the conventional plot exhibited a GWP of 11,077 kg CO_2e ha^{-1}, whereas the eco-friendly water-saving plot recorded a reduction to 3,970 kg CO_2e ha^{-1}, marking a 64% decrease. The non-water-saving eco-friendly plot showed 5,032 kg CO_2e ha^{-1}, representing a 55% reduction compared to the conventional plot.

It is important to note that these values may be subject to change as the second crop cycle is ongoing. Nonetheless, the results clearly indicate that the water-saving plot consistently produced lower GWP emissions across both crops relative to the non-water-saving plot. The water-saving plot in 2024 reduced emissions by 6,264 kg CO_2e ha^{-1} compared to the conventional plot, underscoring the efficacy of water-saving practices in mitigating greenhouse gas emissions.

Further analysis of Greenhouse Gas Intensity (GHGI) calculations for the year 2023 revealed that the eco-friendly water-saving plot exhibited the lowest GHGI, totaling 1.28, while the conventional plot had a GHGI of 1.44, a decrease of 11%. In the 2024 annual production period, the conventional plot recorded a GHGI of 1.58, the eco-friendly plot had a GHGI of 1.77, and the eco-friendly water-saving plot exhibited the lowest GHGI at 1.22, indicating a clear trend of reduced greenhouse gas emissions in the latter, which decreased by 22.8%. Moreover, apart from a lower GHGI observed in the second rice season of 2024, the conventional plot generally exhibited a higher GHGI across all production periods. Similarly, the eco-friendly plot did not demonstrate a significant effect in reducing greenhouse gas emissions, suggesting that water-saving practices, rather than eco-friendly management alone, play a more crucial role in mitigating emissions.

The relationship between greenhouse gas emissions and environmental factors

Further analysis of the relationship between greenhouse gas emissions and environmental factors, using Pearson correlation, revealed a significant positive correlation between CH_4 emissions and both water level and soil temperature (Table 3), with minimal correlation to soil moisture content. In contrast, N_2O emissions showed no significant correlation with soil temperature, water level, or soil moisture content (Table 4). This suggests that N_2O emissions may be influenced by more complex environmental interactions, making single environmental factors less effectful. However, a negative correlation between N_2O emissions and water level was observed, indicating that increased flooding depth may reduce N_2O emissions.

Examining the correlation between agricultural practices and CH_4 emissions during the 2024 growing crops reveals that peak CH_4 emissions in the first rice crop occurred between the first and panicle fertilizations, ranging from approximately 2–12 mg m^{-2} hr^{-1}, while in the second crop, peaks were observed from transplanting through panicle fertilization (Figs. 4A and 4B). When compared with water level data, it is evident that in the first crop, water-saving plots maintained water depths of 20–60 mm during the fertilization phases (Fig. 5A), suggesting that water-saving irrigation was not consistently applied, potentially resulting in higher-than-expected CH_4 emissions. In contrast, the second crop water-saving plots exhibited clear drying and re-watering cycles (Fig. 5B), which effectively reduced CH_4 emissions in these plots.

For N_2O emissions in conventional plots, there was an upward trend following the first and panicle fertilizations, and two weeks post-panicle fertilization. Notably, in the first crop, N_2O emissions spiked to 1.35 mg m^{-2} hr^{-1} post-panicle fertilization, while water-saving plots showed minimal variation, with emissions ranging from 0.01 to

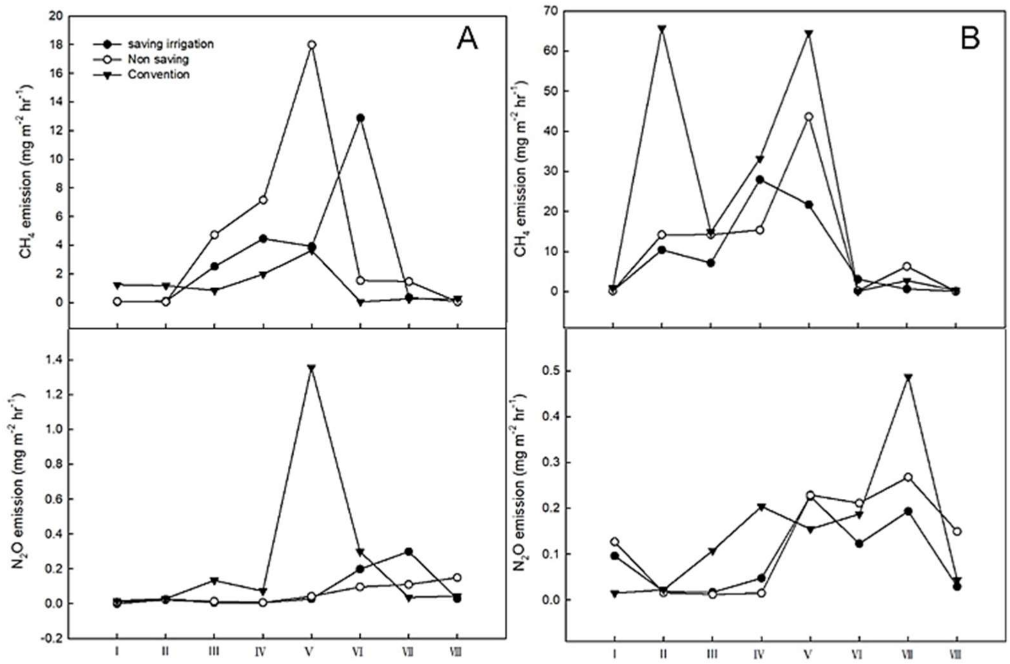


Fig 4. CH_4 and N_2O emissions at each agricultural method node of rice in the first crop (**A**) and the second crop (**B**) of Wufeng in 2024. Ⅰ: transplanting；Ⅱ: post-transplant；Ⅲ: first fertilizations；Ⅳ:second fertilizations；Ⅴ: post-panicle fertilization；Ⅵ: 2 weeks after post-panicle fertilization；Ⅶ: pre-harvest；Ⅷ: post-harvest.

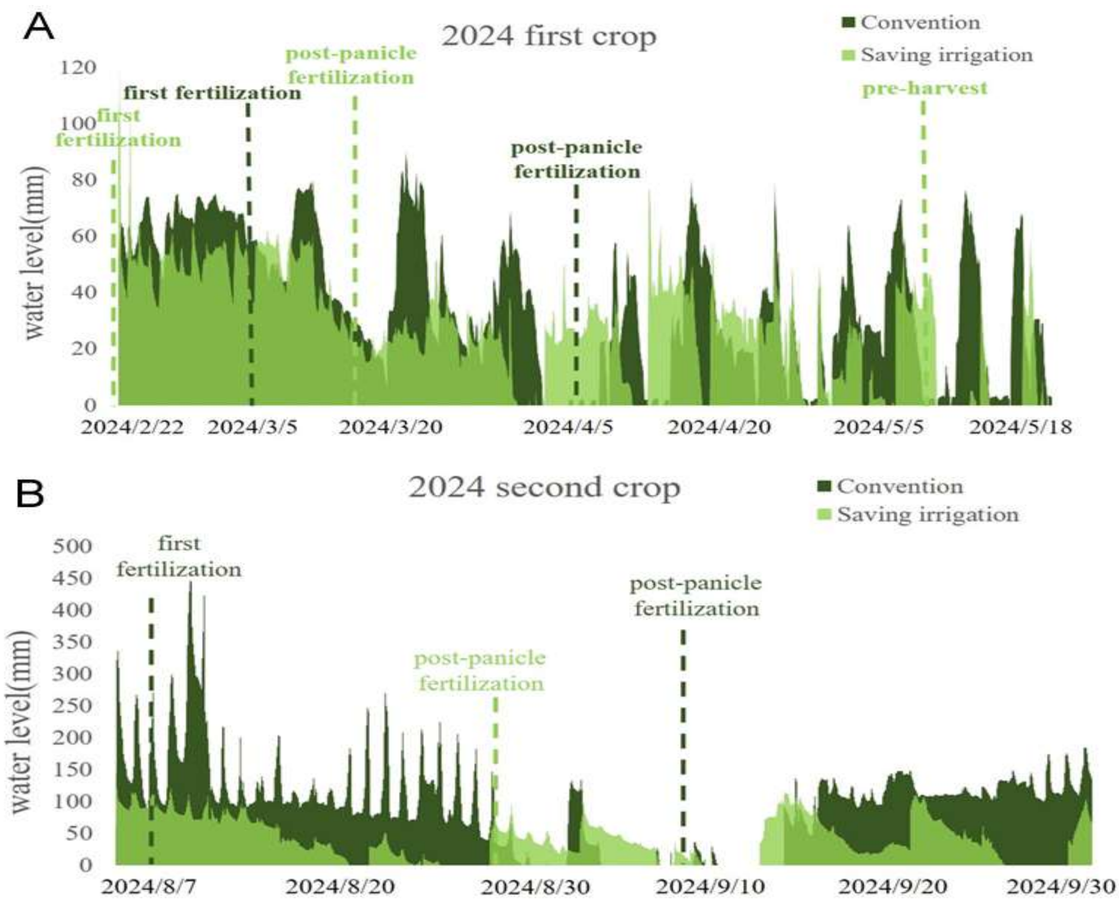


Fig 5. Water level of first (**A**) and second (**B**) crop season at Wufeng in 2024.

0.3 mg m^{-2} hr^{-1}. In the second crop, N_2O emissions in conventional plots gradually increased following the first fertilization, reaching a peak of 0.48 mg m^{-2} hr^{-1} two weeks after panicle fertilization. In eco-friendly plots, emissions remained around 0.2 mg m^{-2} hr^{-1} after the second fertilization, likely due to the onset of drying cycles facilitating N_2O release.

DISCUSSION

AWD's greenhouse gas reduction benefits

The traditional practice of continuous flooding in rice paddies is a significant source of CH_4 emissions. When organic fertilizers are applied in rice fields under eco-friendly cultivation, a shift in traditional water management practices is essential to reduce CH_4 emissions; otherwise, the fields may experience increased CH_4 release. This two-season study, conducted on farmer-owned fields in central Taiwan, demonstrates that eco-friendly plots, which included both reduced fertilizer application and water-saving measures (Tab 1), achieved a CH_4 emission reduction of 34.29% (3,891.45 kg CO_2e ha^{-1}) in 2023 and a 21.2% reduction (842 kg CO_2e ha^{-1}) in 2024. These findings highlight that water-saving practices and reduced fertilizer use can significantly mitigate CH_4 emissions in intensive rice production systems, consistent with previous studies (Chidthaisong *et al*., 2018; Anapalli *et al*., 2023; Matsuda *et al*., 2023; Echegaray-Cabrera *et al*., 2024; Loaiza *et al*., 2024; Pramono *et al*., 2024).

After converting greenhouse gas emissions for each cropping season into CO_2 equivalents (CO_2e) according to AR6 GWP standards, it was observed that emissions from the second crop consistently exceeded those from the first crop. The higher CH_4 emissions in the second crop may be due to the elevated temperatures of the summer season (Tariq *et al*., 2017; Li *et al*., 2024b). In central Taiwan, average seasonal temperatures in 2024 were recorded as 17.7–26.4°C in spring and 25.5–28.9°C in summer. Elevated summer temperatures accelerate the decomposition of organic matter (Tang *et al*., 2014) and alter microbial activity (Dalal *et al*., 2008), which may explain the CH_4 emissions reaching 5,033 kg CO_2e ha^{-1} in the eco-friendly non-water-saving plot, a 61% increase compared to the conventional plot. We analyzed greenhouse gas (GHG) emissions, particularly methane (CH_4), across three key growth stages of rice: vegetative, reproductive, and maturity stages. Our findings indicate that the majority of emissions occur between transplanting and heading, accounting for approximately 60–80% of total emissions. In contrast, drier conditions during the reproductive stage may have limited the formation of anaerobic environments, resulting in reduced CH_4 flux. Baldocchi *et al*. (2012) indicated that soil becomes anaerobic after flooding, enabling methanogenic bacteria to decompose organic acetate into CH_4 and CO_2, which then diffuses into the atmosphere. Additionally, flooding promotes the formation of aerenchyma in rice plants, facilitating the rapid transfer of CH_4 from the soil to the atmosphere (Holzapfel-Pschorn *et al*., 1986). These findings align with the high correlation observed in this study between CH_4 emissions from rice paddies and soil temperature and moisture levels (Tab 3). Pao *et al*. (2025) provides critical findings on the interplay between microbial community modulation and greenhouse gas emissions in rice paddies, demonstrating that the application of probiotics can enhance methane mitigation. This highlights the potential of influencing soil microbial communities to achieve methane reduction. Similarly, AWD irrigation, by improving soil aeration, can exert comparable effects on modulating soil microbial communities.

Reflection of N_2O emissions on AWD

Periodic drying cycles during the growing season may lead to increased N_2O emissions under AWD (Alternate Wetting and Drying) conditions. The drying phase can enhance nitrification, thereby promoting N_2O emissions during subsequent aerobic phases (Loaiza *et al*., 2024). Furthermore, fertilization has been shown to further amplify N_2O emissions (Koukoutsi *et al*., 2023). However, upon re-flooding, denitrification processes may occur, which could also elevate N_2O emissions (Balaine *et al*., 2019; Oertel *et al*., 2016). Reducing fertilizer application during AWD implementation can help lower N_2O emissions, aligning with this study's findings, which demonstrated an annual N_2O reduction of 2,193 kg CO_2e ha^{-1}.

From an irrigation perspective, AWD is a well-researched water-saving technique in rice cultivation (Anapalli *et al*., 2023; Matsuda *et al*., 2023; Pramono *et al*., 2024). However, whether the increase in N_2O emissions from field drying during AWD outweighs the reduction in CH_4 emissions will determine if AWD effectively contributes to a net decrease in GWP. Lagomarsino *et al*. (2016) observed that AWD reduced water use by 70% and CH_4 emissions by 97%, but N_2O emissions increased fivefold in clay-textured soils. Similarly, Abid *et al*. (2019) reported higher N_2O emissions under AWD compared to continuous flooding, and Islam *et al*. (2018) found that while AWD reduced seasonal CH_4 emissions, it increased N_2O emissions by 23%. These findings align with our results (Tab 4), where N_2O emissions during soil aeration in rice paddies were strongly correlated with soil moisture levels. Our experiments also indicate that emission peaks primarily occur during dry periods when field aeration is relatively high; however, soil moisture must be maintained at sufficient levels to sustain continuous nitrification activity in the soil. Overall, this study demonstrates that although N_2O emissions increase, AWD combined with reduced fertilizer application and the application of probiotics can still lower GWP (Jiang *et al.*, 2019; Pao *et al.* 2025) and GHGI. An important consideration, however, is that most research contrasts AWD with continuous flooding, highlighting the CH_4 reduction benefits relative to N_2O. Comparatively, few studies evaluate GWP and GHGI under non-continuous flooding conditions. Greenhouse Gas Intensity (GHGI) is a crucial parameter in evaluating the environmental impact of food production, as highlighted in previous studies (Wu *et al.*, 2021; Umemiya and White, 2022; Lin *et al.*, 2024). It quantifies the greenhouse gas emissions per unit of agricultural yield, serving as an essential metric for assessing the trade-off between food security and climate change mitigation. A lower GHGI during the production process implies a reduced carbon footprint per unit yield, which in turn alleviates the burden of greenhouse gas emissions on the environment. By achieving a balance between sustaining human food systems and minimizing climate change pressures, GHGI reduction plays a fundamental role in advancing sustainable agricultural practices.

Our study findings demonstrate that the eco-friendly water-saving plot effectively reduces GHGI, contributing to significant greenhouse gas mitigation. This reduction underscores the importance of integrating water-saving strategies with sustainable farming practices to optimize both productivity and environmental sustainability. By lowering GHGI, such approaches can play a pivotal role in promoting low-emission agriculture, enhancing carbon efficiency, and supporting global efforts to mitigate climate change while ensuring food security. The outcomes of this study may serve as agronomic practices for water and nutrient management in rice production, promoting sustainable agriculture in Taiwan and further contributing to greenhouse gas mitigation.

CONCLUSION

This study demonstrates that eco-friendly, water-saving practices in rice cultivation substantially reduce CH_4 and N_2O emissions compared to conventional practices. In 2023, the eco-friendly system reduced CH_4 emissions by 41.97% in the first crop and by 31.98% in the second crop, leading to an annual reduction of 34.29% (3,891.45 kg CO_2e ha^{-1}). In 2024, this system resulted in an overall CH_4 emissions reduction of 17.91% (842 kg CO_2e ha^{-1}). For N_2O, annual emissions decreased by 60.21% (2,193 kg CO_2e ha^{-1}) under eco-friendly conditions. Greenhouse gas potential (GWP) assessments for the 2024 second crop further revealed a 64% GWP (3,970 kg CO_2e ha^{-1}) reduction with water-saving practices compared to conventional methods. These findings underscore the effect of water-saving and reduced fertilization strategies on lowering GWP, with promising implications for sustainable rice cultivation and greenhouse gas mitigation. Additionally, a strong correlation was observed between CH_4 emissions and both soil temperature and moisture, while N_2O emissions were closely linked to soil moisture levels. Given the limited research on AWD under non-continuous flooding conditions in Taiwan, these findings offer valuable insights for optimizing water and nutrient management in rice production, supporting the advancement of sustainable agriculture and effective greenhouse gas mitigation strategies.

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