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Effect of Alternate Wetting and Drying on the Emission of Greenhouse Gases from Rice Fields on the Northern Coast of Peru

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Abstract: The cultivation of rice is one of the main sources of greenhouse gas (GHG) emissions due to continuously flooded irrigation (CF), which demands large volumes of water. As an alternative solution, alternate wetting and drying (AWD) irrigation has been developed as a water-saving strategy. This study was conducted at the Experimental Agricultural Station (EEA) in Vista, Florida, in the Lambayeque region located on the northern coast of Peru. Thus, it was analyzed the effect of AWD irrigation at different depths (5, 10, and less than 20 cm below the surface) compared to CF control on methane (CH_4) and nitrous oxide (N_2O) emissions and rice grain yield. AWD treatments reduced CH_4 emissions by 84% to 99% but increased N_2O emissions by 66% to 273%. In terms of Global Warming Potential (GWP), the AWD_{10} treatment demonstrated a 77% reduction and a Water Use Efficiency (WUE) of 0.96, affecting only a 2% decrease in rice grain yield, which ranged between 11.85 and 14.01 t ha^{-1}. Likewise, this study provides sufficient evidence for the adoption of AWD irrigation as a strategy for the efficient use of water resources and the mitigation of GHG emissions in rice cultivation in the study area, compared to continuous flooded irrigation.

Keywords: global warming potential; water management; grain yield

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1. Introduction

Rice is a fundamental food source for over 60% of the global population [1]. Currently, it is cultivated on approximately 153 Mha, which is equivalent to 11% of the world's arable land [2]. With the increasing global population, the demand for rice is estimated to rise by 56% by the year 2050 compared to the production level of 25.1 million tons recorded in 2001 [3]. Therefore, there is a need to increase rice production to meet this demand.

Rice cultivation is one of the major sources of greenhouse gas (GHG) emissions, such as methane (CH_4) and nitrous oxide (N_2O) [2]. These GHGs exert a significant influence on global warming, as they have warming potentials 28 and 273 times higher than that of carbon dioxide (CO_2), respectively [4].

The irrigation system used in rice fields, the choice of varieties, and fertilizer management have a significant impact on these emissions from rice fields [5]. Traditional irrigation methods, such as continuous flooding (CF), not only lead to the loss of water and nitrogen resources but also turn rice fields into a significant source of CH_4 [6]. On the other hand, good agricultural management practices and genetically improved rice varieties can reduce GHG emissions in fields by 20% to 50% [7].

Climate change will affect water availability in agriculture due to extreme events such as floods and damage to irrigation infrastructure [8]. This threatens food security in rice-producing countries, and adaptation strategies are required to maintain sustainable production [9].

In recent years, non-continuous flooding irrigation methods have been developed as a solution, reducing water use by up to 38% without affecting yield [10]. The Alternate Wetting and Drying (AWD) irrigation regimen stands out as one of the most studied and globally employed methods [5]. It involves cycles of wetting and drying the soil, leading to changes in soil moisture and redox conditions [5,6,11]. It has been proven that this irrigation regimen can reduce GHG emissions by up to 40%, as it decreases CH_4 emissions by enhancing aerobic processes in the soil during the drying period [10,11].

However, this reduction is offset by an increase in N_2O emissions in terms of GWP [11,12]. For example, Islam et al. [5] reported a 46% increase in cumulative seasonal N_2O emissions. Additionally, some studies claim that alternating between aerobic and anaerobic periods increases N_2O emissions through nitrification and denitrification processes, respectively [12–15].

Differences in soil textures, climate, and field management practices create controversy regarding this new irrigation regimen and its effects on GHG emissions [14,16]. For instance, Ariani et al. [14] compared GHG emissions under AWD between coarse (loamy sand) and fine (silty clay) soil textures. Meanwhile, Sha et al. [16] conducted their studies under the AWD regimen in a temperate monsoonal continental climate with an average annual temperature of 8 °C and average precipitation of 716 mm over a 3-year period. Another influencing factor is the drying depth threshold, as rice crop roots need to extract water for optimal yield and to avoid plant stress [12]. Therefore, it is important to generate information on greenhouse gas emissions in rice cultivation in different agroecological zones and irrigation management practices.

Field-level measurements will also help develop baseline data for studies in other rice fields with similar agroecological characteristics, soil types, and management practices. This will enable farmers, researchers, and policymakers to develop mitigation strategies and planning for climate-smart agriculture [17].

Therefore, this study focused on investigating CH_4 and N_2O emissions at three different AWD irrigation levels (5, 10, and greater than 20 cm depth) and their influence on grain yield compared to the conventional CF regimen. The specific objectives of the study were to (i) quantify CH_4 and N_2O emission flows, (ii) calculate the Global Warming Potential (GWP) and its relationship with the crop yield (YGWP), and (iii) determine the emission factors (EF) for CH_4 and N_2O.

2. Materials and Methods

2.1. Location and Experimental Design

The experiment was conducted from January to June 2023 at the Agricultural Experimental Station (EEA) Vista, Florida, of the National Institute of Agricultural Innovation (INIA) (06°43′34″ S, 79°46′44″ W, and an altitude of 35 m above sea level), at the tropical coastal agroecological zone located at km 8 on the Chiclayo to Ferreñafe road in the district of Picsi, province of Chiclayo, Lambayeque region. According to Köppen and Geiger, the climate is classified as arid and warm (BWh). It is important to highlight that despite the majority of the population in the study area being engaged in rice production and commercialization, the Lambayeque region is characterized by frequent droughts [18].

The experiment covered a total area of 1100 m^2, divided into four plots measuring 24 m in length and 11 m in width, with each plot further divided into three subplots (Figure 1). Different irrigation regimens were established in each plot, with the control plot using continuously flooded irrigation (CF) with a constant water depth of 5 cm until two weeks before harvest. The other plots used AWD_5, AWD_{10}, and AWD_{20} irrigation, corresponding to depths (H) of −5, −10, and ≤−20 cm, respectively. The reference point was the ground level relative to the soil surface based on the decline in water level. PVC perforated piezometers were installed 50 cm below the soil surface to control the flooding depth of the plots [6,19]. Irrigation water was sourced from the Tinajones reservoir and distributed through the main channel to the channels feeding the plots. An observational design with repeated measures was considered.

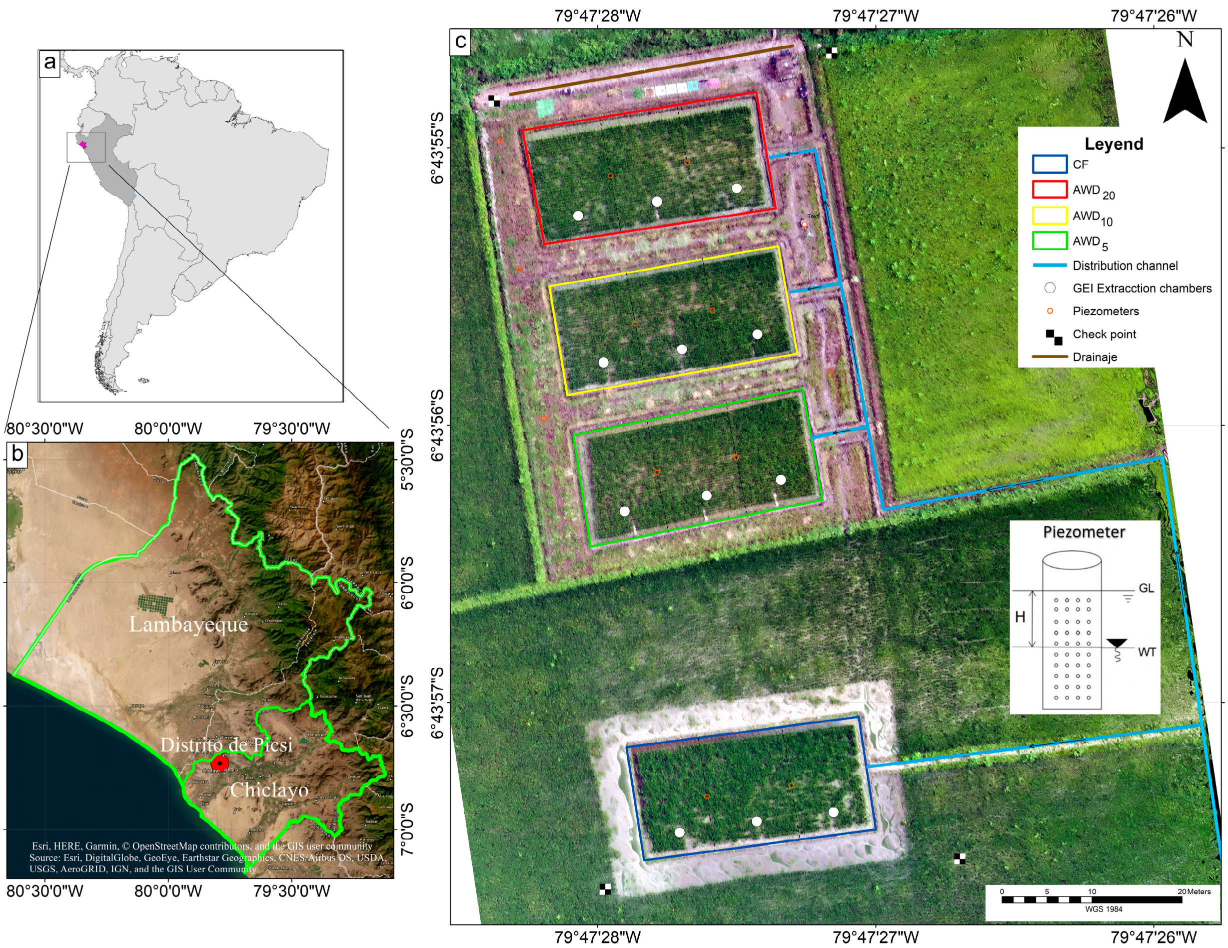

Figure 1. Location of the study area on the northern coast of Peru (**a**), Lambayeque region (**b**), Agricultural Experimental Station (EEA) INIA—Vista Florida, Lambayeque (**c**).

2.2. Meteorological Characterization

Meteorological data from the study area encompassed a series of key variables, including air temperature (Ta), relative humidity (HR), solar radiation (Rs), and wind speed (Vv). These data were recorded every minute using a portable automatic station (ATMOS 41, METER, Pullman, WA, USA) during the greenhouse gas (GHG) monitoring hour. Daily precipitation data (Pa) were recorded at the Vista Florida automatic weather station (SENAMHI) throughout the crop development (Figure 2).

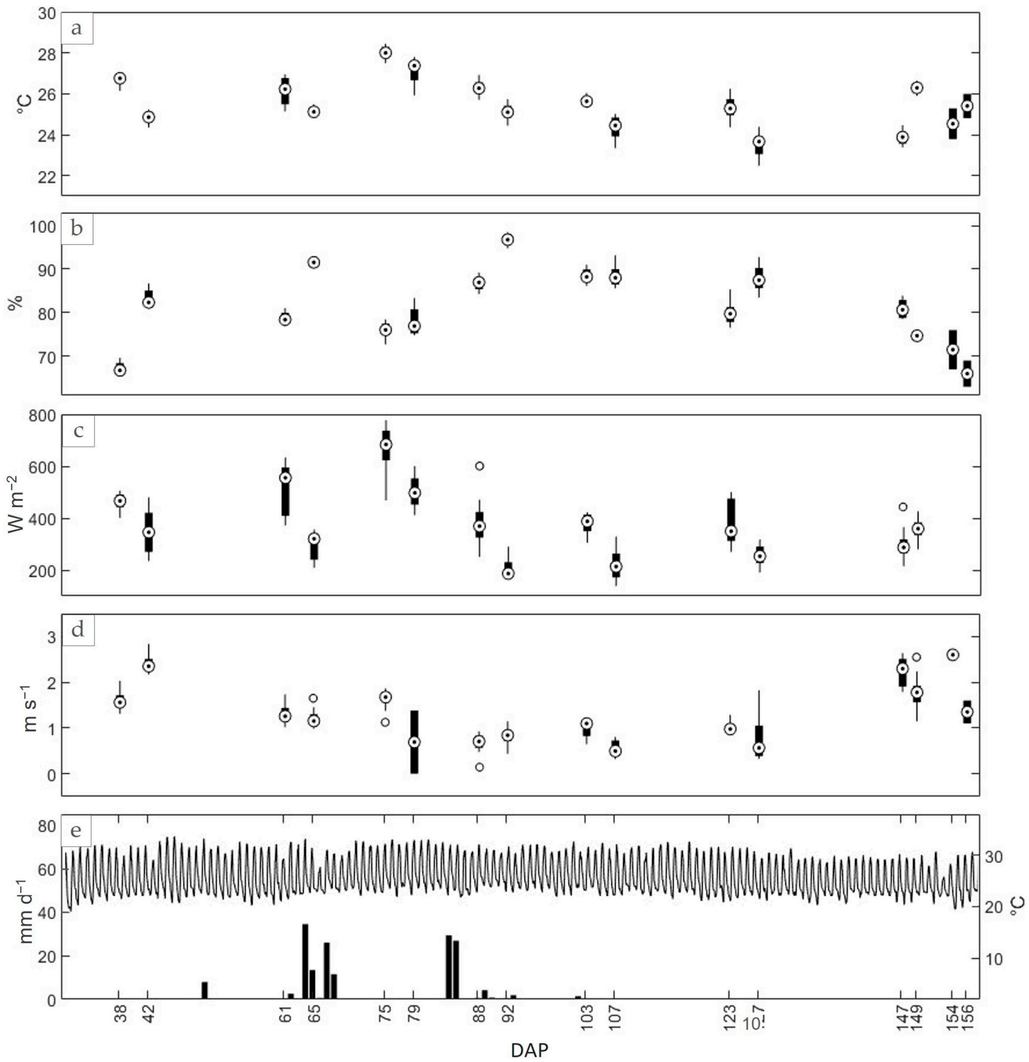

Figure 2. Variation in Ta (**a**), HR (**b**), Rs (**c**), and Vv (**d**) every five minutes during the monitoring hour with the portable automatic station. Daily variation in Ta and cumulative precipitation during crop development (**e**) with the Vista Florida SENAMHI automatic station.

2.3. Soil and Irrigation Water Characterization

The soil has a loamy sand texture (26% sand, 39% silt, 35% clay), electrical conductivity (EC) of 0.42 dS m^{-1}), pH of 7.64, cation exchange capacity (CEC) of 220 meq kg^{-1}, organic matter (OM) of 1.22%, total nitrogen (N) of 0.11% (N-NO of 14.01 ppm, N-NH_3 of 29.40 ppm), organic carbon of 0.71%, available sulfur of 3.76 ppm, bulk density (da) of 1.41 g cm^{-3} real density (dr) of 2.67 g cm^{-3}, porosity of 47.2%, field capacity (FC) of 29.76 cm^3 cm^{-3}, wilting point (WP) of 16.27 cm^3 cm^{-3}, $CaCO_3$ of 4.02%, P of 12 ppm, K of 376 ppm, exchangeable cations (Ca^{2+} de 180.5, Mg^{2+} de 28.1, Na^+ de 2.5, K^+ de 9.7) meq kg^{-1}, soluble B of 0.42 ppm, soluble gypsum of 0.01%, exchangeable sodium percentage (ESP) of 1.14, sodium adsorption ratio (SAR) of 0.08 meq L^{-1}, Pb of 14.82 ppm and Cr of 13.50 ppm.

The irrigation water has a pH of 7.34, EC of 0.31 dS m^{-1}, cations (Ca^{2+} of 1.91; Mg^{2+} of 0.43; Na^+ of 0.59; K^+ of 0.10) meq L^{-1}, anions (Cl^{-1} of 1.00; $HCO_3{}^{2-}$ of 1.89; $SO_4{}^{2-}$ of 0.29) meq L^{-1}. The irrigation water classification is C2-S1, indicating low sodium and salinity content, with a SAR of 0.55. All analyses were performed at the Soil, Plant, Water, and Fertilizer Analysis Laboratory of the Faculty of Agronomy—UNALM.

The water usage was measured using the volumetric method. To enhance precision, a water balance that included an account for cumulative precipitation, percolation, and crop evapotranspiration was used using the AquaCrop model [20]. The Penman-Monteith equation was employed, considering all parameters related to energy exchange and latent heat flux [21]. As shown in Table 1:

Table 1. Water balance in mm according to the different irrigation regimens.

Components	CF	AWD_5	AWD_{10}	AWD_{20}
Precipitation	164.6	164.6	164.6	164.6
Irrigation	1997	1428	1434	1447
Percolation	1723.3	1180.9	1206.9	1330.7
Evapotranspiration	738	722.6	717.3	729.9

Water Use Efficiency (WUE) is determined by the ratio of the grain yield to the irrigation volume.

2.4. Crop Management

The planting of the INIA 515—Capoteña variety was conducted in seedbeds on 2 January 2023. Thirty days after planting (DAP), two seedlings were transplanted per hill with a spacing of 0.25 × 0.25 cm. The cropping system at the experimental site was dominated by a seasonal rotation of rice and wheat; however, in the last season before the experiment, a rice seed harvest was conducted. After this harvest, the residues were burned and incorporated into the land preparation before transplanting. The fertilization dose was 250-120-50 in the form of urea, diammonium phosphate, and potassium sulfate, respectively (Figure 3). One hundred percent of P and K and 36% of N were applied at transplanting, while the remaining nitrogen fertilizer was distributed equally in the budding, tillering, and cotton setting stages [22].

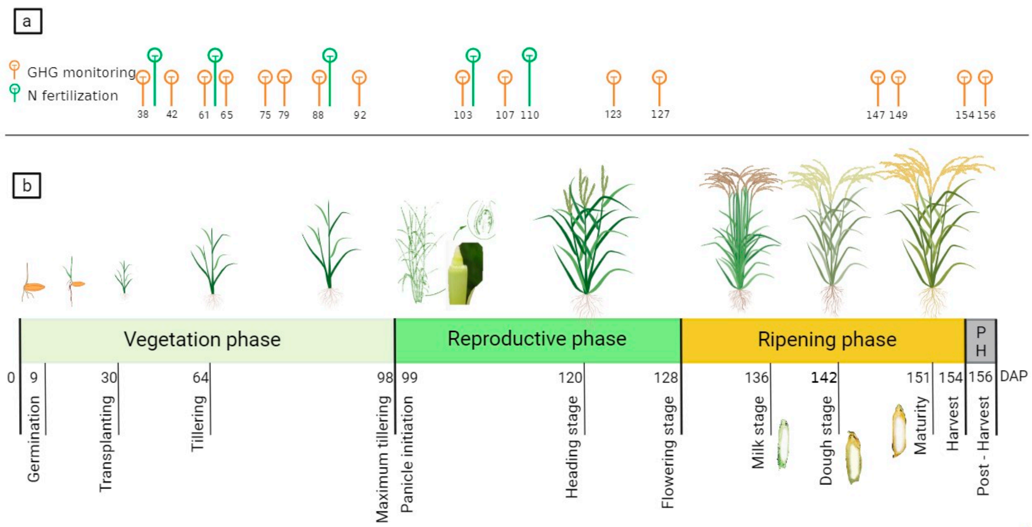

Figure 3. Greenhouse gas (GHG) monitoring and nitrogen fertilization (**a**), Crop phenology (**b**).

2.5. Sampling and Analysis of GHG

Gas samples were collected using the closed static chamber method to monitor CH_4 and N_2O emissions. The opaque polyethylene chamber consisted of a 30 cm tall base with a diameter of 43 cm, equipped with 5 cm diameter holes spaced at 22 cm intervals allowing water entry and exit. The base was hermetically sealed to the drum, which was 84 cm tall and 50 cm in diameter, through a hydraulic seal (Figure 4). A gas sampling connection was incorporated into one side of the drum, consisting of a silicone hose attached to a three-way valve connected to a 60 mL syringe for gas sample extraction. Additionally, a thermometer was installed at the top to measure the chamber's internal temperature [23]. To ensure homogeneous gas distribution during sample collection, a fan powered by a portable battery was installed inside [7,24–26].

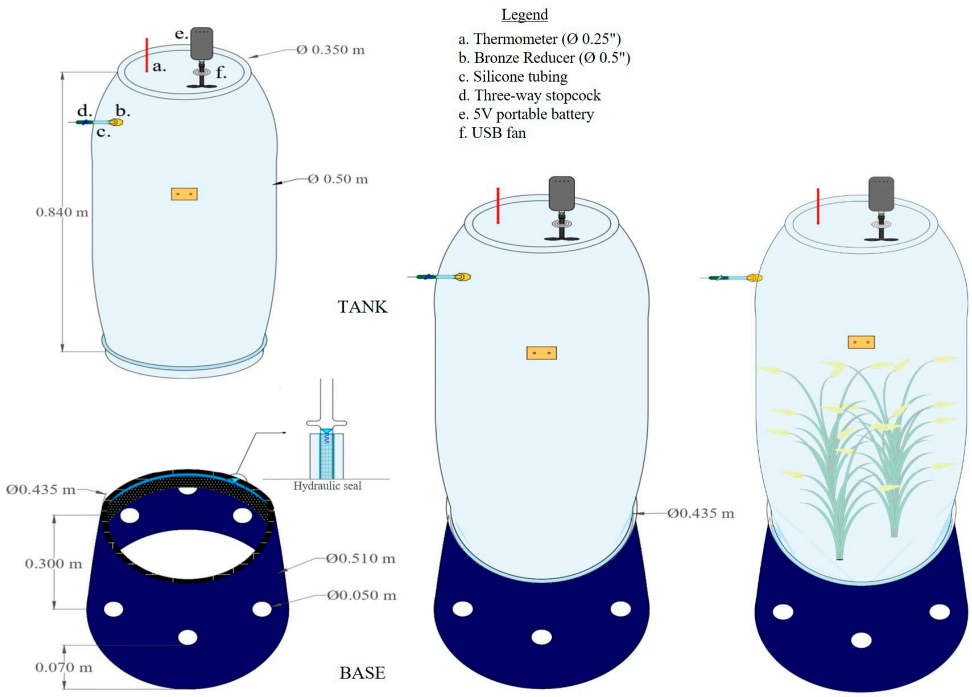

Figure 4. Diagram of the opaque closed static chamber.

Monitoring took place on the same day as nitrogen fertilization application, three days after it, and then every 15 days to assess changes in phenology and irrigation management. The sampling was carried out in the morning between 8:00 and 11:00 a.m., under clear skies. For each sampling date, samples were taken at 0, 20, 40, and 60 min [6]. Samples collected throughout the crop growth period were immediately transferred to empty 15 mL glass vials sealed with a rubber protector (EXETAINER, Labco Limited, Lampeter, UK) for later laboratory measurement.

GHG concentrations were measured using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan) equipped with flame ionization detectors (FID) for CH_4 and electron capture detectors (ECD) for N_2O at the Greenhouse Gas Laboratory (CIAT, Cali, Colombia) [23].

2.6. Correlation of Transparent and Opaque Chambers

Blocking light under opaque chambers during greenhouse gas (GHG) sampling can impact GHG production, transport, or emission processes [27]. Additionally, the absence of sunlight reduces plant photosynthetic capacity by causing complete or partial closure of stomata, thus limiting external CO_2 absorption by leaves [28]. As this effect has the potential to reduce GHG emission rates through plants, comparative measurements between transparent and opaque chambers were conducted. The aim was to establish a correction relationship through the correlation between GHG emissions measured in both chambers.

The transparent chamber consisted of a square metal base (area 0.26 m^2, height 0.15 m) permanently installed in the soil at a depth of 10 cm in each subplot (Figure 5. The 1 m tall chamber body was placed on the flange at the top of the base with a hydraulic seal [14]. The chamber was covered by a lid containing the connection for gas sample collection and the thermometer, like the opaque chamber. Inside, two fans connected to a portable battery were installed for air mixing [1,29].

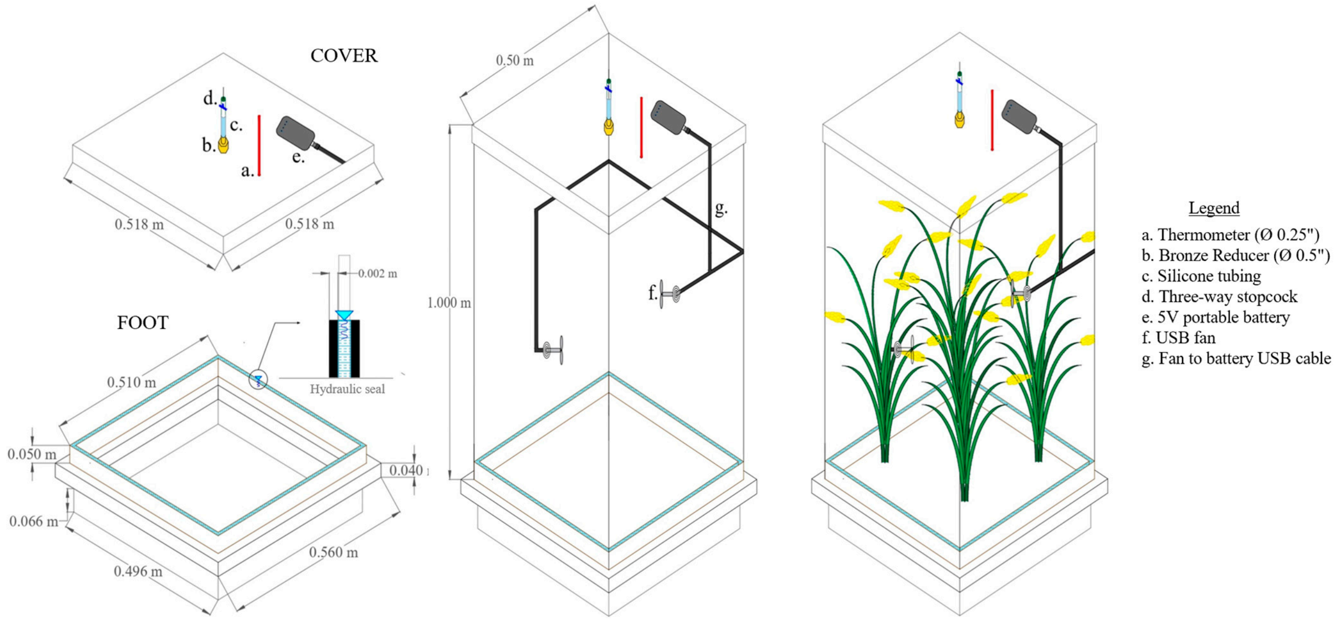

Figure 5. Diagram of the transparent closed static chamber.

A set of paired measurements with transparent and opaque chambers was carried out in three 2.5 m × 4.0 m plots installed in the Irrigation Experimental Area (AER), located within the campus of the National Agrarian University La Molina (12°00′05″ S, 76°57′06.5″ W, altitude 233 m above sea level) between November 2022 and May 2023 (Figure 6).

Figure 6. Closed static chambers in the field: transparent (**a**) and opaque (**b**).

The data gathered from both chambers was performed for the statistical analysis of normality and distribution. It was concluded that the distribution was non-parametric. Consequently, Box-Cox transformations were used to assess the necessary adjustments.

Pearson's R, for the relationship between chambers, for CH_4 and N_2O flux, was 0.823 and 0.693, respectively. Resulting in Equations (1) and (2):

$$Ln(CH_{4,o}) = 1.3796\ Ln(CH_{4,t}) + 1.1293 \tag{1}$$

where $CH_{4,o}$ is the CH_4; emission flux from the opaque chamber, and $CH_{4,t}$ is the CH_4 emission flux from the transparent chamber, both expressed in mg m^{-2} h^{-1}.

$$Ln(N_2O_{,o}) = 0.7723\ Ln(N_2O_{,t}) - 0.9227 \quad (2)$$

where $N_2O_{,o}$ is the N_2O emission flux from the opaque chamber, and $N_2O_{,t}$ is the N_2O emission flux from the transparent chamber, both expressed in mg m^{-2} h^{-1}.

2.7. Calculation of GHG Emissions

Emission fluxes were determined from the slope through linear regression, the concentration of CH_4 or N_2O against chamber closure time [13,30]. Then, the slope was converted to mass per unit area per unit time (mg m^{-2} h^{-1}) through Equation (3) [3,29]:

$$Emission\ rate\ of\ CH_4\ and\ N_2O = \frac{slope\ (ppm\ min - 1) \times P \times Vc \times MW \times 60}{R \times T_k \times Ac} \quad (3)$$

where P is pressure under normal conditions, Vc is the gas chamber volume in m^3, MW is the molecular weight of the respective gas, 60, min h^{-1}, R is the ideal gas constant 0.082057 in atm m^{-3} $kmol^{-1}K^{-1}$, T_k is the temperature inside the chamber expressed in Kelvin, and Ac is the chamber area in m^2.

Considering the results obtained in the correlation between the transparent and opaque chambers, the correction equation was applied to the calculated emission rate, using Equation (1) for CH_4 flux and Equation (2) for N_2O flux.

The *GWP* of CH_4 and N_2O was calculated with Equation (4):

$$GWP\ \left(kg\ CO_2\ equivalent\ ha^{-1}\right) = (TCH_4 \times 28 + TN_2O \times 273) \quad (4)$$

where TCH_4 is the total accumulated CH_4 emissions (kg ha^{-1}), TN_2O is the total accumulated N_2O emissions (kg ha^{-1}), and 28 and 273 are the *GWP* values for CH_4 and N_2O, respectively, relative to CO_2 over a 100-year horizon [4].

The yield-scaled global warming potential was calculated with the following Equation (5) [11]:

$$YGWP = \frac{PCG}{Yield} \quad (5)$$

where *YGWP* is the total GHG emissions per unit of grain yield (kg CO_2 eq kg^{-1} grain yield).

The scale factor for AWD was estimated by dividing cumulative AWD emissions by cumulative CF emissions [5].

The emission factor (EF) was estimated by dividing cumulative AWD emissions by the GHG measurement period.

2.8. Data Analysis

The normality of distribution and homogeneity of variances for each treatment were assessed using the Shapiro-Wilk test and the Bartlett test, respectively. The results indicated a non-normal distribution; therefore, an observational design with repeated measures using the non-parametric Kruskal-Wallis test was employed. Cumulative emissions, grain yield, GWP, YGWP, and EF of each treatment were compared with the control group (CF) using the Dunn test [31]. For the statistical calculations, R Studio software (v2023.06.1) was used. A significance level of α = 5% was considered.

3. Results

3.1. Methane CH_4 Emission Dynamics

The temporal variation of CH_4 throughout the experiment period, from the germination stage to post-harvest, is depicted (Figure 7). The magnitudes and trends of CH_4 emission flux varied with AWD treatments, crop growth phase, and meteorological conditions. An increase in emissions was observed during the tillering stage (61 and 65 DAS) under both AWD and CF irrigation regimens, with emissions ranging from 0.167 to 2.778 mg m^{-2} h^{-1}. This trend persisted for the CF condition, while there was a rapid decline for the AWD treatment (Table 2). A second increase in CH_4 emissions were observed during the flowering stage (103 and 107 DAS) under both AWD and CF irrigation regimens, with emissions ranging from 0.028 to 8.124 mg m^{-2} h^{-1}.

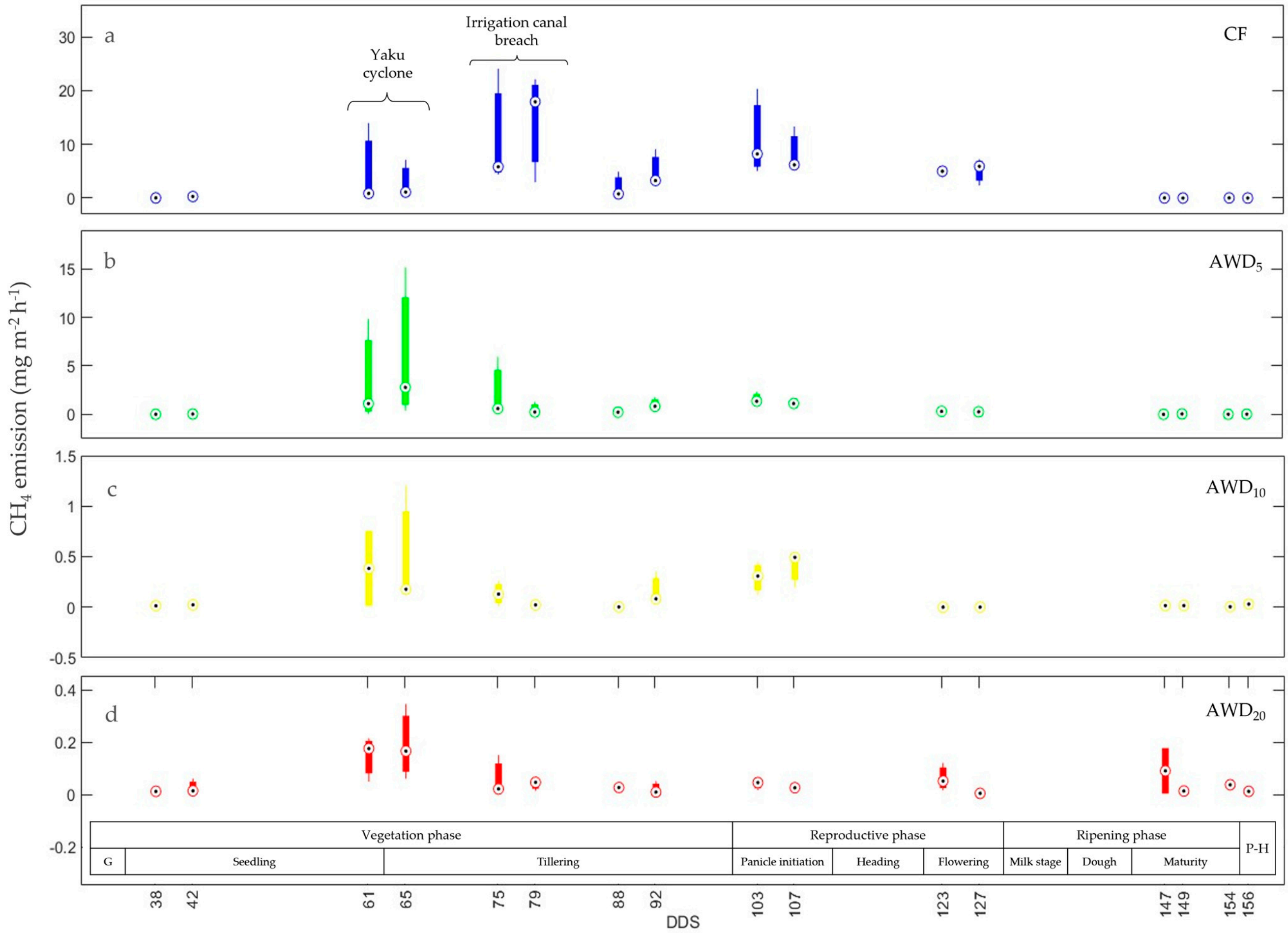

Figure 7. Temporal Variation of CH_4 Flux (mg m^{-2} h^{-1}) during the crop development under CF irrigation regimen (**a**), AWD_5 (**b**), AWD_{10} (**c**), and AWD_{20} (**d**).

The results indicate that CH_4 emissions under CF, ranging from 0.025 to 17.924 mg m^{-2} h^{-1}, were significantly higher than those under other AWD treatments. The maximum CH_4 emission values were 2.778, 0.493, and 0.177 mg m^{-2} h^{-1} for AWD_5, AWD_{10}, and AWD_{20}, respectively.

From 7 March (62 DAS), an unorganized tropical cyclone named "Cyclone Yaku" was present near the north and central coast until 18 March (73 DAS) [32]. This presence facilitated the entry and accumulation of moisture on the occidental watershed. As a result, intense rainfall and unprecedented daily precipitation records occurred along the northern coast, significantly impacting the hydrological regimen during the experimental period.

Table 2. Flux of CH_4 and N_2O Emissions under Continuous Flooding (CF) and AWD Treatments.

Fecha	DAP	C-CH_4 (mg m^{-2} h^{-1})				N-N_2O (mg m^{-2} h^{-1})			
		CF	AWD_5	AWD_{10}	AWD_{20}	CF	AWD_5	AWD_{10}	AWD_{20}
11 February 2023	38	0.025	0.008	0.013	0.014	0.007	0.010	0.027	0.021
15 February 2023	42	0.289	0.033	0.023	0.016	0.008	0.043	0.081	0.379
6 March 2023	61	0.857	1.102	0.384	0.177	0.016	0.013	0.034	0.009
10 March 2023	65	1.110	2.778	0.177	0.167	0.019	0.017	0.030	0.028
20 February 2023	75	5.816	0.603	0.129	0.023	0.011	0.178	0.623	0.148
24 March 2023	79	17.924	0.242	0.022	0.048	0.011	0.131	0.320	0.059
2 April 2023	88	0.769	0.223	0.002	0.028	0.029	0.045	0.040	0.019
6 April 2023	92	3.263	0.831	0.083	0.011	0.016	0.010	0.033	0.041
17 April 2023	103	8.214	1.353	0.307	0.047	0.019	0.020	0.019	0.014
21 April 2023	107	6.188	1.122	0.493	0.028	0.008	0.028	0.028	0.211
7 May 2023	123	4.996	0.310	0.102	0.053	0.018	0.003	0.020	0.010
11 May 2023	127	5.902	0.263	0.050	0.006	0.017	0.013	0.024	0.007
31 May 2023	147	0.020	0.003	0.015	0.092	0.076	0.018	0.026	0.027
2 June 2023	149	0.002	0.042	0.016	0.015	0.046	0.046	0.010	0.024
7 June 2023	154	0.025	0.005	0.004	0.039	0.027	0.030	0.005	-
9 June 2023	156	0.006	0.020	0.031	0.014	0.050	0.018	0.025	0.016

3.2. Dynamics of N_2O Emissions

The temporal variation of N_2O throughout the experiment period, from germination to post-harvest, is observed (Figure 8). The increase in emissions during the maximum tillering stage (75 and 79 DAS) under both AWD and CF irrigation regimens corresponds to a period of extreme drought, with emissions ranging from 0.011 to 0.623 mg m^{-2} h^{-1}. Some high values were observed after urea fertilization, with emissions ranging from 0.008 and 0.379 mg m^{-2} h^{-1} on 42 DAP and between 0.008 and 0.211 mg m^{-2} h^{-1} on 107 DAP, for the AWD irrigation regimen.

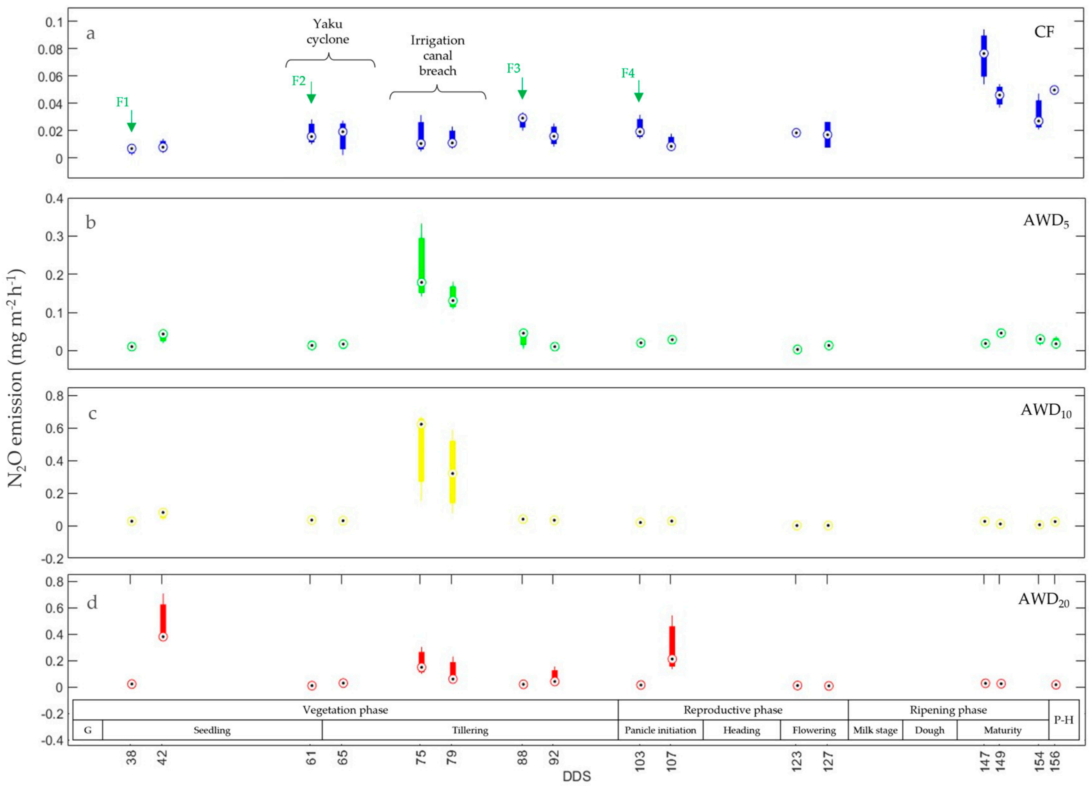

Figure 8. Temporal Variation of N_2O Flux (mg m^{-2} h^{-1}) during the crop development under CF irrigation regimen (**a**), AWD_5 (**b**), AWD_{10} (**c**), and AWD_{20} (**d**).

The highest peaks of N_2O emission occur under the AWD regimen, 0.178, 0.623, and 0.379 mg m^{-2} h^{-1} for AWD_5, AWD_{10}, and AWD_{20}, respectively, compared to the emission under CF, which was 0.029 mg m^{-2} h^{-1}.

3.3. Cumulative Emissions of CH_4 and N_2O

The effects of irrigation regimens significantly influenced ($p < 0.05$) the cumulative greenhouse gas emissions (Table 3). For CH_4, significant differences among treatments are observed. Values range from 1.59 kg ha^{-1} for the AWD_{20} irrigation regimen to 108.55 kg ha^{-1} under the CF regimen. In Figure 9a, the significance and Spearman's R values are observed. Cumulative CH_4 emissions were significantly higher under the CF irrigation regimen. The AWD irrigation regimen reduced CH_4 emissions, decreasing by 84%, 96%, and 99% in AWD_5, AWD_{10}, and AWD_{20}, respectively.

Table 3. Effect of Irrigation Regimens and Their Levels on Rice Yield, CH_4 and N_2O Emissions, Emission Factor, GWP, and YGWP.

Water Regimens	Grain Yield	EUA	Emission (kg ha^{-1})		EF (kg ha^{-1} d^{-1})		GWP [a]	YGWP [b]
	(t ha^{-1})	(kg m^{-3})	CH_4	N_2O	CH_4	N_2O		
CF	14.01 [a]	0.70	108.55 [a]	0.63 [a]	0.92 [a]	0.01 [a]	3211.54 [a]	0.23 [a]
AWD_5	11.85 [b]	0.83	17.72 [a]	1.05 [a]	0.15 [a]	0.01 [a]	782.11 [b]	0.07 [b]
AWD_{10}	13.72 [c]	0.96	4.02 [b]	2.36 [b]	0.03 [b]	0.02 [b]	755.58 [b]	0.06 [c]
AWD_{20}	13.32 [c]	0.92	1.59 [c]	2.24 [c]	0.01 [c]	0.02 [b]	656.46 [b]	0.05 [c]

[a] WUE (regarding the water use efficiency; kg m^{-3}) is calculated by dividing grain yield by irrigation volume. [b] GWP (global warming potential; kg CO_2 equivalent ha^{-1}) of CH_4 and N_2O was calculated using GWP values of 28 and 273 for CH_4 and N_2O, respectively. [c] YGWP (global warming potential at yield scale, kg CO_2 equivalent kg^{-1} grain yield) was calculated by dividing the global warming potential by yield (kg ha^{-1}).

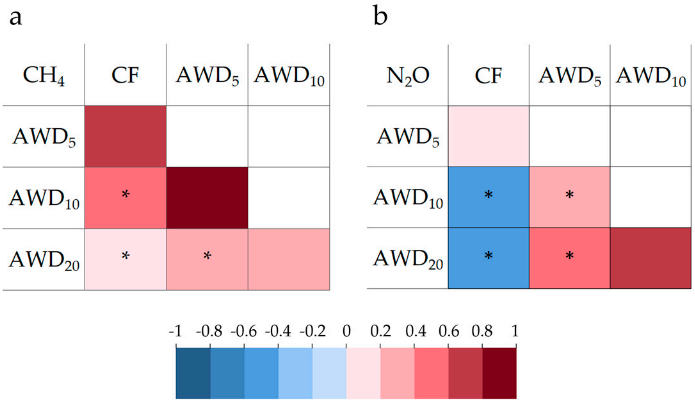

Figure 9. Non-parametric Spearman correlation and Dunn statistical test between irrigation regimens based on CH_4 emission (**a**) and N_2O emission (**b**). The (*) indicates significant differences between treatments ($p < 0.05$).

Regarding cumulative N_2O emissions, significant differences among treatments are observed. Values range from 0.63 kg ha^{-1} for the CF irrigation regimen to 2.36 kg ha^{-1} under the AWD_{10} regimen. In Figure 9b, the significance and Spearman's R values are observed. Cumulative N_2O emissions were significantly higher under the AWD irrigation regimen. The AWD irrigation regimen increased N_2O emissions at all levels, increasing by 66%, 273%, and 255% in AWD_5, AWD_{10}, and AWD_{20}, respectively.

The highest cumulative methane (CH_4) emissions from crops are observed during the vegetative stage across all treatments. In contrast, when it comes to the total N_2O emissions based on crop growth stages, the maturity phase produces the most emissions in the CF system. Whereas in the AWD system, the growth phase, coinciding with nitrogen fertilization results in the maximum emissions (Table 4).

Table 4. Cumulative emissions according to the phenological stage of rice cultivation.

Phenological Stage	Emission CH_4 (kg ha^{-1})				Emission N_2O (kg ha^{-1})			
	CF	AWD_5	AWD_{10}	AWD_{20}	CF	AWD_5	AWD_{10}	AWD_{20}
Vegetation	64.017	25.703	2.214	1.021	0.168	0.740	1.970	1.489
Reproductive	24.926	3.930	0.697	0.107	0.068	0.066	0.104	0.101
Ripening	51.989	4.816	1.611	0.467	0.303	0.165	0.256	0.622
Post-Harvest	0.030	0.046	0.030	0.076	0.092	0.072	0.025	0.030

3.4. Rice Yield, Water Use Efficiency, GWP, YGWP, and Emission Factors

Irrigation regimens significantly influenced ($p < 0.05$) yield, GWP, and YGWP (Table 3). In all three AWD treatments, GWP was reduced compared to the CF regimen. GWP values were 782.11, 755.58, and 656.46 kg CO_2 equivalent ha^{-1} for the AWD_5, AWD_{10}, and AWD_{20} regimen, respectively, while for the CF regimen, values reached 3 211.54 kg CO_2 equivalent ha^{-1}. The reduction in GWP compared to the CF regimen was 76%, 77%, and 80% for the AWD_5, AWD_{10}, and AWD_{20} regimens, respectively.

With respect to WUE, AWD irrigation demonstrates higher efficiency, with 0.83, 0.96, and 0.92 kg m^{-3} for AWD_5, AWD_{10}, and $AWD_{20,}$ respectively; thus, there is a 28% reduction in water use in AWD irrigation compared to CF.

YGWP values were 0.065, 0.054, and 0.048 kg CO_2 equivalent kg^{-1} for the AWD_5, AWD_{10}, and AWD_{20} regimens, respectively, while for the CF regimen, a value of 0.229 kg CO_2 equivalent kg^{-1} was obtained. The AWD regimen reduced YGWP values compared to the CF regimen by 71%, 76%, and 79% for the AWD_5, AWD_{10}, and AWD_{20}, regimens, respectively. No significant differences were shown between treatments ($p < 0.05$), regarding YGWP.

The CH_4 EF ranged from 0.01 kg ha^{-1} d^{-1} for the AWD_{20} regimen, while for the CF regimen, a value of 0.92 kg ha^{-1} d^{-1} was obtained. The N_2O EF ranged from 0.005 kg ha^{-1} d^{-1}.

4. Discussion

4.1. CH_4 Emission Dynamics

CH_4 emissions from rice fields were influenced by the AWD irrigation regimen [11]. In Figure 7, it can be observed that the highest emission rates were under the CF regimen. Although these emission rates are comparable to those recorded in other locations (Table 5) [3,5,14,16], there are studies reporting higher [2,12,19] or lower values [6,10].

According to the crop phenology, CH_4 emissions increase as the plants grow until reaching the flowering stage. This increase is due to the optimal development of aerenchyma tissue, especially in the early stages of plant development, leading to increased exudate release and fermentation of easily degradable soil organic matter [10]. Thus, peak emission levels were recorded during the vegetative stage (17.924 mg m^{-2} h^{-1} in CF and 2.778 mg m^{-2} h^{-1} in AWD) and the reproductive stage (8.214 mg m^{-2} h^{-1} in CF and 1.353 mg m^{-2} h^{-1} in AWD). This increase can also be explained by microbial degradation, root exudate release, and microbial biomass growth during the maximum tillering phase [14]. These results are consistent with previous research [10,12,16].

The decrease in emissions under the CF regimen started during the maturation stage (0.002–0.025 mg m^{-2} h^{-1}), which coincides with the period when irrigation is suspended, where there is greater availability of oxygen in the rhizosphere. Furthermore, soil aeration promotes the oxidation of CH_4 by methanotrophic bacteria in underground soil layers and consequently reduces CH_4 emissions [3].

Despite this, these CH_4 fluxes were higher throughout almost the entire crop development compared to the fluxes under the AWD treatment. Despite the climatic and soil conditions of previous studies, they reported differences when compared with the CF treatment (Table 5). This can be attributed to the fact that in rice cultivation systems, the transfer and release of CH_4 to the atmosphere mainly occur through three mechanisms, with the most important being the diffusion of gas dissolved in interfaces between water and air, as well as between soil and water [33]. This diffusion process can be promoted by the porosity of the soil; in this study the soil texture was sandy loam. This restricts the time available for methanotrophs to degrade CH_4 [14].

The aerated conditions of the AWD treatment could be affected by the strong and abnormal rainfall caused by the natural phenomenon Cyclone "Yaku". These coincided with the beginning of the tillering period (Table 4), which resulted in an increase in emissions because the soil remained saturated, generating longer anoxic conditions [34].

Table 5. Maximum flux of CH_4 and N_2O emissions under continuously flooded irrigation and AWD treatments according to various authors.

Site	Climate by Köppen	Season	Soil	Year	N [1] (kg ha^{-1})	CH_4 Emission (mg m^{-2} h^{-1})		N_2O Emission (mg m^{-2} h^{-1})		Ref.
						CF	AWD	CF	AWD	
Alabama, United States	Humid subtropical	Dry	Loamy	2013	105	-	-	0.01	0.06	[13]
Daca, Bangladesh	Savanna	Dry	Clay loam	2018	78	35	34	0.13	0.12	[5]
				2019		19	14	0.05	0.05	
Mymensingh, Bangladesh	Monsoonal	Dry	Loamy	2018	90	7	3	0.03	0.06	
				2019		7	5	0.04	0.03	
Daca, Bangladesh	Savanna	Dry	Clay loam	2018	78	19	17	0.08	0.09	[3]
				2019		20	13	0.09	0.08	
				2020		17	13	0.09	0.08	
Guangzhou, China	Dry winter subtropical	Dry	Clay loam	2017	180	29	29	0.26	0.3	[12]
		Wet		2018	150	25	21	0.2	0.3	
		Dry			160	26	25	0.21	0.31	
		Wet		2019	150	31	31	0.15	0.24	
		Dry			180	39	33	0.4	0.31	
Hubei, China	Cool summer	Wet	Loamy	2021	180	7	4	0.01	0.2	[6]
				2022		7	5	0.01	0.23	
Hung Yeng, Vietnam	Dry winter subtropical	Dry	Clay	2017	-	30	24	-	-	[19]
		Wet				84	96	-	-	
Jakenan, Indonesia	Monsoonal	Dry	Loamy	2020	120	10	7	0.1	0.1	[14]
Wedarijaksa, Indonesia			Loamy clay			1	0.8	0.12	0.14	
Liaoning, China	Warm continental summer	Dry	Loamy	2017	180	17	3	0.9	1.2	[16]
				2018		4	1.5	0.3	0.4	
				2019		3	2	0.05	0.09	
Mymensingh, Bangladesh	Monsoonal	Dry	Loamy	2019	180	7	4	-	-	[10]
Tamil Nadu, India	Savanna	Wet		2020	180	28	9	0.5	0.9	[2]
		Dry		2021		20	8	0.8	0.8	

[1] fertilizante nitrogenado.

4.2. Dynamics of N_2O Emission

N_2O emissions in rice fields are directly influenced by the AWD irrigation regimen and the quantity of fertilizers used. Figure 8 shows that the highest N_2O emission rates occur when using the AWD irrigation regimen (0.003–0.623 mg m^{-2} h^{-1}), compared to emissions under the CF regimen (0.007–0.076 mg m^{-2} h^{-1}).

It is important to highlight that recent research has observed higher emission peaks under the AWD regimen [2,16], although most of them are lower than the maximum value recorded in this study (0.623 mg m^{-2} h^{-1}), as detailed in Table 2 [3,5,13]. This could be due to the use of a high amount of nitrogen fertilizers (250 kg N ha^{-1}), which is the conventional dose in this study area, as reported by local farmers [35]. It is important to mention that this nitrogen amount exceeds that used in previous research, as shown in Table 5. Therefore, it led to higher inorganic nitrogen production and excessive growth of the nitrifying microorganism population. Moreover, the lower moisture conditions during intermittent drainage periods favor N_2O overproduction [12]. The alternation between oxygenated and anoxic conditions during the AWD regimen can enhance nitrification and denitrification processes, depending on oxygen availability [3]. It is suggested that the alternation of soil wetting and drying stimulated N_2O production due to the use of endogenous nitrogen released from soil organic matter, originating from both fertilizer application and nutrients released by plant roots [16].

However, N_2O emissions were also affected by the long periods without irrigation due to a break in a water distribution channel between days 70 and 80 DAP. This interruption had a major impact on emissions under AWD (0.178–0.623 mg m^{-2} h^{-1}). Despite this change in conditions, emissions under CF did not increase significantly, as the soil remained waterlogged for an extended period, resulting in complete denitrification [15,36].

4.3. Effect of Water Regimens on Cumulative GHG Emissions

Water management affected CH_4 emissions from rice cultivation. In this study, AWD irrigation significantly reduced ($p < 0.05$) CH_4 emissions compared to the conventional farmers practice (Table 3). These results are consistent with previous findings (Table 5) [5,12], with reductions of 99% in the AWD_{20} treatment. Because, intermittent aeration makes an oxygen-rich soil environment, resulting in CH_4 oxidation by methanotrophs, causing a drop in CH_4 emissions (1.670 kg ha^{-1} para AWD_{20}). It has been reported that up to 80% of CH_4 produced during the rice cultivation season is oxidized by these methanotrophs [17,34].

In contrast, rice cultivation under the CF regimen creates an anaerobic soil environment, i.e., a reducing environment. Leading to a low redox potential (−150 mV), this medium favors the anaerobic decomposition of complex organic substances by methanogens [5,14]. Generating two important reactions: the reduction of CO_2 with H_2 derived from organic compounds or methylated compounds and the decarboxylation of acetic acid, which is known as methanogenesis, driving the production of CH_4 [37].

Water management also had a significant impact on cumulative N_2O emissions (Table 3). Under CF conditions, N_2O emissions were minimal (0.631 kg ha^{-1}). In contrast, in fields with AWD irrigation, emissions were significantly higher, with the highest in the AWD_{10} treatment (2.354 kg ha^{-1}). The variation in water regimens, transitioning from CF to AWD, influenced nitrification and denitrification rates, depending on oxygen availability. During the flooding period, nitrification of ammonium ions (NH_4^+) is low, inhibiting N_2O production [3]. However, during the drying cycle, the upper soil layer initially becomes aerobic, but the lower layer remains anaerobic, even if the water level is more than 15 cm below the soil surface [14]. This explains that despite the AWD_{20} treatment having the longest aeration time (2.243 kg ha^{-1}) it did not surpass the cumulative emissions of the AWD_{10} treatment (2.354 kg ha^{-1}).

4.4. Effect of AWD Irrigation on Emission Factors, Grain Yield, Water Use Efficiency, GWP and YGWP

Water management influenced the CH_4 emission factor. Under the AWD regimen, values ranged between 0.01 and 0.92 kg ha^{-1} d^{-1}, compared to the CF regimen, where 0.92 kg ha^{-1} d^{-1} was obtained. It is relevant to mention that the value obtained in the CF regimen falls within the range of values presented by the IPCC for South America (0.86–1.88 kg CH_4 ha^{-1} d^{-1}) [38]. FE measured by the IPCC is based on specific assumptions, such as the absence of organic amendments in the fields and aeration conditions for 180 days before planting, conditions that were applied in our experiment.

Regarding grain yield, a decrease is observed with respect to the AWD treatments. It is possible that this decrease is due to the rapid drainage of water in the sandy loam soil, which caused the plant to suffer from drought stress, in addition to the high temperatures in the area [15]. However, for AWD_{10} only a 2% decrease was recorded. This suggests that increasing soil air exchange with AWD can provide sufficient oxygen to the root system to facilitate the mineralization of soil organic matter. This increases soil fertility and improves rice production, which does not happen in the AWD_5 treatment [39].

In contrast, the maximum grain yield value is observed in the CF regimen (14.01 t ha^{-1}), which coincides with the maximum CH_4 emissions (140,963 kg ha^{-1}). This is related to optimal vegetative and root development, which generates an increase in available carbon and root exudation. The latter is a substrate used by methanogenic bacteria that cause high yields and emissions of CH_4 [12,33].

It is observed that AWD irrigation could increase WUE mainly due to the reduction in the amount of irrigation [40]. Of the three AWD levels, AWD_{10} had the highest efficiency due to its high performance and low irrigation level due to intermittent drainage periods, which is an alternative for times of low water supply for irrigation.

On the other hand, the AWD scale factor for CH_4 varied between 0.01 and 0.16, significantly lower values than those presented by the IPCC (0.41–0.72 kg CH_4 ha^{-1} d^{-1}), corresponding to the water regimen with multiple drainage periods [38]. The IPCC also specifies that crop fields must have a period without flooding. However, in this study, this period was interrupted due to the presence of Cyclone "Yaku", explaining the notable difference in emission factor values in the AWD regimen.

Different water regimens revealed a trade-off relationship between CH_4 and N_2O emissions. Despite the 100% increase in cumulative N_2O emissions with AWD irrigation compared to CF irrigation, this only offset less than 1% of the total GWP. Overall, the AWD irrigation regimen reduced GWP by 77% compared to the CF irrigation. These results confirm that the total GWP in rice fields is mainly determined by CH_4 emissions, even though N_2O (265 kg CO_2) has a higher radiative forcing in terms of CO_2 [41]. Consequently, CH_4 represents the main contributor to GWP in rice cultivation, accounting for over 90% of the total GWP. In this study, CH_4 emissions represented 94.78% in AWD and 98.9% in CF. These findings align with previous research [6,12,16,34]. In other studies, it is mentioned that the primary contributor to GWP in CF irrigation corresponds to N_2O due to variations in drainage to field capacity during fertilization, leading to increased N_2O emissions [15]. Therefore, the most effective measures to reduce GWP and greenhouse gas emissions in rice cultivation should focus on reducing CH_4 emissions.

The YGWP, or the relationship between total GHG emissions and grain yield, was used to measure the efficiency and sustainability of a rice management system. Similarly to the GWP, AWD irrigation demonstrated the potential to reduce YGWP by an average of 75% compared to CF irrigation [5,16]. Although the AWD_{20} regimen presented the lowest YGWP value (0.05), it is considered that the AWD_{10} regimen effectively mitigates GWP, as it only reduces grain yield by 2%. Additionally, neither treatment shows significant differences regarding YGWP. This means that AWD irrigation has an environmental improvement effect, contributing to a reduction in water use with the additional potential of saving fossil fuel-based energy and reducing CO_2 emissions, which is why it can be considered as a strategy for mitigation for decision-makers and policymakers. In addition, it supports the state's commitment to the United Nations Framework Convention on Climate Change.

4.5. Challenges and Viability

In this study, the challenge was due to the transportation of the closed static chambers to the field, which is why they were replaced with a lighter material using opaque chambers. In addition, the presence of abnormal precipitation caused by Cyclone "Yaku" significantly altered soil moisture conditions, generating variations in greenhouse gas (GHG) emissions in the proposed treatments. Despite these challenges, AWD irrigation stood out as a low GHG emission regimen, establishing itself as an effective mitigation option to reduce emissions in rice fields.

This is an irrigation system practiced in the Lambayeque region during periods of drought caused by a lack of rain [18]. However, this regimen can be applied in any season to benefit the predominantly family-based agriculture practiced by the population. This can contribute to the economic viability of the locality and ensure food security.

5. Conclusions

In the context of climate change, both the availability of water resources and food security have significant risks. For this reason, the AWD method becomes relevant by greatly reducing greenhouse gas emissions and the demand for irrigation water. In this study, grain yield and greenhouse gas emissions were evaluated under the CF regimen and irrigation levels AWD_5, AWD_{10}, and AWD_{20}. An average 93% reduction in CH_4 emissions was observed, as well as a 198% increase in N_2O emissions. Regarding grain yield, it experienced a decrease of 15%, 2%, and 5% for the AWD_5, AWD_{10}, and AWD_{20} levels, respectively. With respect to WUE, AWD irrigation shows greater efficiency, with 0.83, 0.96, and 0.92 kg m^{-3} for AWD_5, AWD_{10}, and AWD_{20}, respectively, and a 28% water reduction in AWD irrigation. Despite the increase in N_2O emissions, the GWP was mainly influenced by the reduction of CH4. This resulted in a notable decrease in GWP under the AWD irrigation regimen. This pattern was also reflected in the total GHG emissions in relation to grain yield (YGWP), being 0.07, 0.06, and 0.05 kg CO_2 eq kg^{-1} grain yield for irrigation regimens AWD_5, AWD_{10}, and AWD_{20}, respectively. The findings highlight the importance of a more detailed and specialized approach in AWD_{10} treatment, considering its minimal impact on grain yield. The results of this study support the adoption of AWD irrigation as a strategy to mitigate CO_2 emissions while contributing to the reduction of water use. This approach acquires relevance in the socioeconomic and climatic context of the northern coast of Peru, since it safeguards the supply of rice in the population's diet during times of drought.

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