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Research article

Identifying rice varieties for mitigating methane and nitrous oxide emissions under intermittent irrigation

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A R T I C L E I N F O

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A B S T R A C T

Context or problem: Most of the research evaluating rice varieties, a major global staple food, for greenhouse gas (GHG) mitigation has been conducted under continuous flooding. However, intermittent irrigation practices are expanding across the globe to address water shortages, which could alter emissions of methane (CH_4) compared to nitrous oxide (N_2O) for reducing overall global warming potential (GWP). To develop climate-smart rice production systems, it is critical to identify rice varieties that simultaneously reduce CH_4 and N_2O emissions while maintaining crop productivity under intermittent irrigation.
Objective: This study assessed CH_4 and N_2O emissions, grain yield, and GWP of four rice varieties cultivated under intermittent irrigation in Colombia.
Methods: Four common commercial rice varieties were evaluated over two seasons–wet and dry in 2020 and 2021–in two Colombian regions (Tolima and Casanare).
Results: Wet-season crop productivity was similar among varieties. However, F68 in Tolima and F-Itagua in Casanare significantly reduced yields in the dry season, likely due to periods of crop water stress. Overall, CH_4 emissions and GWP were relatively low due to frequent field drainage events, with GWP ranging from 349 to 4704 kg CO_2 equivalents ha^{-1}. Accordingly, N_2O emissions contributed 73% to GWP across locations, as wet-dry cycles can increase N_2O emissions, creating a tradeoff for GWP when reducing CH_4 through drainage. Varieties F67 in Tolima and F-Itagua in Casanare significantly reduced GWP by 32–61% across seasons, primarily by decreasing N_2O rather than CH_4 emissions.
Conclusions: Rice varietal selection achieved significant GWP mitigation with limited impacts on grain yield, mainly due to reduced N_2O emissions under non-continuously flooded irrigation.
Implications/significance: This research underscores the critical role of rice varietal selection in addressing global climate-change and water-scarcity challenges, which drive the adoption of intermittent irrigation practices. By focusing on reducing N_2O emissions through appropriate variety selection, this study provides valuable insights for rice systems worldwide that are adapting to these pressing environmental challenges.

1. Introduction

The concentration of methane (CH_4) and nitrous oxide (N_2O) in the atmosphere has risen to 1866 ppb and 332 ppb, respectively, which is more than double and triple the concentration that existed before the beginning of the industrial revolution (IPCC, 2021). One of the primary anthropogenic sources of CH_4 and N_2O emissions is rice production, which contributes to approximately 6–22% of CH_4 emissions (Smartt

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et al., 2016; Smith et al., 2021) and 11% of N_2O emissions globally (Mboyerwa et al., 2022). Given that CH_4 and N_2O have 27.2 and 273 times greater global warming potential (GWP) than carbon dioxide (CO_2) over a 100-year time horizon (IPCC, 2021), greenhouse gas (GHG) emissions from rice-cropping systems represent an obvious concern related to climate-change scenarios/mitigation and management (Wassmann et al., 2000; Van Groenigen et al., 2011; Zhang et al., 2019a). While extreme weather variation is already having adverse impacts on crop productivity (Challinor et al., 2014; Ortiz-Bobea et al., 2021), global demand for rice continues to increase, highlighting the urgent need for climate-smart approaches to mitigate GHG emissions while maintaining rice yields and food security.

Variety choice can strongly influence GHG emissions from rice fields, especially CH_4 production and release from the soil−plant system (Aulakh et al., 2000; Ma et al., 2010; Jiang et al., 2017; Li et al., 2022). Soil CH_4 production occurs through the anaerobic decomposition of soil organic matter and plant carbon (C) inputs, with the rice plant acting as the primary pathway for the transport of CH_4 from the soil to the atmosphere (Conrad, 2007; Malayan et al., 2016). Differences in rice biomass production, root development, aerenchyma, and grain yields all influence the amount of carbon captured and incorporated into plant biomass and how much enters the soil, which in turn becomes the substrate for CH_4 emissions (Denier van der Gon et al., 2002; Gutierrez et al., 2013; Jiang et al., 2017). Previous research has shown significant variation in seasonal CH_4 emissions among different varieties due to contrasting growth habits, root exudates, internal physiology, and variety-specific effects on soil methanotrophic communities (Ma et al., 2010; Zheng et al., 2014). For example, Japonica varieties tend to produce lower GHG emissions than Indica varieties (Ma et al., 2010; Zheng et al., 2014; Uyeh et al., 2021). Similarly, breeding for high yields has resulted in changes over time for Japonica varieties, with Li et al. (2022) reporting grain yield increases of 19–94% between the 1960s and 2010s, while CH_4 emissions decreased by 9–41% compared to the 1950s. Varietal replacement over several decades in China has also generated large rice yield increases with substantial GHG reductions (Zhang et al., 2019b).

Rice varieties may also influence N_2O emissions through different mechanisms. Soil N_2O emissions are produced through microbial nitrification and denitrification reactions, depending on available carbon, inorganic nitrogen (N) substrate, soil oxygen (O_2) concentrations, soil pH, and temperature (Markfoged et al., 2011; Signor and Cerri, 2013; Song et al., 2019). Different rice varieties affect these microbial processes depending on root characteristics influencing O_2 and organic carbon availability in the rhizosphere (Chunmei et al., 2020; Firestone and Davidson, 1989; Xiong et al., 2021). Moreover, varieties that efficiently capture applied N fertilizer may decrease N_2O emissions by decreasing the amount of excess soil N serving as substrate to fuel microbial processes (Jiang et al., 2016; Qian et al., 2023). There have been fewer studies investigating the effect of rice variety on N_2O compared to CH_4 emissions, hence the combined GHG mitigation potential remains poorly understood. Zheng et al. (2014) found significant differences between Indica and Japonica varieties for CH_4 emissions, while N_2O emissions were similar. Other studies report the main driving forces influencing N_2O emissions in rice soils as including inorganic NO_3-N concentration, soil organic carbon content, and varietal differences in root dry weight, shoot dry weight, root length, stomatal conductance, and transpiration rate (Firestone and Davidson, 1989; Gogoi and Baruah, 2012; Gorh and Baruan, 2019).

Given the urgent need to reduce rice production systems' water footprint in the face of climate change (Arenas-Calle et al., 2019; Wang et al., 2020), identifying rice varieties for climate-smart production with reduced irrigation inputs is needed to fill a key knowledge gap. The majority of studies on GHG mitigation in rice systems has been conducted under flooded conditions, where the contribution of CH_4 to GWP is much larger than N_2O (Qian et al., 2023). However, intermittent or non-continuously flooded irrigation is becoming increasingly important in rice-growing areas across the globe due to water scarcity (Bo et al., 2022). With a higher frequency of soil drainage, N_2O emissions are likely to increase as CH_4 emissions decrease, causing a change in GWP (Jiang et al., 2019). As rice varieties influence CH_4 and N_2O emissions differently due to the distinct underlying mechanisms discussed above, the net impacts on GWP under non-continuously flooded conditions remain unclear. Previous research has often focused on how different varieties affect CH_4 emissions but, considering the growing global shift towards non-continuously flooded rice systems to save water resources and improve sustainability, it is critical to investigate whether changes in N_2O emissions triggered by frequent drainage periods could offset the benefits for CH_4 mitigation, thus negatively impacting overall GWP.

Due to rice being a staple food crop and economic livelihood for smallholder farmers, it is essential to identify varieties that can maintain or increase yields under intermittent irrigation while reducing GWP (GWP = CH_4 + N_2O emissions). Colombia is the third largest rice producer in Latin America, trailing only behind Peru and Brazil (FAOSTAT, 2023), where rice production plays a crucial role in sustaining/ensuring Colombia's food security and promoting rural development. Colombia's rice production system is characterized mostly by three water-management systems: irrigated, flooded, and rainfed production. Rice is grown in five regions of Colombia, with the Llanos and Centro regions accounting for the most significant production. Various rice varieties are cultivated, including commercial varieties such as Fedearroz 67 (F67) and Fedearroz 2000 (F2000), which are bred from a panel of intercrosses with Indica materials. The average rice yield is around 5 Mg ha^{-1}, although yield levels may differ based on the production system and variety used (DANE, 2023).

Considering the mechanisms underpinning CH_4 and N_2O emissions in rice cultivation is critical to understanding the potential impacts of different rice varieties. Methane emissions are primarily associated with anaerobic soil conditions that are prevalent in flooded rice systems, while N_2O emissions arise from nitrification and denitrification processes, influenced by variety-specific growth rates and nutrient requirements. Previous studies indicate that certain rice varieties can significantly reduce CH_4 and N_2O emissions through optimized water and nutrient management. Currently, there is no information available regarding the impact of the cultivated rice varieties on GHG emissions in the country, highlighting the need to assess how variety-specific traits can mitigate GHG emissions in Colombia's rice production. Therefore, this experimental study aimed to fill this knowledge gap by evaluating the effects of four common rice varieties on crop yield, CH_4 and N_2O emissions, and GWP under intermittent irrigation in both dry and wet seasons in two of Colombia's primary rice-growing regions (Tolima and Casanare). Identifying the rice varieties that decrease N_2O emissions, without increasing CH_4 emissions or compromising yields, offers a promising strategy for climate-smart/food security solutions and sustainable smallholder livelihoods.

2. Methodology

2.1. Experimental site and methodological design

Field experiments were conducted at the two representative experimental sites in Colombia, Tolima and Casanare. Rice farmers in the Tolima region primarily grow irrigated rice, while Casanare rice farmers cultivate both irrigated and rainfed rice. The study was conducted during two cropping seasons: the dry season covering the end of 2020 (Season I) and the wet season during the first half of 2021 (Season II). The field experiment in Tolima was located at the "Las Lagunas" Experimental Center of Fedearroz in the southern region of Saldaña (3° 55′ 59″ North, 75° 1′ 1″ West). The Saldaña River irrigation district provides irrigation water. In Casanare, the experiment was conducted in the municipality of Aguazul, specifically at the "La Primavera" farm (5° 28′ 54″ North, 72° 38′ 8″ West), in a foothill environment where rice crops were established under rainfed conditions–relying solely on rainfall for water in the wet season–and under an irrigation system supplied by water from the Charte River during the dry season.

The topsoil layer (0−10 cm) at the Tolima site is classified as a Typic Ustorthent soil (IGAC, 1997) with loamy texture, low organic matter (1.47%), slight acidity (pH 5.81), and moderately fertile. This soil is characterized by low cation exchange capacity (6.36 cmol kg^{-1}), low sulfur content (6.32 Mg kg^{-1}), and high iron content (147.98 mg kg^{-1}). The sandy soil at the Casanare site is classified as an Inceptisol (FAO, 2007; IGAC, 1992). The topsoil layer (0−10 cm) has a total organic carbon content of 1.60%, pH of 4.75, cation exchange capacity of 7.9 cmol kg^{-1}, sulfur content of 32 mg kg^{-1}, and high iron content of 227 mg kg^{-1}.

Each field trial was conducted as a randomized complete block design with three replicates per treatment. Four commercial rice varieties were evaluated at each site: F2000, F67, F70, and F68 at Tolima and F2000, F67, F70, and FL Fedearroz Itagua (F-Itagua) at Casanare. Rice varieties were chosen based on their commercial relevance and agronomic characteristics for each region. F-Itagua was selected because it is more representative than F68 of the Casanare rice-growing area. Plot size was 50 m^2. At the Tolima site, the rice was sown using a mechanized method with a seeding density of 100 kg ha^{-1} in a laser-leveled basin. In Casanare, the soil was prepared by harrowing twice and micro-sorting with a grader. The seed was sown by hand in the furrow at a density of 135 kg ha^{-1}.

Intermittent irrigation methods were different for each site according to standard practices for each region. In Tolima, intermittent irrigation was applied during crop establishment and vegetative growth stages in both seasons. Once the soil was saturated with water, natural drainage was allowed to occur until soil moisture levels reached near-field capacity, after which irrigation was resumed. Following rice flowering, the soil was kept under a small layer of continuous flooding until plant physiological maturity was reached. In Casanare, irrigation management followed conventional dry and wet season practices. In the dry season, irrigation was conducted intermittently, as described above for Tolima, which involved alternating wet and dry periods throughout the growing season until the flowering stage. After plant flowering, the soil was maintained under a thin layer of continuous water until plants reached physiological maturity. In the wet season (Season II), intermittent irrigation events were scheduled according to the intensity and frequency of rainfall, ensuring that the combination of water inputs adequately met crop water requirements. Fertilization practices varied based on regional standards for each site. The study aim was to achieve greater nitrogen fertilization efficiency by integrating soil moisture control and proper fertilization timing. Table 1 provides further details of the agricultural practices, such as planting and harvesting dates, and fertilizer application.

Phosphorus pentoxide (P_2O_5), sulfur (S), Zinc (Zn), Boron (B), Copper (Cu), Manganese (Mg), Calcium oxide (CaO), magnesium oxide (MgO), silicon dioxide (SiO_2).

2.2. Greenhouse sampling and global warming potential

Sampling for field GHG emissions was performed using the closed static chamber technique (Chirinda et al., 2017)–see Loaiza et al. (2024) for a full description of the methodology. In brief, the GHG chambers were composed of two parts: a polyethylene base (40 cm height) and lid (114 L, 80 cm height). Three days before the first sampling, after rice sowing in both regions, the bases were placed in each plot and inserted into the soil (~15 cm depth). Each base had an open bottom and canals on the sides to allow irrigation water to flow freely. Each chamber covered three rice seedlings inside the bases. The chamber lid had: (i) a 10 cm-long vent to avoid overpressure, (ii) a battery-operated fan to circulate and homogenize the confined gases during monitoring; (iii) a steel thermometer to record chamber temperature; and (iv) a gas sampling port.

Sampling was conducted every week during the rice-growing season, with more frequent measurements following fertilization events. Measurements were taken one day before fertilization, three consecutive days after, and during irrigation. Subsequently, weekly monitoring was conducted until harvest. Gas samples were collected between 8 a.m. and 11 a.m. Each chamber was enclosed for 45 min, and four samples were removed (t0, t15, t30, and t45) using 20 ml propylene syringes with an adapted three-way valve. Immediately after collection, gas samples were transferred to pre-evacuated 10 ml glass Exetainer vials (Labco Ltd).

The concentrations of each gas were determined by gas chromatography (shimadzu gc-2014) with a Flame Ionization Detector (FID) for CH_4 and ^{63}Ni Electron capture detector (ECD) for N_2O. The detection limit was 0.06 ppm for CH_4 and 0.1 ppm for N_2O. Gas concentrations were converted to fluxes based on the duration of chamber closure combined with the ideal gas law equation, and measured chamber temperature, atmospheric pressure, and volume. The seasonal cumulative fluxes for CH_4 and N_2O emissions (kg ha^{-1}) were calculated by

Table 1
Crop management events conducted at the Tolima and Casanare experimental study sites.

Agronomic practices	Season I: Irrigation	Season II: Irrigation	Season I: Irrigation	Season II: Rainfed
Region - Location	**Tolima – Saldaña**		**Casanare - Aguazul**	
Commercial varieties	F67; F68, F70 and F2000		F67; F70; F2000 and F-Itagua	
Sowing date (mm/dd/yy)	10/15/20	06/17/21	10/1/20	06/12/21
Germination date (mm/dd/yy)	10/24/20	07/04/21	10/13/20	06/22/21
Fertilizer application dates (mm/dd/yy), Fraction of dose (**kg ha^{-1}**), and Fertilizer sources	11/05/20 → **296** (U + KCl + ME + V + SF)	07/14/21 → **321** (U + KCl + ME + V + SF)	10/28/20 → **200** (TS)	07/06/21 → **200** (TS)
	11/17/20 → **200** (U + KCl + SAM + SCM)	07/27/21 → **250** (U + KCl + SAM + Active3+SM)	11/04/20 → **200** (TS)	07/13/21 → **200** (TS)
	11/30/20 → **225** (U + KCl + SAM)	08/10/21 → **275** (U + KCl + SAM + Active3+SM)	11/11/20 → **200** (TS)	07/21/21 → **200** (TS)
	12/17/20 → **200** (U + KCl + SAM + SM)	08/24/21 → **175** (U + KCl + SAM)	11/25/20 → **100** (TS)	08/23/21 → **75** (U)
Nitrogen applied (**kg N ha^{-1}**)	U + ME + V → **37**	U + ME + V → **48**	TS → **48**	TS → **48**
	U + SAM→ **34**	U + SAM + Active 3 → **37**	TS → **48**	TS → **48**
	U + SAM→ **50**	U + SAM + Active 3 → **58**	TS → **48**	TS → **48**
	U + SAM →**13**	U + SAM →**45**	TS → **24**	U → **35**
Harvest date (mm/dd/yy)	02/9–12/21	10/20–26/21	01/29/21	10/06/21

Fertilizer sources.
Urea (**U**) – 46% N; Potassium chloride (**KCl**) – 60% K_2O; MicroEssentials (**ME**) – 12% N (ammoniacal nitrogen), 40% P_2O_5, 10%S, 1% Zn; Vicor (**V**) – 3% N (ureic nitrogen), 15% CaO, 5% MgO, 3% S, 1% B, 0.02% Cu, 0.02% Mn, 2.5% Zn; Sulfazinc (**SF**) – 5.51% CaO, 4.39% S, 8.85% Zn, 36.12% SiO_2; Ammonium sulfate (**SAM**) – 21% N (ammoniacal nitrogen), 24% S; Sulcamag (**SCM**) – 3% P_2O_5, 25% CaO, 13% MgO, 8% S; SOL*MAG (**SM**) – 46% SiO_2, 4 % P_2O_5, 6% CaO, 20% MgO; **Active 3**–24% N (19.2% ureic nitrogen, 4.8% ammoniacal nitrogen), 17% P_2O_5, 5% Mg, 6% S, and urea (**U**) – 46% N; Third state (**TS**) – 24% N (22.4% ureic nitrogen, 1.6% ammoniacal nitrogen), 12% K_2O, 5.3% SiO_2 and 3% MgO.

linear interpolation between sampling dates. The GWP of each gas was calculated as 27.2 for CH_4 and 273 for N_2O, according to the Intergovernmental Panel on Climate Change (IPCC) GWP 100-year time horizon (IPCC, 2021).

2.3. Grain yield and aboveground biomass

The aboveground rice plant biomass was sampled at both sites during three phenological stages: floral primordium, maximum tillering, and flowering, for both seasons. The samples were collected by randomly placing 0.25 m^2 quadrants within the treatment plots and cutting all aboveground biomass (including stems, leaves, and panicles). Samples were dried at 70 °C until they reached constant weight (Yepes et al., 2011). A 20 m^2 area was harvested from each plot at physiological maturity to calculate rice-grain yield. The grains were dried in an oven at 70 °C for 72 h. The grain yield is reported at 14% grain moisture content.

2.4. Statistical analysis

Statistical analysis was performed using the R environment (R Development Core Team, 2004). Data were checked for independence, normality, and homogeneity of variance. The effects of season, rice variety, and their correlation with GHG emissions and rice yields were analyzed using analysis of variance (ANOVA) with repeated measuring of CH_4 and N_2O daily emissions performed separately using tidyverse and rstatix libraries (Kassambara, 2023). Relationships between the dependent variables of grain yield, biomass, GWP, CH_4, and N_2O emissions were analyzed using Pearson and Spearman correlation metrics. All differences were considered significant at the 95% level ($p < 0.05$) using Tukey's Honest Significant Difference (HSD) test for mean separation.

3. Results

3.1. Climatic conditions during crop development

The average minimum and maximum daily temperature ranges in Tolima were 23.3–31.8 °C in Season I and 22.9–32.5 °C in Season II (Fig. 1). Cumulative precipitation reached 371 and 633 mm for Seasons I and II, respectively. Similarly, in Casanare, the average minimum and maximum daily temperature ranges were 22.5–32.2 °C for Season I and 22.5–30.7 °C for Season II. The cumulative precipitation was 363 mm for Season I and 691 mm for Season II. The relative humidity, on average, was lower in Season II compared to Season I in Tolima, but not in Casanare (Fig. 2).

3.2. Daily CH_4 and N_2O emissions

The pattern of CH_4 and N_2O emissions differed across locations and between seasons (Fig. 3). Higher CH_4 emissions were observed at Tolima than at Casanare, with the two highest peaks occurring for F67 (138 and 69 mg CH_4 - C m^{-2} d^{-1} in Seasons I and II, respectively), and considerably lower peaks for F2000 in Casanare (16 and 9 mg CH_4 - C m^{-2} d^{-1} in Seasons I and II, respectively). By contrast, higher N_2O emissions were found at Casanare, particularly during the first growing season. In Casanare, F70 and F2000 produced the highest N_2O fluxes during Seasons I and II, respectively (90 and 11 mg N_2O - N m^{-2} d^{-1}, respectively), while lower N_2O emission peaks occurred each season in Tolima for F68 and F2000 (25 and 8 mg N_2O - N m^{-2} d^{-1}, respectively). At both sites, slightly higher CH_4 and N_2O fluxes occurred during the dry season due to lower precipitation. However, precipitation and temperature did not have a significant correlation with daily CH_4 and N_2O emissions at either site ($P > 0.05$).

Daily CH_4 fluxes in Tolima exhibited a similar variation across different varieties throughout the first 60 days of both growing seasons. However, CH_4 emissions for F67 and F70 increased during the flowering stage, when a constant layer of water was maintained on the soil until physiological maturity. For F67, these CH_4 emission peaks during flowering contributed to 50–90% of total emissions in both seasons. On the other hand, daily CH_4 fluxes in Casanare remained relatively low throughout both growing seasons across all varieties.

Peak N_2O fluxes were associated with fertilizer application events in both sites, which varied according to the timing of the emissions and effect of the different rice varieties (Fig. 3). For example, three days after the second fertilizer application in Season I in Tolima, N_2O emissions

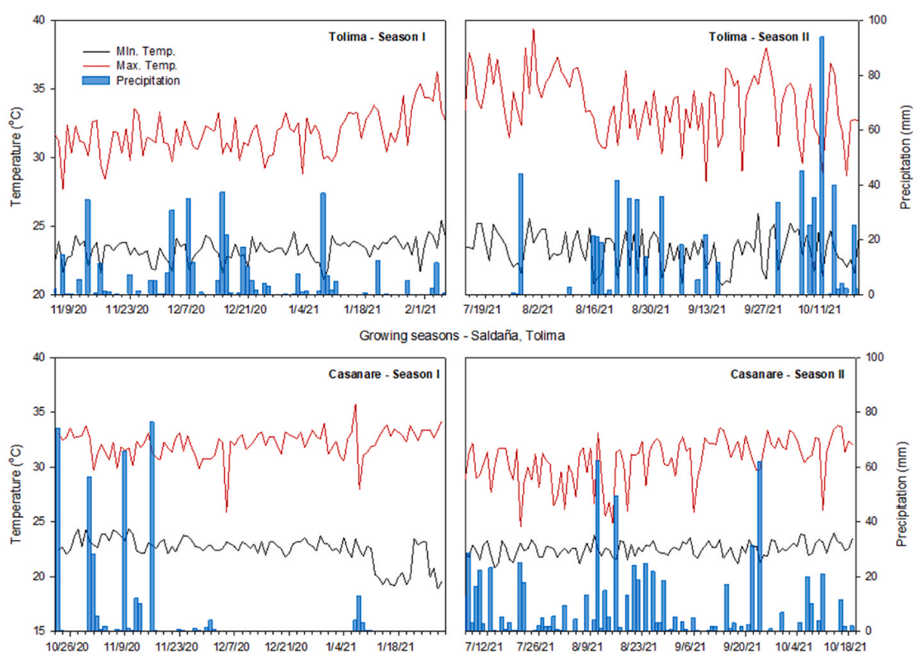

Fig. 1. Minimum and maximum temperature and precipitation at the Tolima–Saldaña and Casanare–Aguazul during two rice-growing seasons (Season I and Season II) in 2020 and 2021.

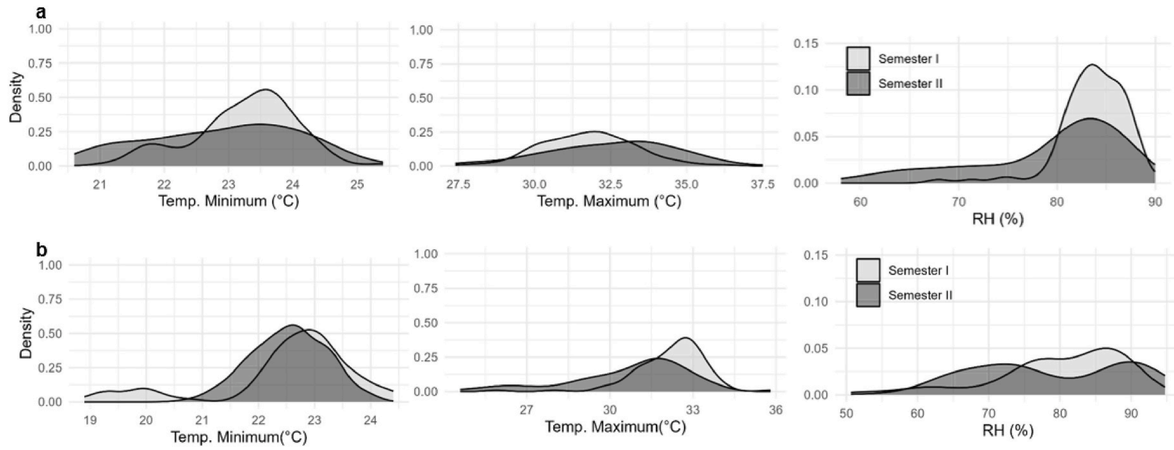

Fig. 2. Frequency distribution for climatic variables including minimum and maximum temperature, and relative humidity (RH) for Seasons I and II in Tolima (a) and Casanare (b).

increased for all varieties. In Season II, the main N_2O emission peak was observed for F2000 three days after the fourth application of fertilizer. In Casanare, the peak N_2O flux was for F70 in Season I following the third application of fertilizer and for F2000 in Season II after the first application of fertilizer. Generally, N_2O emissions remained between 5 and 10 mg N_2O - N m^{-2} d^{-1}, except in Casanare, where high emissions were observed for several sampling events early in Season I.

3.3. Grain yield and aboveground biomass

Significant differences in grain yields were observed among rice varieties during Season I under dry weather conditions (Table 2). In Tolima, yields for 68 were 26% and 30% lower than for F2000 and F70, respectively, whereas rice-grain yields for F67 and F68 did not differ significantly. Meanwhile, F-Itagua produced a 12–17% lower yield compared to F67, F70, and F2000 in Casanare. However, there were no yield differences in Season II under wet weather conditions in either location. Generally, higher grain yields were observed for Season II compared to Season I in Tolima, whereas productivity levels were similar for both seasons in Casanare.

Several differences in the varieties' aboveground biomass were observed for different phenological stages (Table 2). In Tolima, F2000 had lower aboveground biomass at primordium during Season I, while F68 and F70 had lower aboveground biomass at primordium and F67 at flowering in Season II. In Casanare, only F70 had lower aboveground biomass at maximum tillering in Season II. However, none of the rice biomass differences translated into significantly lower or higher grain yields. Comparing the two cropping seasons at Tolima, relatively higher aboveground biomass was observed at primordium and at maximum tillering during Season II, but not Season I. Aboveground biomass at different phenological stages was similar for both seasons in Casanare.

3.4. Cumulative GHG emissions and GWP

In Tolima, GWP ranges were 537–809 and 349–605 kg CO_2 equivalents ha^{-1} for Seasons I and II, respectively (Table 3). Variety had a significant effect on CH_4, N_2O emissions and GWP. The varieties exhibiting the highest GWP were F68 and F70 in Seasons I and II, respectively. By comparison, the other two varieties (F67, F2000) both exhibited lower GWP in Seasons I and II, whereas only F67 showed significantly lower GWP in Season II. F67 exhibited reduced N_2O emissions in both seasons, particularly because of several negative flux dates in Season II; however, F67 also produced the highest CH_4 emissions in both seasons. Meanwhile, F2000 had lower CH_4 emissions with moderate to high N_2O emissions compared to other varieties. In Season II, all varieties showed higher CH_4 and lower N_2O emissions (Table 3), as evidenced by a significant variety-by-season interaction for CH_4 and N_2O emissions ($p = 0.01$). Yet, there was no significant correlation between weather conditions and GHG emissions detected in either season. During the dry season in Tolima, CH_4 and N_2O emissions contributed approximately 13–76% and 24–91% to GWP, respectively (31% and 69% across varieties). During the wet season, CH_4 and N_2O emissions contributed to approximately 40–100% and 0–60% of total GWP (62% and 38% across varieties).

In Casanare, GWP ranges were 9,264,704 and 544–935 kg CO_2 equivalents ha^{-1} for Seasons I and II, respectively. Variety had a significant effect on CH_4 and N_2O emissions, and GWP. The variety with the highest GWP in both seasons was F67; F70, F2000, and F-Itagua all exhibited a lower GWP in Season I, while only F-Itagua exhibited a lower GWP in both seasons. F-Itagua had the lowest N_2O emissions in both seasons and was among the lowest CH_4 emitting varieties/emitters. Emissions of both gases were lower in the Season II than in Season I. No significant correlations were observed among soil GHG emissions, yield, aboveground biomass, and meteorological conditions. During the dry season, CH_4 and N_2O emissions contributed approximately 1–27% and 73–99% to GWP, respectively (9% and 91%, respectively across varieties). During the wet season, CH_4 and N_2O emissions contributed approximately 3–9% and 91–97% to total GWP (5% and 95%, respectively across varieties).

4. Discussion

4.1. Grain yields under intermittent irrigation

The rice varieties evaluated in this study produced moderate to high grain yields under intermittent irrigation, ranging from 4.2 to 7.3 Mg ha^{-1} during the study period (Table 1). Rice varietal selection plays a significant role in cropping-system yield potential, due to varying morphological, physiological, and biochemical responses under different weather conditions (Laenoia et al., 2018; Luo et al., 2019). Comparing the Tolima to Casanare experiments, an important finding is that yield reductions were observed for several varieties in the dry season at both locations, but not during the wet season. Interestingly, this result occurred despite weather differences between regions in the dry season (Figs. 1 and 2). For example, while total precipitation (363–371 mm) was similar at both sites, it was more evenly distributed in Tolima and less evenly distributed in Casanare, with the majority of rainfall occurring early in the growing season in Casanare. Meanwhile, the range of relative humidity and maximum and minimum temperatures observed in Tolima potentially induced thermal stress, while the frequency distributions for these weather variables were more favorable in Casanare (Fig. 2).

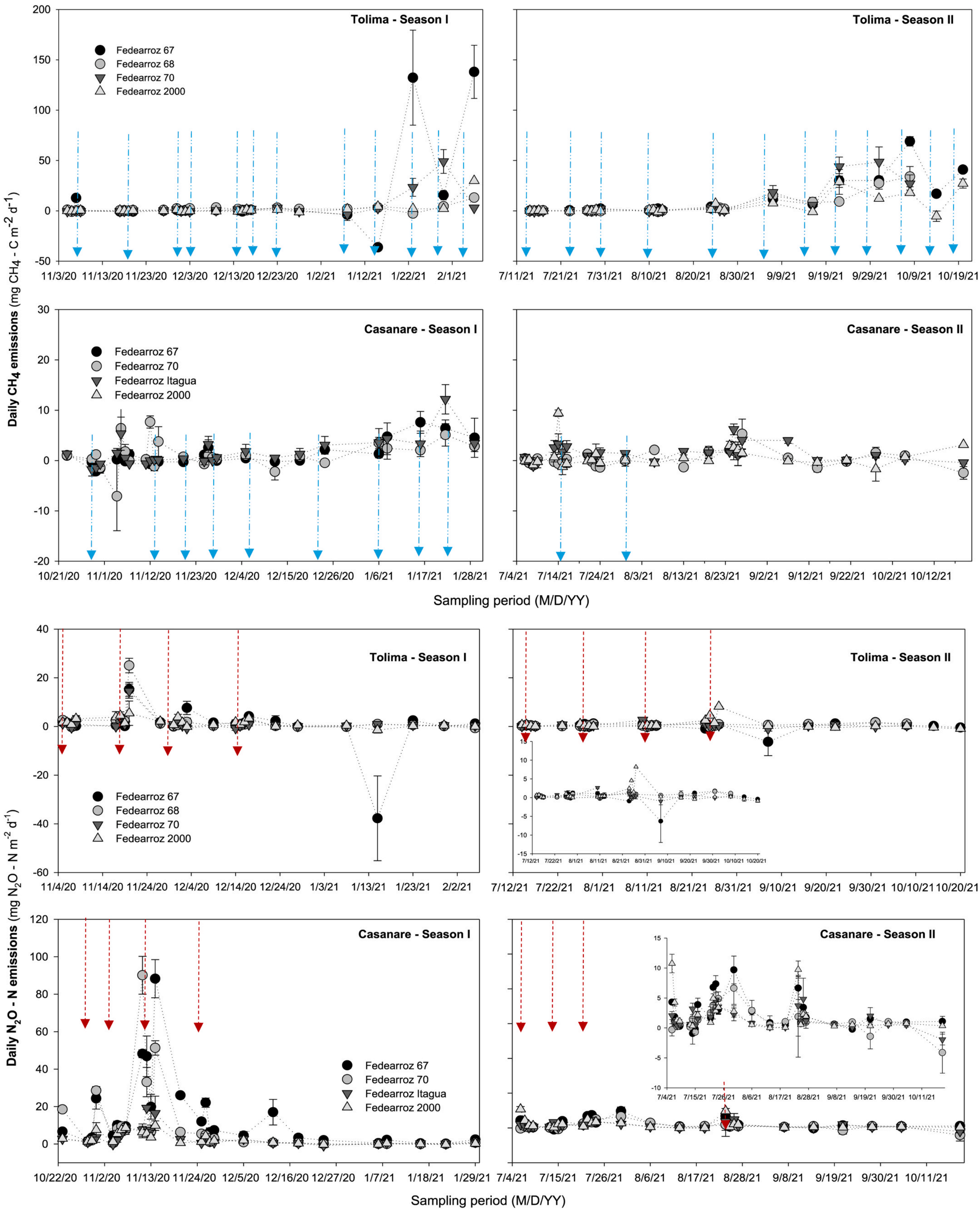

Fig. 3. Daily CH_4 and N_2O fluxes from four rice varieties during two seasons at Tolima and Casanare experimental sites. Daily CH_4 - C emission - Seasons I and II; Daily N_2O - N emission - Seasons I and II. Error bars indicate ± SE (n = 3). Blue arrows in the CH_4 graphs indicate the irrigation events, while red arrows in the N_2O emission graphs denote fertilizer events.

Table 2
Rice aboveground biomass for different growth stages and grain yield in Tolima and Casanare regions. Values followed by the same letter are not significantly different within each column at $p < 0.05$.

Seasons	Tolima							
	I				II			
	Aboveground biomass (Mg ha^{-1})			Grain yield (Mg ha^{-1})	Aboveground biomass (Mg ha^{-1})			Grain yield (Mg ha^{-1})
Treatments	Primordium	Maximum tillering	Flowering		Primordium	Maximum tillering	Flowering	
F67	4.6 ± 0.1 ab	9.5 ± 0.5 a	12.3 ± 0.9 a	4.8 ± 0.1 ab	7.5 ± 0.9 a	11.4 ± 1.2 a	12.8 ± 0.8 b	7.3 ± 0.4 a
F68	5.3 ± 0.2 ab	10.0 ± 0.2 a	13.3 ± 1.2 a	4.2 ± 0.3 b	4.7 ± 0.4 b	11.8 ± 0.5 a	15.4 ± 0.9 a	6.7 ± 0.3 a
F70	5.5 ± 0.4 a	9.7 ± 0.6 a	14.3 ± 1.5 a	6.0 ± 0.1 a	3.7 ± 0.6 b	9.8 ± 0.6 a	13.7 ± 0.6 ab	6.7 ± 0.3 a
F2000	4.3 ± 0.03 b	9.7 ± 0.3 a	12.9 ± 0.6 a	5.7 ± 0.6 a	7.8 ± 0.5 a	11.8 ± 1.0 a	13.3 ± 0.5 ab	6.1 ± 0.1 a
Seasons	**Casanare**							
	I				**II**			
	Aboveground biomass (Mg ha^{-1})			**Grain yield (Mg ha^{-1})**	**Aboveground biomass (Mg ha^{-1})**			**Grain yield (Mg ha^{-1})**
Treatments	**Primordium**	**Maximum tillering**	**Flowering**		**Primordium**	**Maximum tillering**	**Flowering**	
F67	5.0 ± 0.4 a	10.6 ± 0.8 a	13.9 ± 0.8 a	5.0 ± 0.01 a	4.6 ± 0.3 a	8.7 ± 0.1 a	13.2 ± 1.0 a	5.5 ± 0.4 a
F70	4.1 ± 0.3 a	6.8 ± 1.2 a	11.6 ± 1.3 a	5.1 ± 0.1 a	3.4 ± 0.3 a	5.0 ± 0.3 b	9.4 ± 0.8 a	5.2 ± 0.2 a
F2000	3.8 ± 0.1 a	8.2 ± 0.6 a	13.5 ± 1.3 a	5.3 ± 0.05 a	3.1 ± 0.2 a	7.1 ± 0.5 ab	11.6 ± 0.5 a	5.9 ± 0.2 a
F-Itagua	4.2 ± 0.6 a	8.9 ± 1.1 a	11.0 ± 1.2 a	4.4 ± 0.1 b	3.5 ± 0.5 a	7.6 ± 1.1 ab	11.6 ± 1.2 a	5.5 ± 0.4 a

Table 3
Cumulative CH_4 and N_2O emissions from four rice varieties and the corresponding Global Warming Potential (GWP) (kg CO_2 equivalents ha^{-1}). Values represent the mean ± SE. Within each column, values followed by the same letter are not significantly different at the 0.05 level.

	Tolima					
	Season I – 2020			Season II – 2021		
Varieties	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	GWP (kg CO_2 eq. ha^{-1})	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	GWP (kg CO_2 eq. ha^{-1})
F67	17.6 ± 3.1 a	0.5 ± 0.2 c	**631 b**	18.4 ± 0.6 a	−0.5 ± 0.1 c	**349 b**
F68	2.6 ± 0.1 b	2.7 ± 0.1 a	809 a	8.9 ± 1.0 b	1.1 ± 0.1 a	540 a
F70	6.7 ± 0.3 b	1.6 ± 0.2 b	633 b	14.4 ± 1.6 a	0.8 ± 0.1 b	605 a
F2000	2.5 ± 0.2 b	1.7 ± 0.05 b	**537 b**	7.8 ± 0.9 b	1.2 ± 0.1 a	**534 a**
	Casanare					
	Season I – 2020			**Season II – 2021**		
Varieties	**CH_4 (kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 eq. ha^{-1})**	**CH_4 (kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 eq. ha^{-1})**
F67	2.3 ± 0.2 b	17.0 ± 0.7 a	4704 a	1.0 ± 0.01 bc	3.3 ± 0.5 a	935 a
F70	1.7 ± 0.2 b	10.8 ± 0.5 b	2994 b	1.5 ± 0.3 b	2.9 ± 0.2 ab	828 ab
F2000	11.4 ± 3.2 a	3.1 ± 0.9 c	1165 c	0.9 ± 0.3 c	2.1 ± 0.2 ab	604 ab
F-Itagua	2.3 ± 0.6 b	3.2 ± 0.6 c	**926 c**	1.8 ± 0.3 a	1.8 ± 0.4 b	**544 b**

Peng et al. (2004) and Qiong et al. (2023) demonstrated that heat stress can reduce crop yields by approximately 7–10% for every degree Celsius increase above the average temperature. Thus, in Tolima the increase in minimum temperature by more than 5 °C, combined with high humidity levels of 80–90% during the reproductive growth stage, may explain the larger yield reduction for F68 observed at this location in the dry season. Thermal stress and high relative humidity may cause spikelet sterility due to reduced pollen production and increased respiration rates (Matsui, 2009; Mohammed and Tarpley, 2010). In addition, by shortening the growth period before reaching physiological maturity, seed production and grain yield can be reduced as a result of shortened embryo and endosperm development (Sanwong et al., 2023).

The intermittent irrigation program implemented during vegetative growth may also have contributed to crop water stress in the dry season. Research has shown the benefits of correctly managed intermittent irrigation coupled with fertilizer application in helping to reduce water use by around 20−40% or more, while increasing fertilizer efficiency (Bo et al., 2022; Thakur et al., 2014). However, this approach requires greater control over irrigation timing and soil moisture management compared to flooded rice systems, with frequent field drainage events possibly increasing the risk of crop water stress during key phenological growth stages (Carrijo et al., 2017; Feng et al., 2021). Low precipitation during the dry season in our study likely affected the ability to maintain sufficient soil water status between irrigation events and a constant flood layer during the reproductive phase, especially in Casanare where irrigation water was not as consistently available, depending on the base flow of the Charte River.

Water stress during the early reproductive and flowering stages negatively impacts yield (Boonjung and Fukai, 1996; Zaman et al., 2018) by adversely impacting gas-exchange capacity, especially stomatal conductance and photosynthesis (Anjum et al., 2011). This is consistent with our observed decrease in aboveground biomass during rice development in the dry season trials, particularly during maximum tillering and flowering (Table 1). Bahuguna et al. (2018) and Nithya et al. (2020) demonstrated that during a 15-day drought period in the rice reproductive stage, yields were reduced by up to 88% when measured during flowering and 52% during grain fill. In these studies, drought during the flowering stage resulted in incomplete panicle development, with 30% spikelet sterility and a 20−46% reduction in seed production in several rice varieties. However, it is likely that the occurrence of relatively brief drainage periods and aerobic soil conditions only induced moderate crop water stress in our study, with yield reductions ranging from 12 to 17% and 26−30% at Casanare and Tolima, respectively (Table 1).

Wet season yields were generally 2−3 Mg ha^{-1} higher than the dry season yields in Tolima, but not Casanare. Torres and Henry (2018) and

Noor et al. (2019) also reported higher rice yields for wet compared to dry seasons. As noted above, water and heat stress during the dry season can reduce root dry weight and stomatal conductance. The varieties evaluated here are commercially available and widely grown in each region, with significant on-farm yield variation observed in earlier research, owing to differences in climate and agronomic management (Delerce et al., 2016). For the most productive varieties in the present study, previous reports have shown that F67, F70, and F2000 have intermediate–late growth periods, good resistance to temperature change, and high grain-yield capacity (Fedearroz, 2000a, 2000b, 2009). Additionally, these varieties have intermediate–high tiller numbers with a similar N requirement (24 kg N Mg^{-1}). The absence of yield differences among varieties during the wet season in both locations is consistent with previous studies on intermittent irrigation, which generally show minor changes in yield (Carrijo et al., 2017; Feng et al., 2021; Wang et al., 2016, 2017). These results underscore the importance of timely management of water inputs when practicing intermittent irrigation, especially when coupling fertilization events with field drainage periods during vegetative growth as a strategy for enhancing yields and fertilizer-use efficiency.

4.2. CH_4 and N_2O emissions

Cumulative CH_4 emissions (0.9–18.4 kg CH_4 ha^{-1}) and GWP (4704 and 544–935 kg CO_2 equivalents ha^{-1}) were relatively low compared to prior studies for irrigated rice systems (Table 3). A recent global synthesis reported an average of 283 kg CH_4 ha^{-1} and 7870 kg CO_2 equivalents ha^{-1} per year, with CH_4 contributing to around 94% of total GWP (Qian et al., 2023). By contrast, CH_4 contributed only 5–9% to GWP across two seasons in Casanare and 32–63% to GWP across two seasons in Tolima. The relatively low CH_4 emissions in both sites can be attributed to intermittent irrigation practices applied during vegetative growth, with repeated cycles of soil drainage and aeration suppressing methanogenesis (Conrad, 2007; Malyan et al., 2021; Singh et al., 2018). Our findings corroborate the broader literature documenting intermittent irrigation as an effective GHG mitigation practice in rice systems (Bo et al., 2022; Carrijo et al., 2017; Jiang et al., 2019).

Soil CH_4 emissions primarily increased during reproductive growth, when flooded soil conditions were maintained to sustain yields and prevent stress (Fig. 3). Yet there was variation in CH_4 flux across sites, with the most significant CH_4 emissions recorded at the end of both growing seasons in Tolima. In soils isolated beneath a water layer, the loss of oxygen leads to a decrease in redox potential, triggering methanogenesis and subsequently increasing CH_4 concentrations, favoring emissions transported through the rice plant to the atmosphere in waterlogged soils (Ma et al., 2010; Humphreys et al., 2019). Our observation that the highest daily CH_4 emissions occurred during the continuous flooding period, encompassing tillering, flowering, and grain filling, is supported by previous work (Habib et al., 2023; Malayan et al., 2016). Compared to Tolima, CH_4 emissions remained at lower levels for both seasons in Casanare. The rice varieties' successful adaptation to the local climatic conditions, combined with early season management of water resources, may have helped the rice plants to develop constitutive aerenchyma, which promoted oxygen diffusion into the soil without experiencing notable abiotic stress (Yamauchi and Nakazono, 2022).

Soil N_2O emissions generally occurred during vegetative growth due to repeated flood–drain intermittent irrigation cycles and fertilizer application (Fig. 3). The magnitude of N_2O emissions was generally around 1–3 kg N_2O-N ha^{-1}, except for the dry season in Casanare where it ranged from 3 to 17 kg N_2O-N ha^{-1}. Accordingly, N_2O emissions represented 37–68% and 90–95% of GWP at the two sites, respectively. There is a known risk of elevated N_2O emissions when rice soils are not flooded and alternating wet–dry cycles stimulate nitrification–denitrification reactions, especially when sufficient C and N substrates are present (Firestone and Davidson, 1989; Zhou et al., 2020). Thus, while drainage periods are effective for reducing CH_4 emissions, the associated increase in N_2O emissions may present a tradeoff for GWP (Hung et al., 2022; Jiang et al., 2019). Evidence for this was the relatively low CH_4 emissions coupled with high N_2O emissions in Casanare, resulting in a four-fold increase in GWP when averaged across varieties compared to other seasons, while the opposite was observed in Tolima.

One reason for the low N_2O emissions in Tolima may be that the applied N fertilizer was ammonium sulfate. Hence, the NH_4^+ had to undergo nitrification and then denitrification before it was susceptible to atmospheric losses, allowing better NH_4^+ capture by the plants while also reducing nitrate leaching into the soil (Mazzetto et al., 2020; Rahman and Forrestal, 2021). Another probable factor was the improved soil moisture control during irrigation and fertilizer application events. Water levels were accurately maintained between saturation and field capacity at this site, facilitating N absorption in roots and limiting the nitrification and denitrification processes contributing to N_2O emissions (Chapuis-lardy et al., 2007; Loaiza et al., 2024). On the other hand, higher N_2O emissions in Casanare may have been related to urea application, which can increase soil pH and stimulate denitrification, especially in combination with labile C availability (Weier et al., 1993). Intermittent irrigation practices may have also promoted soil organic carbon mineralization and nitrification of applied N fertilizer, especially during the dry season, which could have increased denitrification rates (Arce et al., 2018; Congreves et al., 2018).

4.3. Effect of rice varieties on GWP mitigation

Two rice varieties displayed promising GHG mitigation under intermittent irrigation in Tolima and Casanare. Notably, these effects were primarily achieved by a reduction in N_2O emissions rather than in CH_4 emissions, resulting in an overall decrease in GWP. In Tolima, F67 exhibited reduced N_2O but not CH_4 emissions, while only F-Itagua exhibited reduced N_2O emissions in Casanare, but produced mixed effects related to CH_4 emissions (Table 3).

The importance of N_2O mitigation for lowering GWP in rice systems is a newer finding compared to previous work, which has mostly occurred under flooded conditions and focused on the reduction of CH_4 emissions (Qian et al., 2023). Relatively little research has focused on the mechanisms by which varieties can reduce N_2O emissions for rice systems experiencing frequent flood–drain cycles. Some studies in the broader literature show that reductions in N_2O emissions can be due to the release of carbon substrates from roots, fueling denitrification (Gu et al., 2017; Van Groenigen et al., 2015). Others have reported that it may be related to changes in soil inorganic N dynamics (Firestone and Davidson, 1989; Kim et al., 2021; Zhou et al., 2020). For example, F67 in the current study may have produced lower N_2O emissions because of its higher tissue N requirements for foliar development, favoring root N acquisition rather than microbial activity leading to gaseous N losses.

Most studies to identify rice varieties for GWP mitigation have focused on CH_4 emissions. We also found differences among varieties, with F2000 producing the lowest and F67 having the highest CH_4 emissions in Tolima. This difference is possibly related to variations in the morphology and physiology of the rice plant, such as the presence and architecture of aerenchyma, which can influence the transport of CH_4 from the roots to the atmosphere (Gupta et al., 2016; Kim et al., 2018; Iqbal et al., 2021; Yuan et al., 2023). It is conceivable that F2000 may possess constitutive aerenchyma that can rapidly increase root porosity, facilitating oxygen diffusion and root elongation, thereby promoting CH_4 oxidation (Visser et al., 2000; Gutierrez et al., 2013; Jiang et al., 2017). In contrast, F67 might exhibit inducible aerenchyma, providing more resistance to air diffusion under abiotic stress conditions, indicating this variety is more susceptible to adverse weather conditions (Colmer and Voesenek, 2009; Yamauchi and Nakazono, 2022).

In another study on continuous flooding in Colombia, daily CH_4 emissions were strongly correlated with aboveground biomass at maximum tillering, as well as root length, root volume, and root surface area (Soremi et al., 2023). This illustrates how different varieties can affect soil microbial communities, the supply of C substrates, and gas transport pathways through roots and plant tissues. Aulakh et al. (2000) also demonstrated that tiller number was related to CH_4 transport capacity in different varieties, indicating that the number of transport channels rather than plant size or biomass determines CH_4 emissions. By contrast, other studies have found that aboveground traits are poor predictors of CH_4 emissions. Zhang et al. (2015) compared 66 rice varieties and found that CH_4 flux was not driven by differences in plant biomass, but was strongly correlated with dissolved CH_4 in soil solution, supporting the conclusion that differences in CH_4 emissions among varieties were primarily due to changes in belowground CH_4 production and oxidation. Similarly, Gutierrez et al. (2013) found that CH_4 fluxes were significantly correlated with methanogen and methanotroph abundances, but not with any of the measured physiological and anatomical characteristics of different rice varieties. Meanwhile, Ma et al. (2010) reported that rice varieties with higher aboveground biomass reduced CH_4 emissions, most likely by increasing CH_4 oxidation potential, highlighting the importance of variety effects on microbial communities. Future research must adopt an integrated approach to investigating variety effects of CH_4 emissions under intermittent irrigation, considering the multiple mechanisms related to CH_4 production in soil and subsequent transport through plants. For example, understanding potential interactions and tradeoffs between CH_4 oxidation within the rice rhizosphere and plant-mediated gas transport to the atmosphere among varieties is necessary, especially in response to different environmental and management factors (Bhattacharyya et al., 2019).

4.4. Broader implications

The findings of this study underscore the potential for mitigating GHG emissions through the selection of rice varieties that reduce N_2O emissions without increasing CH_4 emissions under intermittent irrigation. Previous studies have compared varieties in regions outside of Latin America to highlight differences in CH_4 emissions (Bhattacharyya et al., 2019; Susilawati and Setyanto, 2018; Yu et al., 2022), yet variety selection has yet to be extensively studied or recognized as a GHG-mitigation strategy in Latin America, as reported by Chirinda et al. (2018). By selecting varieties with favorable GHG-emission profiles and implementing intermittent irrigation with appropriately timed N fertilizer application events, our study identified a 32−61% reduction in GWP across two seasons (wet and dry) in two different regions in Colombia. Recent studies elsewhere have also shown that variety selection can significantly impact both grain yield and GWP. For instance, Jiang et al. (2017) showed that high-yielding rice cultivars reduce CH_4 emissions, with the authors estimating that increasing rice biomass by 10% could reduce annual CH_4 emissions from Chinese rice agriculture by 7%. Zheng et al. (2014) also found lower yield-scaled GWP for Japonica (711 kg CO_2 equivalents Mg^{-1}) than Indica rice varieties (1102 kg CO_2 equivalents Mg^{-1}), attributing these differences to variation in gas-transport capacity among rice varieties.

An important implication of this work is that N_2O needs to be recognized as a pathway for GWP mitigation in non-continuously flooded rice production systems. Despite a historical focus on water management and C inputs for CH_4 mitigation, more research is needed to identify varieties for reducing N_2O emissions in different rice production contexts. Water shortages are increasing worldwide and there is interest in intermittent irrigation to reduce the water footprint and associated GWP of rice systems (Bo et al., 2022). However, introducing more-frequent drainage periods will change soil C and N cycling, with consequences for which GHG mitigation practices should receive the most attention. Compared to flooded systems, we note that investigating controls on N_2O emissions under intermittent irrigation is more complex due to extreme fluctuations in soil-water content, with rapid changes in O_2 availability, microbial activity, and C and N transformations causing peak flux events. Under flooded conditions, N_2O has been found to travel through the plant (Timilsina et al., 2020; Yan et al., 2000), while under drained conditions it is released through the soil (Yan et al., 2000), indicating that different mechanisms may be more or less desirable, depending on the irrigation regime.

5. Conclusions

Results from this study demonstrate considerable potential for mitigating GHG emissions from rice systems under intermittent irrigation without sacrificing food security by strategically selecting rice cultivars that decrease N_2O emissions without increasing CH_4 emissions. Yield differences were not observed in the wet season at either test site, but several varieties produced lower yields in the dry season at both locations, likely due to water stress during soil-drainage periods. Meanwhile, F67 in the Tolima region and F-Itagua in the Casanare region reduced overall GWP by 1–42% and 9−80%, respectively, compared to other varieties. A key finding from this study is that GWP mitigation was primarily achieved through a decrease in N_2O rather than CH_4 emissions. The higher GWP in Casanare was largely driven by high N_2O emissions observed in F67 and F70 in the dry season, resulting in an additional release of 7–14 kg N_2O ha^{-1}, thereby increasing GWP by 1910−3620 kg CO_2 equivalents ha^{-1}. Thus, N_2O was the major contributor to GWP in both seasons due to intermittent irrigation practices, ranging from 73% to 99% in the dry season and 91%–97% in the wet season across sites. These results highlight the need for rice variety development focusing on N_2O emission reductions as an important pathway for GWP mitigation in non-continuously flooded rice systems. Moreover, these findings showcase the adaptability and resilience of commercially available rice varieties under different climate and soil conditions across regions, providing a foundation for broader GHG mitigation efforts in the Colombian rice sector. This research considered key factors such as geography, climate, production systems, locally adapted rice varieties, and robust GHG monitoring. The insights generated are valuable for research centers, farmer federations, and local producers, in addressing the environmental challenges for sustainable rice production. The findings show that GHG emissions can be mitigated through efficient irrigation and climate-suited rice varieties. By reducing emissions and optimizing water and soil management, this work supports global Sustainable Development Goals, including achieving Clean Water and Sanitation, Climate Action, and Zero Hunger, while aligning with international commitments to emissions reduction and sustainable agriculture in Colombia and beyond.

CRediT authorship contribution statement

Sandra Loaiza: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Louis Verchot:** Writing – review & editing, Supervision, Investigation. **Drochss Valencia:** Writing – review & editing, Supervision, Conceptualization. **Ciniro Costa:** Writing – review & editing, Conceptualization. **Catalina Trujillo:** Writing – review & editing, Methodology. **Gabriel Garcés:** Writing – review & editing, Methodology. **Oscar Puentes:** Writing – review & editing, Methodology. **Jorge Ardila:** Writing – review & editing, Methodology. **Ngonidzashe Chirinda:** Writing – review & editing, Methodology. **Cameron Pittelkow:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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