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Effects of Water Management and Rice Varieties on Greenhouse Gas Emissions in Central Japan

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Abstract: Greenhouse gas (GHG) emissions from paddy fields depend on water management practices and rice varieties. Lysimeter experiments were conducted to determine the effect of rice varieties (lowland; Koshihikari (KH) and upland; Dourado Precoce (DP)) on GHG emissions under two water management practices: alternate wetting and drying (AWD) and continuous flooding (CF). A repeated cycle of drying and wetting in AWD irrigation was performed by drying the soil to −40 kPa soil matric potential and then rewetting. Consequently, the closed chamber method was used to measure direct emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The result revealed that water management significantly affected CH_4 and N_2O emissions ($p < 0.05$), while no significant effect was observed between different rice varieties. Although, AWD irrigation reduced CH_4 emissions, it increased N_2O emissions compared to CF irrigation, likely due to increased oxygen supply. AWD irrigation decreased GWP by 55.6% and 59.6% in KH and DP, respectively, compared to CF irrigation. Furthermore, CH_4 and N_2O emissions significantly correlated with soil redox potential and volumetric water content. These results suggest that AWD irrigation might be an effective water management method for mitigating GHG emissions from rice fields in central Japan.

Keywords: alternate wetting and drying; rice cultivars; methane; nitrous oxide; emission factor

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1. Introduction

Global freshwater scarcity, labor shortages, and high greenhouse gas (GHG) emissions from traditional continuous flooding (CF) of rice fields are driving the adoption of the alternate wetting and drying (AWD) irrigation system [1]. The practice of AWD incorporates unsaturated soil conditions into irrigation scheduling during the growing season. It allows the depth of the water table to be reduced until the soil is slightly dry before the next irrigation [2,3]. AWD and other water management techniques (e.g., intermittent irrigation) are widely practiced in tropical and temperate regions, including Japan [4].

An AWD irrigation regime with organic amendments significantly increased rice yield and water use efficiency and improved soil physicochemical properties, including soil microbial biomass carbon and nitrogen [5]. In another study conducted in Central Vietnam, the total water use was reduced by 15% with AWD compared to CF, with no significant difference in rice grain yield [6]. Furthermore, a study conducted in China revealed that the AWD irrigation regime significantly increased root oxidation activity, cytokinin concentrations in roots and shoots, leaf photosynthetic rate, and enzymes involved in sucrose-to-starch conversion in grains. This results in an 11% increase in grain yield compared to CF fields [3]. Likewise, a study conducted in Bangladesh revealed that AWD had no major effect on rice growth and yield, indicating that AWD irrigation could be implemented without any decrease in yield [7]. In contrast, other research found that AWD lowers rice yields and affects the dynamics of soil carbon [8,9].

Multiple studies have demonstrated that AWD irrigation can reduce methane (CH_4) emissions compared to CF irrigation [6,10–12]. The lysimeter used in this experiment, which employed AWD irrigation, reportedly reduced greenhouse gas emissions while maintaining yield [4]. Nitrous oxide (N_2O) emission has also been reported to be increased by cultivation with intermittent irrigation [13], with nitrification occurring when the soil dries out and denitrification occurring when the soil is flooded [14–17]. In addition, previous studies have demonstrated that implementing AWD irrigation can greatly reduce global warming potential (GWP) compared to CF irrigation. It relies on CH_4 as the main contributor to GWP in paddy fields [15,18]. The redox potential is an indicator of the soil. Carbon dioxide (CO_2) and N_2O are the dominant factors in the greenhouse effect when the redox potential is above 180 mV, and CH_4 is the dominant factor when it is below −150 mV [19,20].

There are also various previous studies on the differences in GHG emissions among rice varieties. Some studies suggest that CH_4 fluxes differ among rice varieties [21,22]. Conversely, other studies suggest that CH_4 fluxes remain consistent among different crop varieties subjected to intermittent irrigation, while intermittent irrigation decreases CH_4 fluxes by 65% compared to flooding conditions [23]. Many studies have investigated the effects of fertilizer and water management on GHG emissions from rice fields [21–23]. However, only a limited amount of research has examined the impact of various rice cultivars on these emissions. Therefore, our research aims to identify how rice varieties and environmental factors are related to the effect of AWD on reducing GHG emissions.

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was conducted in the lysimeter facility at Meiji University, Kawasaki, Kanagawa, Japan (latitude: 35°61′ N, longitude: 139°54′ E) from May to September 2022. The facility had six lysimeters, each measuring 4 m^2 (2 m × 2 m). Furthermore, the area was sheltered by a transparent roof that remained closed throughout the entire season. The soil's upper layer (0–0.35 m depth) and lower layer (0.35–1.75 m depth) were low-humic Andosol and Kanto loam, respectively. The drainage pipes were installed at the bottom and between the soil layers every 0.4 m to drain water and control water levels.

A 2 × 2 factorial experiment was arranged in a split-plot design with two water management practices as the main plots (AWD irrigation regime and CF irrigation regime) and two rice varieties as the sub-plots (lowland variety (Oryza Sativa, Temp. Japonica Group, cultivar Koshihikari (KH)) and upland variety (Oryza Sativa, Trop. Japonica Group, cultivar Dourado Precoce (DP)) (Figure 1a,b), with three replications. The growth duration of KH and DP varieties is 110 and 119 days, respectively. Additionally, the average yield of KH is 5.1 ton ha^{-1}, while that of DP is 4.1 ton ha^{-1} [24,25]. Water was flooded and kept to a 2–6 cm depth 15 days after sowing (DAS) for AWD and CF treatments. In the AWD treatment, a repeat cycle of drying the soil to −40 kPa soil matric potential (SMP) measured with a tensiometer at 10 cm depth and wetting the soil to 0 kPa SMP was started at 45 DAS until final drainage. Additionally, the CF treatment flooding depth was increased to 6–8 cm after 65 DAS.

Rice straw, farmyard manure (10 ton ha^{-1}), and fertilizer ($N:P_2O_5:K_2O$ = 60:60:60 kg ha^{-1}) were applied and plowed into the soil on 11 May 2022. Rice seeds were soaked in water for four days at a temperature of 25 °C before sowing at a spacing of 25 cm × 25 cm on 13 May 2022. Note that the rice crop was harvested on 30 September 2022.

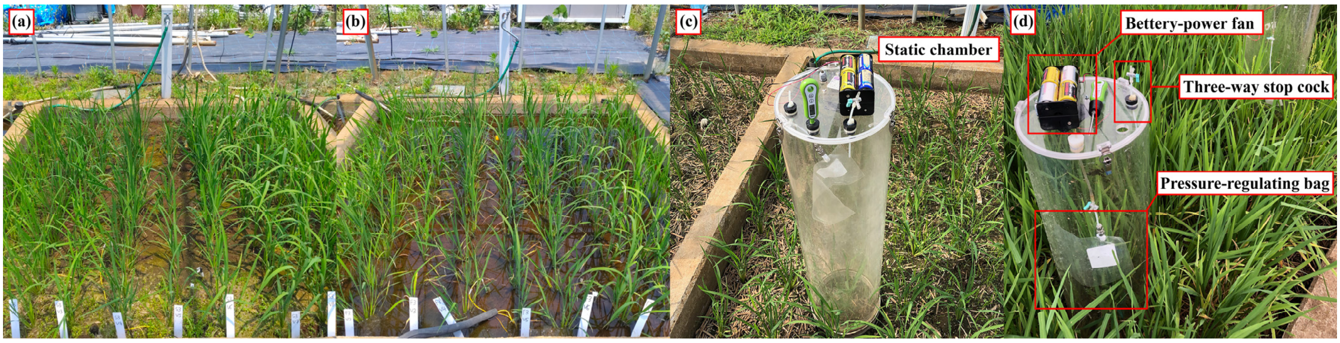

Figure 1. Experiment plots under (**a**) alternate wetting and drying (AWD) irrigation regime, (**b**) continuous flooding (CF) irrigation regime, (**c**) static chamber, and (**d**) equipment.

2.2. Gas Sampling and Analysis

The static chamber method measured the CH_4, N_2O, and CO_2 gas emissions [26]. Transparent cylindrical chambers (24 cm diameter × 110 cm height) were utilized to collect the gas sample (Figure 1c,d). A battery-powered fan was put at the top of each chamber to circulate the air in the chamber. In addition to that, a pressure-regulating bag was installed on each chamber lid to avoid pressure change. The gas samples were collected between 10:00 a.m. and 11:30 a.m. at 60, 68, 70, 77, 80, 82, 103, 110, and 111 DAS, representing three cycles of −20, −40, and 0 kPa SMP. A 50 mL syringe was used to take gas samples at 0, 10, 20, and 30 min from a three-way stop cock fixed in the chamber lid. The samples were immediately transferred into 20 mL evacuated glass vials for laboratory analysis. Consequently, the concentrations of gas samples were analyzed using a gas chromatograph (Agilent Technologies 6890N, Santa Clara, CA, USA) with a flame ionization detector (FID) for CH_4 and CO_2 and an electron capture detector (ECD) for N_2O.

2.3. Estimation of Greenhouse Gas Emissions and Cumulative Emissions

Gas emissions were calculated from the slope of the linear regression changes in CH_4, N_2O, or CO_2 concentrations with time [27]. Subsequently, the gas flux was calculated using the following equation [28,29]:

$$F = \rho \times \left(h \times \frac{\Delta C}{\Delta t} \times \frac{273}{T} \right) \tag{1}$$

where F is the gas flux (mg m^{-2} h^{-1}), ρ is the gas density (mg m^{-3}), h is the height inside the chamber (m), $\Delta C/\Delta t$ is the change in gas concentration with time (m^3 m^{-3} h^{-1}), and T is the mean temperature of the air inside the chamber (K). After that, the trapezoidal rule was used to interpolate and integrate the fluxes across time for each sampling date. The cumulative flux was determined by calculating and adding the area of each trapezoidal from 60 to 111 DAS [22,27].

2.4. Estimation of Global Warming Potential

GWP measures the impact of GHG on radiative forcing compared to CO_2 over a specific period. The GWP of CH_4 and N_2O on a 100-year time horizon was calculated using the following equation [30,31]:

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}) = (\text{TCH}_4 \times 28) + (\text{TN}_2\text{O} \times 265) \tag{2}$$

where TCH_4 is the total amount of CH_4 emission (kg h^{-1}), TN_2O is the total amount of N_2O emission (kg h^{-1}), and 28 and 265 are the GWP values for CH_4 and N_2O, respectively.

2.5. Other Data Acquired

Soil redox potential (Eh) was measured using Pt-tipped electrode sensors (PRN-40, Fujiwara Scientific, Tokyo, Japan) buried at 0.1 m depth. On the other hand, volumetric water content (VWC) and soil temperature (Ts) were measured at 0.05 m depth in each plot using soil moisture and temperature sensors (GS3, METER Group Inc., Pullman, WA, USA). An Em50 data logger (METER Group Inc., Pullman, WA, USA) and a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA) were used to collect sensor data.

2.6. Statistical Analysis

Two-way analysis of variance (two-way ANOVA) of CH_4, N_2O, and CO_2 emissions, and the total emissions of CH_4 and N_2O, and GWP were conducted with SPSS software, version 29 (IBM, Armonk, NY, USA). A least significant difference (LSD) test was conducted to analyze the mean difference of the treatments at a 95% confidence level. Consequently, the relationship between GHG emissions and environmental parameters such as Eh, VWC, and Ts were investigated using linear regression analysis.

3. Results

3.1. Seasonal Variation of Soil Redox Potential, Volumetric Water Content, and Temperature

The seasonal variations of Eh, VWC, and Ts are displayed in Figure 2. Figure 2a illustrates that Eh values decreased after flooding water 15 DAS in the AWD and CF irrigation schemes. Subsequently, the Eh remained between −300 and −600 mV until harvest under the CF irrigation. In contrast, under the AWD irrigation, the Eh increased and remained stable at 200–400 mV after beginning the wetting and drying cycle 45 DAS. This was due to the Eh measurement point being too far from the irrigation area. The VWC under CF irrigation remained between 49 and 53% after flooding water (Figure 2b). Conversely, five wetting and drying cycles were carried out under AWD irrigation and the lowest VWC was 34.19%. The Ts were comparable for the AWD and CF treatments (Figure 2c).

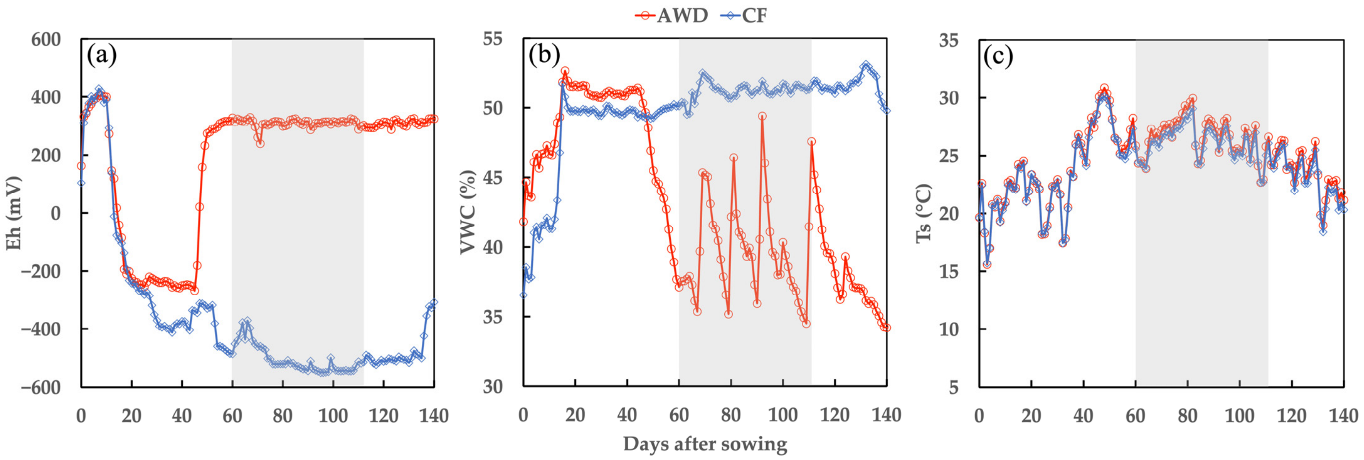

Figure 2. Seasonal variation of (**a**) soil redox potential (Eh), (**b**) volumetric water content (VWC), and (**c**) soil temperature (Ts) under alternate wetting and drying (AWD) and continuous flooding (CF) irrigation regimes. The shaded area indicates the gas measurement period.

3.2. Dynamic of CH_4 Emissions

CH_4 emissions were significantly more profound between irrigation regimes than rice varieties (Figure 3a,b). During the measurement period, the emission rates ranged from −84.99 to 67.49 mg m^{-2} d^{-1} under AWD irrigation and 29.00 to 243.40 mg m^{-2} d^{-1} under CF irrigation in the lowland variety (KH). These ranged from −46.31 to 57.46 mg m^{-2} d^{-1} under AWD irrigation and 3.89 to 255.95 mg m^{-2} d^{-1} under CF irrigation in the upland variety (DP). Correspondingly, the emission peaks under CF irrigation were discovered

77 and 82 DAS in KH and DP, respectively. The CH_4 emission rates under CF irrigation were significantly higher than those under AWD irrigation from 68 to 111 DAS (Table 1, $p < 0.05$). However, CH_4 emission was not significantly affected by rice variety (Table 1). Significant correlations between CH_4 emission and Eh and VWC were discovered in both varieties (Figure 4a,b,d,e), while Ts was not significantly correlated with CH_4 emissions in either variety (Figure 4c,f). Negative and positive correlations were also observed between CH_4 emission and Eh and VWC, respectively (Figure 4), indicating that an increase in soil Eh or a decrease in VWC can reduce CH_4 emission.

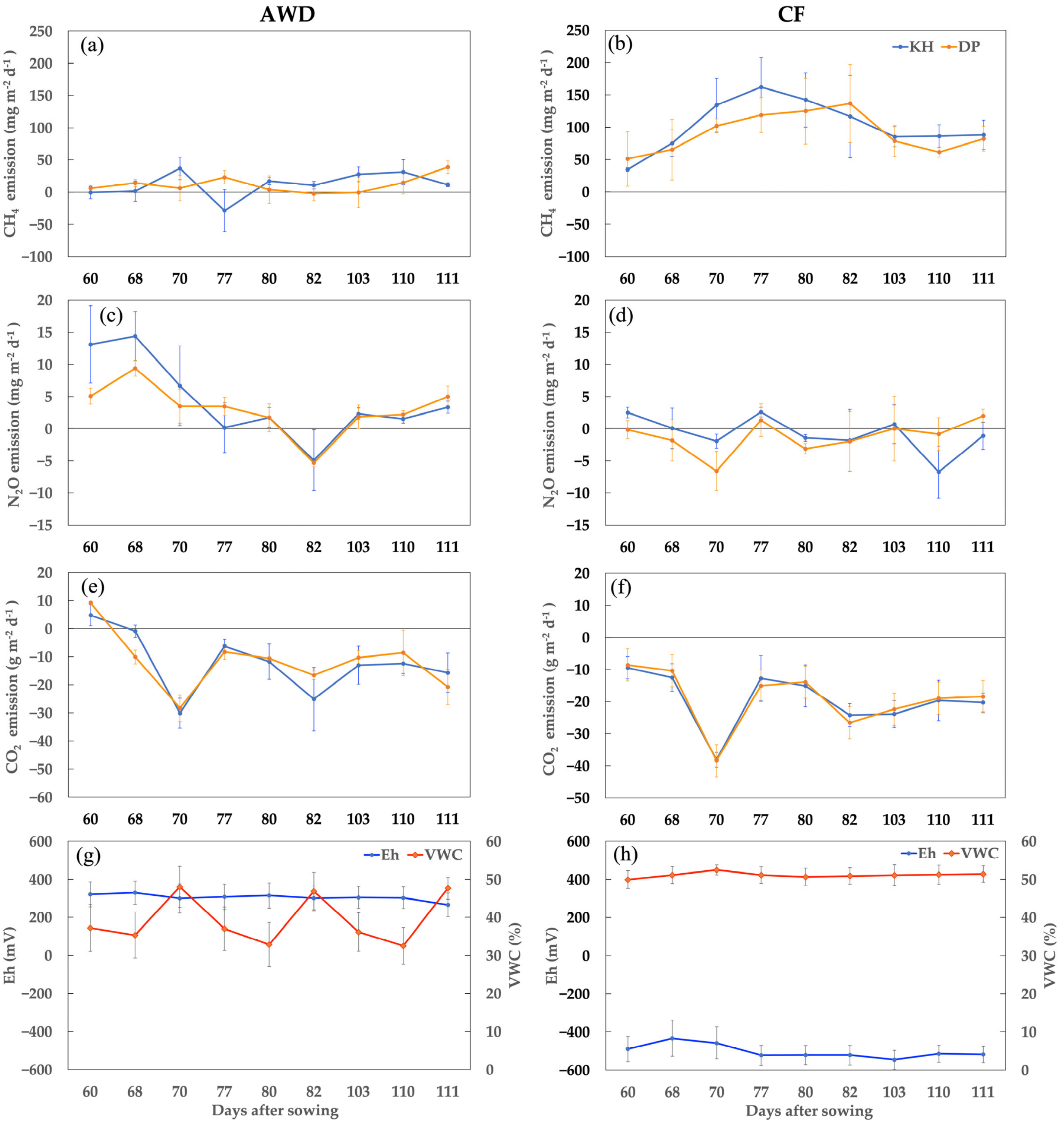

Figure 3. Methane (**a**,**b**), nitrous oxide (**c**,**d**), and carbon dioxide (**e**,**f**) emissions from lowland (Koshihikari, KH) and upland (Dourado Precoce, DP) varieties together with soil redox potential (Eh) and volumetric water content (VWC) under alternate wetting and drying (AWD) (**a**,**c**,**e**,**g**) and continuous flooding (CF) (**b**,**d**,**f**,**h**) irrigation regimes. Vertical bars indicate the standard error of the mean ($n = 3$).

Table 1. Effect of irrigation regimes and rice varieties on CH_4 emissions.

Varieties	**CH₄ Emission (mg m⁻² d⁻¹)**																	
	60 DAS		**68 DAS**		**70 DAS**		**77 DAS**		**80 DAS**		**82 DAS**		**103 DAS**		**110 DAS**		**111 DAS**	
	AWD	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**
KH	−0.5	34.5	1.6 ^{b}	75.3 ^{a}	36.7 ^{bc}	134.1 ^{a}	−28.6 ^{c}	162.1 ^{a}	17.3 ^{bc}	142.5 ^{a}	10.8 ^{b}	116.8 ^{a}	27.7 ^{ab}	85.4 ^{a}	31.1 ^{b}	86.5 ^{a}	11.4 ^{b}	88.2 ^{a}
DP	5.9	51.0	14.3 ^{b}	65.5 ^{a}	6.3 ^{c}	102.2 ^{ab}	23.1 ^{bc}	118.8 ^{ab}	4.0 ^{c}	125.0 ^{ab}	−2.3 ^{b}	136.7 ^{a}	−0.5 ^{b}	78.8 ^{a}	14.7 ^{b}	61.5 ^{a}	38.7 ^{ab}	82.4 ^{a}
ANOVA (p values)																		
I	ns		*		*		*		*		*		*		*		*	
V	ns		ns		ns		ns		ns		ns		ns		ns		ns	
I × V	ns		ns		ns		ns		ns		ns		ns		ns		ns	

Within a column, means followed by the same letters are not significantly different at a 5% level of significance. KH = Koshihikari (lowland variety); DP = Dourado Precoce (upland variety); AWD = alternate wetting and drying; CF = continuous flooding; I = irrigation; V = varieties; ANOVA = analysis of variance; * = significant; ns = non-significant.

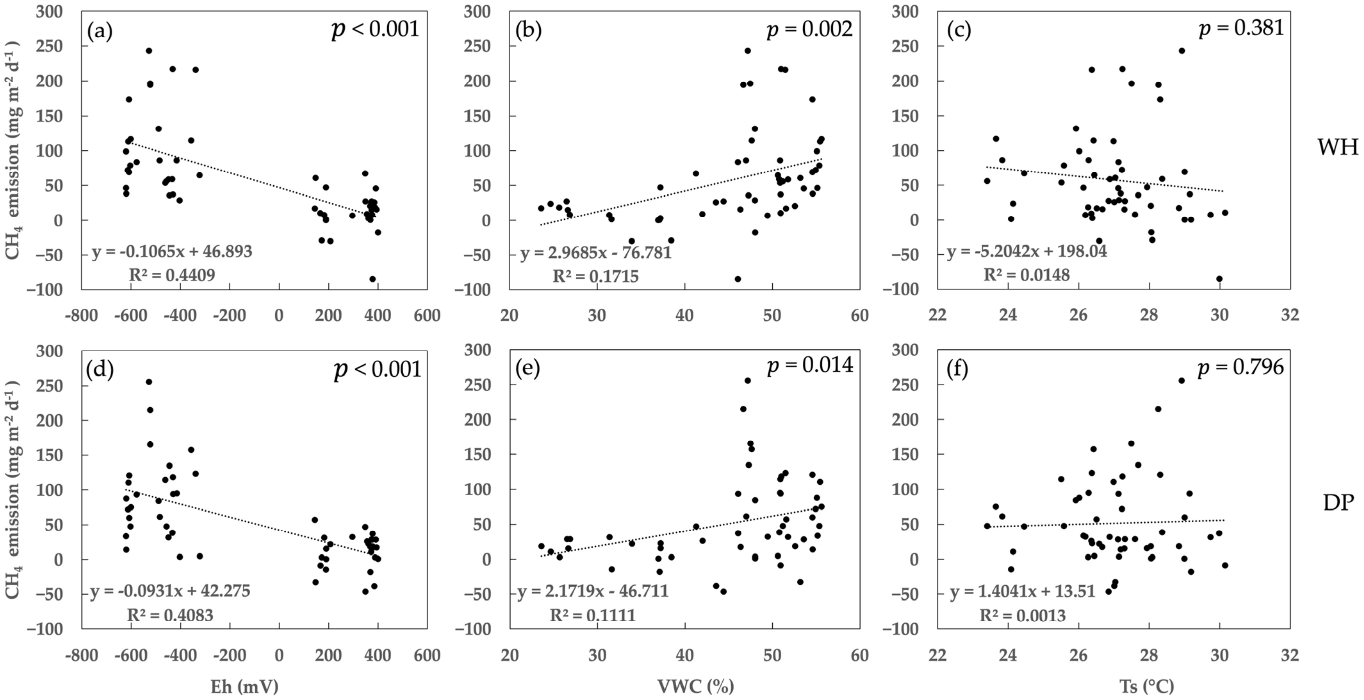

Figure 4. Relationship between methane (CH_4) emission and soil redox potential (Eh) (**a**,**d**), volumetric water content (VWC) (**b**,**e**), and soil temperature (Ts) (**c**,**f**) from lowland (Koshihikari, KH) (**a**–**c**) and upland (Dourado Precoce, DP) (**d**–**f**) varieties.

3.3. Dynamic of N_2O Emissions

N_2O emissions from two varieties under AWD and CF irrigation regimes are portrayed in Figure 3c,d. In the KH variety, the emission rates under AWD irrigation ranged from -14.22 to 22.84 mg m^{-2} $d^{-1,}$ while under CF irrigation, they ranged from -12.27 to 6.71 mg m^{-2} d^{-1}. On the other hand, in the DP variety, the emission rates ranged from -6.38 to 11.52 mg m^{-2} d^{-1} under AWD irrigation and -11.57 to 7.40 mg m^{-2} d^{-1} under CF irrigation. The N_2O emission peaks under AWD irrigation were discovered after the first draining period, while the highest peaks were discovered 68 DAS in both varieties. Note that the N_2O emission rates under CF irrigation were significantly lower than those under AWD irrigation 60, 68, 70, 80, 110, and 111 DAS (Table 2, $p < 0.05$). N_2O emissions were significantly correlated to Eh and VWC but not Ts for both varieties (Figure 5). Additionally, N_2O emission has a positive correlation with the soil Eh and a negative correlation with the

VWC. This means that if the soil Eh increases or the VWC decreases, there is a possibility that N_2O emission will increase.

Table 2. Effect of irrigation regimes and rice varieties on N_2O emissions.

Varieties	**N_2O Emission (mg m^{-2} d^{-1})**																	
	60 DAS		**68 DAS**		**70 DAS**		**77 DAS**		**80 DAS**		**82 DAS**		**103 DAS**		**110 DAS**		**111 DAS**	
	AWD	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**
KH	13.11 a	2.51 b	14.42 a	0.06 bc	6.66 a	−1.93 b	0.15	2.59	1.73 a	−1.42 b	−4.90	−1.81	2.31	0.70	1.53 a	−6.73 b	3.36 a	−1.11 b
DP	5.08 a	−0.17 b	9.39 ab	−1.82 c	3.51 a	−6.59 b	3.47	1.31	1.70 a	−3.12 b	−5.31	−1.97	1.85	0.01	2.19 a	−0.84 b	5.01 a	1.99 b
ANOVA (*p* values)																		
I	*		*		*		ns		*		ns		ns		*		*	
V	ns		ns		ns		ns		ns		ns		ns		ns		ns	
I × V	ns		ns		ns		ns		ns		ns		ns		ns		ns	

Within a column, means followed by the same letters are not significantly different at a 5% level of significance. KH = Koshihikari (lowland variety); DP = Dourado Precoce (upland variety); AWD = alternate wetting and drying; CF = continuous flooding; I = irrigation; V = varieties; ANOVA = analysis of variance; * = significant; ns = non-significant.

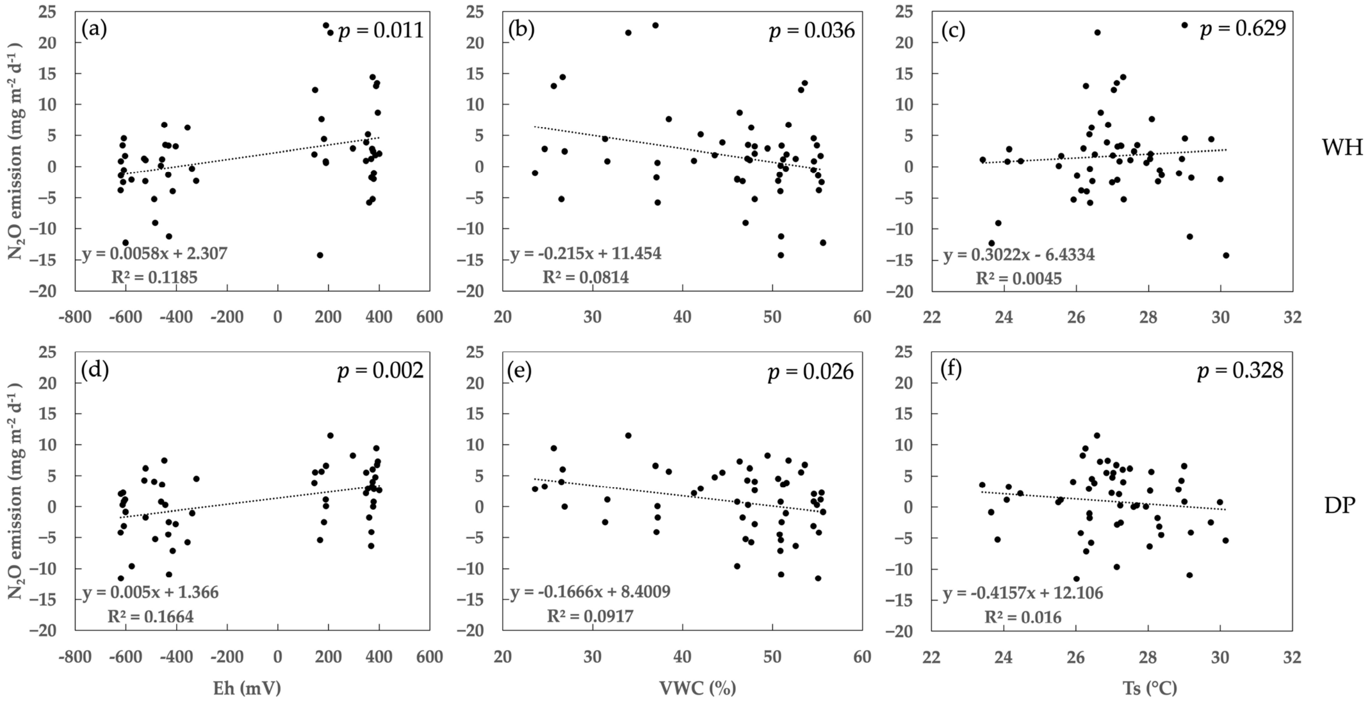

Figure 5. Relationship between nitrous oxide (N_2O) emission and soil redox potential (Eh) (**a**,**d**), volumetric water content (VWC) (**b**,**e**), and soil temperature (Ts) (**c**,**f**) from lowland (Koshihikari, KH) (**a**–**c**) and upland (Dourado Precoce, DP) (**d**–**f**) varieties.

3.4. Dynamic of CO_2 Emissions

CO_2 emissions from two varieties under AWD and CF irrigation regimes are displayed in Figure 3e,f. The emission rates ranged from −46.10 to 10.99 g m^{-2} d^{-1} under AWD irrigation and −42.52 to −3.21 g m^{-2} d^{-1} under CF irrigation for the KH variety. In comparison, these ranged from −36.30 to 10.13 g m^{-2} d^{-1} under AWD irrigation and −57.21 to −2.22 g m^{-2} d^{-1} under CF irrigation for the DP variety. Note that water management and rice variety did not significantly affect CO_2 emissions, except for 60 DAS. Table 3 indicates that emission rates under the AWD irrigation regime 60 DAS were significantly higher than those under the CF irrigation regime ($p < 0.05$). Significant and negative correlations were discovered between CO_2 emission and VWC, while no significant correlation was determined between CO_2 emission and Eh and Ts (Figure 6).

Table 3. Effect of irrigation regimes and rice varieties on CO_2 emissions.

Varieties	**CO_2 Emission (g m^{-2} d^{-1})**																	
	60 DAS		**68 DAS**		**70 DAS**		**77 DAS**		**80 DAS**		**82 DAS**		**103 DAS**		**110 DAS**		**111 DAS**	
	AWD	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**
KH	4.80 a	−9.47 b	−0.92	−12.50	−30.11	−38.13	−6.30	−12.79	−11.78	−15.11	−25.12	−24.22	−13.00	−23.88	−12.41	−19.65	−15.68	−20.30
DP	9.24 a	−8.61 b	−10.11	−10.39	−28.35	−38.44	−8.28	−15.08	−10.64	−13.94	−16.60	−26.59	−10.31	−22.41	−8.59	−18.98	−20.76	−18.48
ANOVA (*p* values)																		
I	*		ns		ns		ns		ns		ns		ns		ns		ns	
V	ns		ns		ns		ns		ns		ns		ns		ns		ns	
I × V	ns		ns		ns		ns		ns		ns		ns		ns		ns	

Within a column, means followed by the same letters are not significantly different at a 5% level of significance. KH = Koshihikari (lowland variety); DP = Dourado Precoce (upland variety); AWD = alternate wetting and drying; CF = continuous flooding; I = irrigation; V = varieties; ANOVA = analysis of variance; * = significant; ns = non-significant.

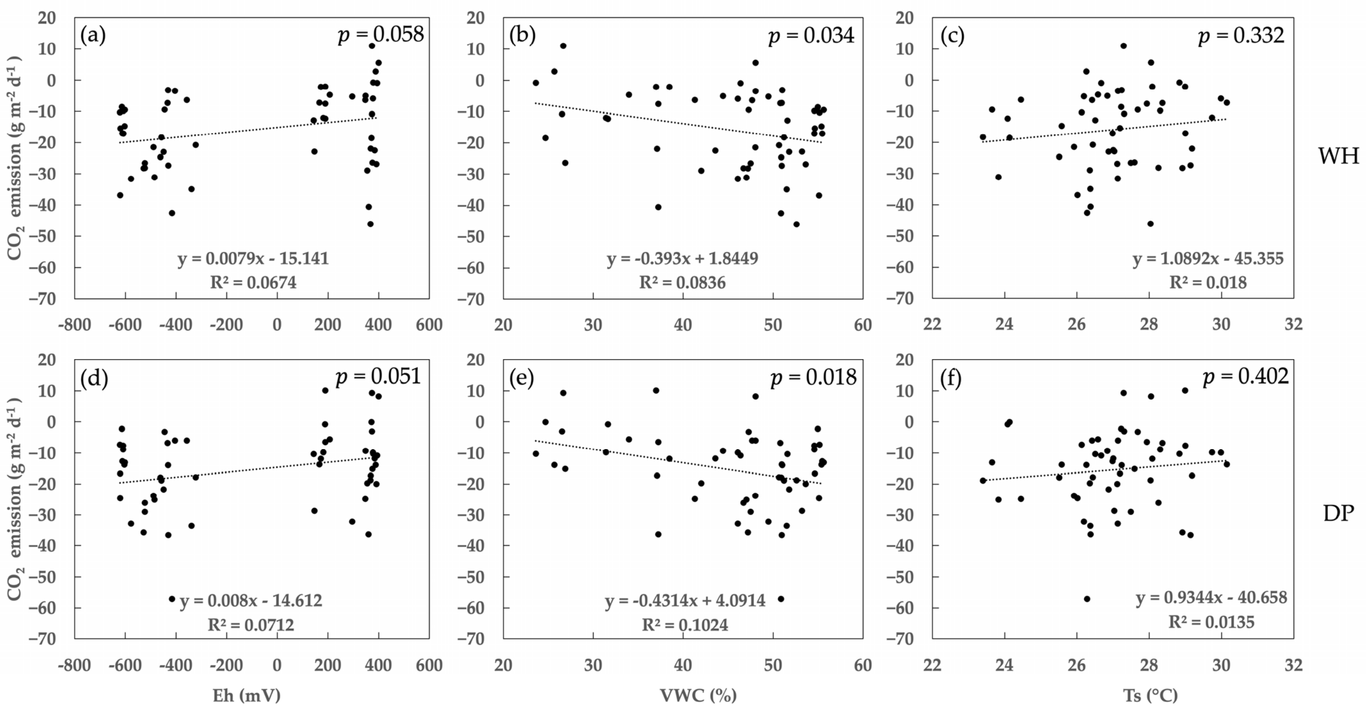

Figure 6. Relationship between carbon dioxide (CO_2) emission and soil redox potential (Eh) (**a**,**d**), volumetric water content (VWC) (**b**,**e**), and soil temperature (Ts) (**c**,**f**) from lowland (Koshihikari, KH) (**a**–**c**) and upland (Dourado Precoce, DP) (**d**–**f**) varieties.

3.5. *Cumulative CH_4 and N_2O Emissions, and GWP*

Water management had significant ($p < 0.05$) effects on the cumulative CH_4 and N_2O emissions and GWP (Table 4). However, rice variety did not significantly affect these emissions and GWP. The cumulative CH_4 emissions were significantly lower under the AWD irrigation regime than the CF irrigation regime in both varieties (Table 4). Note that the highest CH_4 emission was discovered in the lowland variety (KH) under CF irrigation, while the lowest emission was discovered in the upland variety (DP) under AWD irrigation. Conversely, AWD irrigation significantly increased cumulative N_2O emissions compared to CF irrigation (Table 4). The N_2O emission was observed to be the highest in the lowland variety under AWD irrigation, whereas the lowest emission was observed in the lowland variety under CF irrigation. AWD irrigation significantly decreased the GWP in the lowland and upland varieties, with a remarkable reduction of 55.6% and 59.6%, respectively, compared to CF irrigation.

Table 4. Effect of irrigation regimes and rice varieties on cumulative CH_4 and N_2O emissions, and GWP.

Varieties	Water Management	CH_4 (kg ha^{-1})		N_2O (g ha^{-1})		GWP (kg CO_2 Equivalent ha^{-1})	
		AWD	CF	AWD	CF	AWD	CF
KH		8.79^{b}	64.94^{a}	1920.99^{a}	-436.64^{b}	755.24^{c}	1702.61^{a}
DP		8.55^{b}	60.56^{a}	1532.67^{a}	-367.06^{b}	645.49^{c}	1598.46^{b}
Effect of water management							
Mean	AWD	8.67^{b}		1726.83^{a}		700.37^{b}	
	CF	62.75^{a}		-401.85^{b}		1650.54^{a}	
ANOVA (p values)							
Irrigation (I)		*		*		*	
Varieties (V)		ns		ns		ns	
I × V		ns		ns		ns	

Within a column, means followed by the same letters are not significantly different at a 5% level of significance. KH = Koshihikari (lowland variety); DP = Dourado Precoce (upland variety); AWD = alternate wetting and drying; CF = continuous flooding; ANOVA = analysis of variance; * = significant; ns = non-significant.

4. Discussion

4.1. Dynamic of CH_4, N_2O, and CO_2 Emissions

The CH_4 emission rates under the CF irrigation regime increase with rice growth once flooding begins and soil Eh drops below −150 mV [32]. The highest emissions occur during the reproductive stage (65–100 DAS), and the emissions slightly decrease during the ripening stage (100–140 DAS) [23,33,34]. AWD irrigation reduces CH_4 emissions compared to CF irrigation (Figure 3a,b), as observed in previous studies [15,22,31,35,36]. Consequently, the increase in oxygen supply during dry periods under AWD irrigation creates an aerobic soil environment where methanotrophs can oxidize CH_4, which is linked to a decrease in CH_4 emission. Conversely, CF irrigation maintains anoxic soil conditions (soil Eh less than −150 mV), promoting anaerobic microbial decomposition of organic matter and increasing CH_4 emissions [32]. In comparison to emissions from tropical areas, both AWD and CF irrigation exhibited low CH_4 fluxes, which is consistent with findings from previous studies conducted in Japan [4,31]. The CH_4 emissions were not substantially affected by the rice varieties tested (Table 1). This result differs from other studies in which rice varieties significantly affect CH_4 emissions [22,37]. Another study discovered similarities in the CH_4 emissions of different rice varieties and discovered that the varieties with more shoot biomass had lower CH_4 emissions due to their higher CH_4 oxidation potential [38]. Furthermore, it is possible that the Japonica cultivar group under investigation in this study has comparable shoot and root biomass, which could lead to a slight variation in CH_4 emissions. However, the upland variety (DP) did have slightly lower emissions than the lowland variety (KH) (Figure 3a,b). As reported by previous studies, soil Eh and VWC are essential factors that significantly correlate with CH_4 emissions (Figure 4) [38]. Moreover, these factors directly influence the oxidation state of the soil, which impacts methanogenic activity and CH_4 emissions. Although previous findings have indicated a high correlation between Ts and CH_4 emission [39,40], this study only revealed a low correlation (Figure 4c,f). This result may have been caused by a slight variation in Ts resulting from measurements taken at the same time of day.

The N_2O emission peaks after fertilization and the first drying period under AWD irrigation were observed in both varieties (Figure 3c). Hence, these findings align with previous research indicating that N_2O emissions occur sporadically and are linked to specific events such as fertilizer application and wet–dry cycles [15,16,41–44]. The emission rates of N_2O were considerably higher under the AWD irrigation regime than the CF irrigation regime (Figure 3c,d), as reported by previous studies [15,31,41]. According to the availability of oxygen, the alternate oxic and anoxic conditions may have accelerated the nitrification and subsequent denitrification processes, resulting in larger N_2O emissions under AWD irrigation than CF irrigation, which reduces N_2O to N_2 by denitrification [15,16,45]. Note that the rice varieties did not noticeably affect N_2O emissions (Table 2), which aligns with previous research [38]. However, some studies have discovered differences in N_2O emissions between rice varieties, which can be caused by root exudate [38]. Other than that, nitrification and denitrification of inorganic nutrients in the presence of root exudates led to increased N_2O emissions. Previous studies determined that nitrification influenced N_2O production when the Eh values ranged between 350 and 400 mV [46]. Therefore, a positive and a negative linear correlation were discovered between N_2O emissions and soil Eh and VWC (Figure 5), respectively. N_2O emissions were observed without correlation with Ts (Figure 5c,f). Thus, this study's findings are inconsistent with other research [47,48], caused by low variation in Ts.

The CO_2 uptakes under AWD irrigation were discovered 60 DAS (Figure 3e), which may be caused by rice straw decomposition [49]. At this stage, the rice plants are still small, and the capturing of CO_2 by the plant may have a minimal impact on regulating emissions. Later in the season, it was observed that all plots acted as CO_2 sinks (negative flux) during the measurement period of 10:00–11:30 a.m. This was due to increased plant photosynthesis during the daytime. Additionally, it was discovered that there were no significant effects of water management regimes and rice varieties on CO_2 emissions (Table 3). Note that the CO_2 fluxes suggested a distinct seasonal trend, with more negative values (uptake) observed as the rice plants entered the reproductive stage and a slight decrease in CO_2 fluxes as the plants entered the ripening stage (Figure 3e,f). These results are consistent with other studies [9,50]. Figure 6 displays that soil Eh has a low correlation with CO_2 emission, whereas VWC and CO_2 emission have a significant correlation, as reported in previous research [46]. In addition, VWC is a key indicator for analyzing and predicting GHG emissions from soil in various models such as $SoilCO_2$, CASA, and DNDC. This study revealed no correlation between CO_2 emissions and Ts (Figure 6c,f), as low variation in Ts was observed during GHG measurement. Therefore, these findings differ from those in previous studies, demonstrating substantial correlations between CO_2 fluxes and Ts and suggesting that the rates of CO_2 emissions increased exponentially as Ts increased [40,51].

4.2. Cumulative CH_4 and N_2O Emissions, and GWP

The water management practices significantly affected cumulative CH_4 and N_2O emissions and GWP in paddy fields, while the effect of rice varieties was not discovered (Table 4). AWD irrigation significantly reduces CH_4 emissions but also significantly increases N_2O emissions compared to the CF irrigation method [15,31,37,52]. Furthermore, significant O_2 availability during the unflooded stage can also lower CH_4 emissions by promoting CH_4 oxidation [53]. Early CH_4 emissions in rice systems are frequently allocated to the decomposition of previous crop residues, but emissions in the latter season are generally attributed to carbon generated from roots [54]. Moreover, continuously flooded anoxic rice fields typically have low N_2O emissions as the majority of the produced N_2O is further reduced and released as N_2 [17]. On the other hand, AWD irrigation creates the ideal environment for nitrification and subsequent denitrification upon adding water, which can release N_2O gas [53]. Therefore, a tradeoff relationship between CH_4 and N_2O emissions has been discovered through water management [15,31].

In this study, AWD irrigation led to a significant decrease in GWP of 58% compared to CF irrigation, where CH_4 was the main factor responsible for GWP in paddy fields [15,18]. Tariq et al. [18] discovered that CH_4 has a higher impact on GWP than N_2O, contributing over 95% of the total GWP. In the present study, on average, CH_4 was responsible for 78% of the total GWP. The rice cultivars used in this experiment are all from the Japonica group, but KH and DP are from the temperate and tropical Japonica varieties, respectively. Therefore, the difference in cumulative CH_4 and N_2O emissions and GWP was not discovered between rice varieties (Table 4). The result aligns with previous research [38] but varies from other findings [22,55]. Simmonds et al. [38] discovered a few statistical differences in GWP between several rice varieties, exhibiting the potential for breeding low GWP rice cultivars. Additionally, the results in this study only reflect the emissions that occurred during the measurement period rather than across the entire cropping season.

5. Conclusions

This study reveals that AWD irrigation in paddy fields instead of CF irrigation could reduce CH_4 emissions. However, the total N_2O emissions under AWD irrigation were higher than those under CF irrigation. As a result, irrigation schemes have demonstrated the tradeoff relationship between CH_4 and N_2O emissions. Since CH_4 is the main contributor to GWP in paddy fields, AWD irrigation reduced GWP by 55.6% in KH and 59.6% in DP compared to CF irrigation. By comparing rice varieties, our results indicated no significant difference in the emissions of CH_4 and N_2O, as well as the GWP, between KH and DP. In addition, the emissions calculated only represent the measurement period rather than the entire cropping season. These results indicate that water management practice is essential for mitigating GHG emissions from paddy fields in central Japan. Therefore, farmers and policymakers can both benefit from carbon credits and improved food security. Nevertheless, further research is needed to explore the potential for breeding rice cultivars with low GWP and mitigating GHG emissions or comparing GHG emissions between the Japonica and Indica groups. Moreover, our finding suggested that soil Eh and VWC significantly correlate with CH_4 and N_2O emissions, while only VWC influences CO_2 emissions. The relationship between Ts and GHG emissions could not be established since the measurements were taken simultaneously, resulting in only slight variations in Ts. Hence, these correlations help construct models for GHG forecasts in further research.

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