Sustainable Optimization of Rice Production in Colombia: Integrating Intermittent Irrigation Strategies, Cultivar Selection, and Heat-Resistant Genotypes for Greenhouse Gas Emission Mitigation and Preservation of Agricultural Yields in Diverse Climatic Conditions

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Abstract

Enhancing the sustainability of rice production in Latin America is crucial to preserve natural ecosystems, prevent soil degradation, and contribute to climate change mitigation. Through a series of four experiments, this study addressed specific challenges related to water management, rice variety selection, and identifying genotypes resistant to high temperatures for reducing greenhouse gas (GHG) emissions. Implementing practices such as alternate wetting and drying (AWD) irrigation was explored to maintain crop yields while reducing environmental impact. Various rice cultivars were assessed for methane (CH_4) and nitrous oxide (N_2O) emissions, grain yield, and their contribution to global warming. The shift from continuous flooding to intermittent irrigation in different Colombian regions revealed significant benefits in emission reduction and crop yield preservation. Efficient fertilizer application and optimal water management emerged as critical practices for achieving more sustainable rice production. In summary, this study provides a comprehensive and strategic perspective to enhance the sustainability of rice production, considering efficient water management and GHG emission reduction in specific regional contexts.

The escalating demand for rice in Latin America necessitates sustainable irrigation practices to address water scarcity and reduce GHG emissions. This study investigates the potential of AWD irrigation compared to conventional methods in tropical rice cultivation in Colombia. Over four seasons, AWD treatments (AWD_{5cm} and AWD_{10cm}) demonstrated a 19-56% reduction in cumulative water use, particularly in dry seasons. Additionally, AWD significantly lowered CH_4 emissions by 72-100% and N_2O emissions by 12-70%, resulting in a global warming potential (GWP) reduction of 25-73% compared to the control, with minimal impact on crop productivity (5.2-8.2 Mg ha^{-1}). The findings suggest that AWD is a promising strategy for mitigating GHG emissions in tropical rice cultivation despite adoption barriers.

Cultivar selection emerges as a critical factor in GHG mitigation, as demonstrated in a parallel study on four commercial rice cultivars in two regions of Colombia. Results indicated that CH_4 emissions and GWP were relatively low due to frequent field drainage, with N_2O emissions as the majority contributor to the GWP. Specific varieties, such as F-67 and F-Itagua, significantly reduced GWP by 32-61%, primarily through N_2O emissions reduction. This study highlights the role of rice variety selection in reducing N_2O emissions under non-continuously flooded irrigation, a practice crucial in addressing climate change and water shortages.

Furthermore, this research contrasts the impact of water management in intermittent and flooded rice irrigation treatments across two Colombian regions, Tolima, and Casanare. Evaluating CH_4 and N_2O emissions, GWP, and crop yield for two commercial rice varieties reveals that transitioning from flooding to intermittent irrigation significantly reduces CH_4 emissions by approximately 100% in both regions. Notably, a 54 to 78% reduction in N_2O emissions is observed in Tolima, 6 to 46% in rainfed systems, and 100% in irrigated systems with soil moisture management during fertilization in Casanare. Overall, GWP sees a reduction ranging from 62 to 85% in

Tolima, 14 to 62% in rainfed systems, and 100% in the irrigated system in Casanare, highlighting the potential of intermittent irrigation in minimizing overall GWP and preserving yields.

Lastly, a focused investigation on two commercial rice varieties with mitigation potential and heat-resistant genotypes in the Tolima region under intermittent irrigation and flooding conditions revealed reduced CH_4 emissions (74-75% in commercial varieties, 81-95% in genotypes) and a 61-85% reduction in GWP. No significant differences in N_2O emissions between cultivars and treatments were observed, emphasizing the role of water resource management over cultivar selection. Despite yielding valuable insights and acknowledging study limitations, future research is proposed to explore the impact of extreme climatic conditions on the sustainability and productivity of different rice cultivars.

This research opens the door to a deeper study of mitigation strategies in various aspects of rice agronomic practices, such as planting types, fertilizer management, and genotype selection. The goal is to determine the environmental impact of these strategies without compromising farmers' food and economic security. Additionally, this study provides a crucial knowledge base on the behavior of rice crops under different irrigation management practices in contrasting rice-growing conditions. It also offers valuable information on CH_4 and N_2O emission factors, making significant contributions to the development of national and departmental inventories of greenhouse gases in Colombia. These contributions are essential for strengthening Nationally Appropriate Mitigation Actions (NAMAs). Moreover, it aims to support farmers by enabling them to assess and consider which agronomic practices can effectively reduce environmental impact and improve their socio-economic and food security conditions.

This research was conducted in four stages:

I. Evaluation of the environmental impact of adapting AWD irrigation technology in rice cultivation, specifically for the Tolima rice-growing region, compared to traditional irrigation management.

II. Identification of commercial rice varieties with CH_4 and N_2O reduction potential in two rice-growing regions, Tolima and Casanare.

III. Environmental impact analysis of GHG reduction through intermittent irrigation compared to continuous flooding, considering the two most representative rice-growing regions, Tolima and Casanare, without affecting yields.

IV. Evaluation of the impact of genotypes adapted to high-temperature conditions compared to commercial rice varieties in terms of GHG mitigation potential.

In these stages, various aspects related to agronomic practices, the sustainability, and environmental efficiency of agronomic practices in rice production were examined, considering regional and genotypic variability.

Keywords: Intermittent irrigation, Continuous flooding, Methane (CH_4), Nitrous oxide (N_2O), Food security, Global warming potential (GWP), Cultivar, Alternative wetting and drying (AWD), Yield.

Resumen

La sostenibilidad en la producción de arroz en América Latina es crucial para preservar nuestros ecosistemas, prevenir la degradación del suelo y contribuir a la mitigación del cambio climático. Este estudio se centró en enfrentar desafíos específicos relacionados con la gestión del agua, las emisiones de gases de efecto invernadero (GEI), la selección de variedades de arroz e identificación de genotipos resistentes a condiciones de altas temperaturas. La implementación de prácticas como el riego de alternancia de inundación y secado (AWD) se exploró como estrategia para mantener los rendimientos del cultivo, reduciendo al mismo tiempo el impacto ambiental. Se evaluaron diversos cultivares en términos de emisiones de metano (CH_4) y óxido nitrosos (N_2O), rendimiento del grano y su contribución al calentamiento global. Además, se investigó el cambio de inundación a riego intermitente en diversas regiones colombianas, revelando beneficios significativos en la reducción de emisiones y la preservación de los rendimientos del cultivo. La eficiencia en el uso de fertilizantes y la gestión óptima del agua emergieron como prácticas clave para lograr una producción de arroz más sostenible. En resumen, este estudio proporciona una visión integral y estratégica para mejorar la sostenibilidad de la producción de arroz, considerando la gestión eficiente del agua y la reducción de emisiones de GEI en contextos regionales específicos.

La creciente demanda de arroz en América Latina requiere prácticas sostenibles de riego para abordar la escasez de agua y reducir las emisiones de GEI. Este estudio investiga el potencial de AWD en comparación con métodos convencionales en el cultivo de arroz tropical en Colombia. Durante cuatro temporadas, los tratamientos AWD (AWD_{5cm} y AWD_{10cm}) demostraron una reducción del 19-56% en el uso acumulado de agua, especialmente en estaciones secas. Además, AWD redujo significativamente las emisiones de CH_4 en un 72-100% y las emisiones de N_2O en un 12-70%, resultando en una reducción del 25-73% en el potencial de calentamiento global (PCG) en comparación con el control, con un impacto mínimo en la productividad del cultivo (5.2-8.2 Mg ha^{-1}). Los hallazgos sugieren que AWD es una estrategia prometedora para mitigar las emisiones de GEI en el cultivo de arroz tropical a pesar de las barreras de adopción.

La selección de cultivares emerge como un factor crítico en la mitigación de GEI, como se demostró en un estudio paralelo sobre cuatro cultivares comerciales de arroz en dos regiones de Colombia. Los resultados indicaron que las emisiones de CH_4 y el GWP fueron relativamente bajos debido al drenaje frecuente del campo, con las emisiones de N_2O contribuyendo en su mayoría al GWP. Variedades específicas, como F-67 y F-Itagua, redujeron significativamente el GWP en un 32-61%, principalmente a través de la reducción de las emisiones de N_2O. Este estudio destaca el papel de la selección de variedades de arroz en la reducción de las emisiones de N_2O bajo irrigación no continua, una práctica crucial para abordar el cambio climático y la escasez de agua.

Además, esta investigación contrasta el impacto de la gestión del agua en tratamientos de riego intermitente e inundado en dos regiones colombianas, Tolima y Casanare. Al evaluar las emisiones de CH_4 y N_2O, el PCG y el rendimiento del cultivo para dos variedades comerciales de arroz, los hallazgos revelan que la transición de la inundación al riego intermitente reduce significativamente las emisiones de CH_4 en aproximadamente un 100% en ambas regiones. Notablemente, se observa una reducción del 54 al 78% en las emisiones de N_2O en Tolima, del 6 al 46% en sistemas de secano y un 100% en sistemas irrigados con manejo de la humedad del suelo durante la fertilización en Casanare. En general, el GWP experimenta una reducción que oscila entre el 62 y el 85% en Tolima, del 14 al 62% en sistemas de secano y un 100% en el sistema irrigado en Casanare, destacando el potencial del riego intermitente para minimizar el GWP global y preservar los rendimientos.

Por último, una investigación centrada en variedades comerciales de arroz y genotipos resistentes al calor en la región de Tolima bajo riego intermitente e inundado reveló una reducción en las emisiones de CH_4 (74-75% en variedades comerciales, 81-95% en genotipos) y una reducción del 61-85% en el GWP. No se observaron diferencias significativas en las emisiones de N_2O entre cultivares y tratamientos, enfatizando el papel de la gestión de recursos hídricos sobre la selección de cultivares. A pesar de proporcionar valiosos conocimientos y reconocer las limitaciones del estudio, se propone la investigación futura para explorar el impacto de condiciones climáticas extremas en la sostenibilidad y productividad de diferentes cultivares de arroz.

Esta investigación abre la puerta a un estudio más profundo de estrategias de mitigación en diversos aspectos de las prácticas agronómicas del arroz, como los tipos de siembra, el manejo de fertilizantes y la selección de genotipos. El objetivo es determinar el impacto ambiental de estas estrategias sin comprometer la seguridad alimentaria y económica del agricultor. Adicionalmente, este estudio proporciona una base de conocimiento crucial sobre el comportamiento de los cultivos de arroz bajo diferentes prácticas de manejo del riego en condiciones arroceras contrastantes. Asimismo, ofrece información valiosa acerca de los factores de emisión de CH_4 y N_2O, constituyendo contribuciones significativas para la elaboración de inventarios a nivel nacional y departamental de gases de efecto invernadero en Colombia. Estas contribuciones son fundamentales para fortalecer las Acciones de Mitigación Nacionalmente Apropiadas (sigla en inglés: NAMAs). Además, se busca proporcionar apoyo a los agricultores, permitiéndoles evaluar y considerar qué tipo de prácticas agronómicas pueden contribuir efectivamente a reducir el impacto ambiental y mejorar sus condiciones socioeconómicas y de seguridad alimentaria.

Esta investigación se llevó a cabo en cuatro etapas:

I. Evaluación del impacto ambiental de la adaptación de la tecnología de riego AWD en el cultivo de arroz, específicamente para el contexto de la zona arrocera del Tolima, en comparación con el manejo tradicional del riego.

II. Identificación de variedades comerciales de arroz con potencial de mitigación en la reducción de CH_4 y N_2O en dos regiones arroceras, Tolima y Casanare.

III. Análisis del impacto ambiental en la reducción de GEI mediante la implementación del riego intermitente en comparación con un sistema de inundación continua, considerando las dos regiones arroceras más representativas, Tolima y Casanare, sin afectar los rendimientos.

IV. Evaluación del impacto de los genotipos adaptados a condiciones de altas temperaturas en comparación con variedades comerciales de arroz con potencial de mitigación.

En estas etapas, se examinaron diferentes aspectos relacionados con la sostenibilidad y la eficiencia ambiental de las prácticas agronómicas en la producción de arroz, considerando la variabilidad regional y genotípica.

Palabras claves: Irrigación intermitente, Inundación continua, Metano (CH_4), Óxido nitroso (N_2O), Seguridad alimentaria, Potencial de Calentamiento global, Cultivares, Humectación y secado alterno (AWD), rendimiento.

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Dedicatory

This thesis is dedicated to God, my mother, Piedad Mera, my sister Carolina Mera, my cousin Harold Gonzalez, my love Carlos Barcenas, and my friend Isabel, and all the angels who crossed my path, being my strength throughout the doctoral journey, believing in me and my abilities to overcome all the trials and difficulties I faced during this period. This academic stage of my life was a real challenge, from living through a pandemic to studying and working simultaneously.

This thesis is dedicated to all those who want to give up or are going through a difficult situation, demonstrating that everything is possible when we stop thinking about the past, what we did or did not do, and the future, where nothing is written, and everything is uncertain. The magic lies in giving yourself and being in the present, stopping thinking about everything; when you least expect it, you will have the fruit of your efforts. Courage, because everything is possible when you surrender, trust yourself, and don't well on what will happen.

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1 Introduction

Rice is considered the third most important cereal crop globally (Kropff & Morell, 2019; Zhao et al., 2020). Rice plays a crucial role in providing sustenance for half of the world's population (Dhungel & Acharya, 2017; Fukagawa & Ziska, 2019), serving as a fundamental source of calories for over 3.5 billion people (National Geographic, 2024; Zafar & Jianlong, 2023; Zhao et al., 2020). Despite this, cultivating rice in flooded conditions, covering approximately 79 million irrigated hectares worldwide, presents significant sustainability challenges (Brar, 2012; Mackill et al., 2010; Panda & Barik, 2021; Wassmann, 2019). Given that agriculture consumes a substantial portion of global freshwater, with 30-40% allocated to rice cultivation (Lampayan et al., 2015; Maclean et al., 2002; Singh, 2013; Surendran et al., 2021), current continuously flooded rice environments do not show a proportional increase in productivity due to variability and climate change conditions (Bwire et al., 2022; Singh et al., 2021; Surendran et al., 2021). Flooded rice crops contribute to nearly half of global GHG emissions from cropland, highlighting the urgency of adopting innovative rice management practices (Carlson et al., 2017; Mboyerwa et al., 2022). These practices must enable a significant reduction in GHG emissions without compromising yields or the economic sustainability of farmers.

Colombia, the third-largest rice producer in Latin America after Brazil and Peru (World Agricultural Production, 2023), with five rice-producing zones encompassing 22 departments (DANE, 2023), faces food and economic security challenges. One of the most relevant challenges is the climate variability experienced by farmers, in part due to increased global GHG emissions from agricultural practices. Climate extremes pose a threat to the agricultural sector due to the reduced availability of natural resources such as water due to rising temperatures. During certain crop stages, this climate variability also directly impacts rice production, affecting the well-being of rice producers and increasing their vulnerability (Cirad, 2023; Fedearroz, 2023; Inhedge, 2022). The intricate balance between water availability, changes in climate patterns, and the imperative need to meet the growing demand for rice requires a nuanced understanding of rice farming practices that can simultaneously address these challenges (Chirinda et al., 2018; Garg, 2023). Hence, it is crucial to implement more efficient, resilient, and environmentally friendly systems for farmers to remain productive in the face of climate change. In order to accomplish this, it is essential to comprehend the current environmental impacts of agronomic practices characteristic of the Colombian rice sector.

Currently, Sustainable and profitable agricultural practices or technology transfer models are proposed to increase rice yields and reduce production costs, neglecting the potential environmental impacts of such practices or technological transfers (Bhaduri et al., 2023; FAO, 2021; Meijide et al., 2016). According to the latest National Inventory of 2012, the agricultural sector in Colombia, including forestry and other land uses, contributes 43% of GHG emissions, the second-highest sector after the energy sector in Colombia. It contributes 62.9% of CH_4 emissions and 25.8% of N_2O emissions (IDEAM, PNUD, MADS, DNP, CANCILLERÍA. 2016). The agronomic practice with the most significant contribution to greenhouse gas emissions was nitrogen fertilization, accounting for 2.6% of productive systems. As a result, agronomic practices implemented with regard to fertilizer use to ensure environmental sustainability have a significant impact.

In rice systems in Colombia, one of the most crucial agronomic practices is managing water resources throughout the crop cycle. The conventional or traditional practice involves continuous flooding, leading to significant environmental consequences related to CH_4 emissions into the atmosphere and an increase in the GWP (Pineda & Morales, 2018; Loaiza et al., 2024). Flooded rice cultivation accounts for 1.3% of CH_4 emissions and 1.8% of N_2O emissions globally in agricultural, forestry, and other land use sectors (Maraseni et al., 2018; Ritchie, 2020). Flooded rice cultivation is one of the primary anthropogenic sources of CH_4 worldwide and a significant emitter of N_2O due to the effect of the second relevant agronomic practice, nitrogen fertilization, responsible for 25-30% of the increase in GWP (EPA, 2021; Mboyerwa et al., 2022). The overall picture underscores the urgency of mitigating GHG emissions from rice cultivation, primarily CH_4 and N_2O. Existing research emphasizes the fundamental role of water management, especially AWD irrigation, in reducing water use and CH_4 emissions. However, there remains a critical knowledge gap in understanding the implications of AWD in the context of non-continuous flooding, a practice gaining prominence in various agronomic environments due to water shortages, despite the scientific knowledge that non-continuous flooding generally increases N_2O emissions due to aerated soil conditions (Kritee et al., 2018; Mencos et al., 2023; Islam et al., 2022).

In response to these challenges, our research explores the hypothesis that implementing AWD and intermittent irrigation systems without reaching soil water stress can significantly reduce water consumption and CH_4 and N_2O emissions without compromising crop yield. Additionally, we aim to identify practices that could reduce GHG emissions that should be recognized at the Latin American level. In addition, commercial rice cultivars with specific genetic characteristics capable of adapting to reduce greenhouse gas emissions and genetically modified genotypes resistant to extreme conditions can reduce emissions without affecting yields. We intend to contribute to sustainable rice cultivation practices addressing water scarcity, mitigating greenhouse gas emissions, and supporting food security.

This study focuses on rice cultivation practices in Colombia and explicitly assesses CH_4 and N_2O emissions and crop yields under agronomic management proposed by National Federation of rice growers (Fedearroz) with the implementation of intermittent irrigation and the management technique that includes AWD periods at two soil water tension levels during non-critical growth phases of rice crops. Previous research has shown that intermittent irrigation increases water efficiency and CH_4 emissions are reduced by 60-80% (Carrijo et al., 2017; Loaiza et al., 2024) without affecting crop yields. We identify representative commercial rice varieties for Fedearroz (Fedearroz 67, Fedearroz 68, Fedearroz 70, Fedearroz 2000, Fedearroz Itagua) with significant mitigation potential in two representative rice-producing regions. In addition, we identify the mitigation potential of rice genotypes adapted to high-temperature conditions and disseminate knowledge on potential mitigation practices to advance the regional scaling of this technological model of practices. The study includes the impact on CH_4 and N_2O emissions, grain yield and water use in the Tolima and Casanare regions during different rice growing seasons between 2021 and 2023.

Through this research, we aspire to contribute to strategic goals for more eco-efficient agriculture and the sustainability of these production processes. Providing valuable insights that can inform policies, guide agricultural practices, and contribute to the global effort to achieve sustainable and climate-adapted rice cultivation.

1.1 Hypothesis

We could reduce CH_4 emissions by up to 100% and match or decrease N_2O emissions compared to a continuous flooding system without compromising crop yields, simply by effectively controlling water depth and soil moisture.

1.2 General Objective

To comprehensively assess the environmental impact of intermittent irrigation technologies and the selection of commercial varieties and rice genotypes adapted to high-temperature conditions in the rice-producing regions of Tolima and Casanare. The aim is to identify sustainable agronomic practices that contribute to reducing GHG emissions without compromising yields.

1.2.1 Specific Objectives:

1. Conduct a detailed assessment of the environmental impact of AWD technology in the Tolima rice-growing region in terms of GHG emissions, yield, and water use, comparing it with traditional irrigation management. This aims to determine the effectiveness of AWD in reducing water use, CH_4 and N_2O emissions, and crop productivity.

2. Identify commercial rice varieties with mitigation potential for reducing CH_4 and N_2O in the rice-producing regions of Tolima and Casanare through a comprehensive analysis. The goal is to select varieties that have a lower environmental impact.

3. Conduct a detailed analysis of the environmental impact of reducing GHGs by implementing intermittent irrigation compared to continuous flooding. This analysis will consider the two most representative rice-producing regions, Tolima, and Casanare, without compromising crop yields.

4. Evaluate the impact of genotypes adapted to high-temperature conditions compared to commercially identified rice varieties with mitigation potential under intermittent irrigation. The objective is to determine their efficiency in reducing GHG emissions, especially CH_4 and N_2O, without compromising crop productivity.

1.3 General conclusions

The positive impact of a technology or mitigation strategy on reducing greenhouse gas emissions depends on the percentage reduction of these gases without affecting crop yields, the adoption rate, and implementation costs. This doctoral proposal was developed to provide relevant information on how the adaptation of traditional practices in water management throughout the production cycle, along with optimal soil moisture conditions for fertilizer application and the planting of varieties adapted to the climatic conditions of rice-growing regions, can significantly reduce GHG emissions without affecting productivity and the establishment and maintenance costs of the crop.

The doctoral research presents significant findings pointing towards more sustainable management of rice cultivation systems in Colombia. The comprehensive analysis of various strategies highlights the effectiveness of AWD irrigation in reducing GHG emissions, along with the proper selection of rice varieties and optimal water management in intermittent irrigation systems.

Firstly, it was found that implementing AWD technology adaptation to the local rice context considerably reduced both water consumption and CH_4 emissions, as well as N_2O emissions, which usually increase significantly with the implementation of globally recognized traditional AWD technology without negatively affecting crop productivity. This supports the initial hypothesis that adapting AWD to local contexts and practices could maintain rice yields while mitigating GHG emissions, offering a promising strategy for sustainable agriculture in Colombia. However, it is important to acknowledge study limitations, such as barriers to adopting practices like AWD.

In response to these limitations, the research proposal suggests creating a new water management strategy that combines AWD principles with a more comprehensive approach to controlling soil moisture and maximizing efficiency in GHG mitigation without incurring additional costs in establishment and monitoring throughout the production cycle. The proposed intermittent irrigation allowed soil moisture control between field capacity and saturation for fertilizer application and water replenishment conditions. The results of the research support its viability, demonstrating that transitioning from continuous to intermittent irrigation has significant environmental benefits, including a drastic reduction in CH_4 and N_2O emissions, without compromising crop yields.

Based on continuous flooding, the traditional reference system showed a significant increase in CH_4 emissions. However, our findings demonstrate that emissions can be reduced significantly through controlled water replenishment during maturation. This strategy is crucial for crop development and performance, as our findings indicated that the stage of greatest plant development is when the highest percentage of emissions occurs. These results underscore the viability of adapting traditional water management systems by implementing short aeration periods between field capacity and soil saturation. This approach can significantly reduce traditional systems' GWP while emphasizing the importance of raising awareness among farmers about adopting beneficial long-term practices that can reduce production costs and environmental impact. In summary, these findings offer an alternative to reduce CH_4 emissions in continuous flooding systems while initiating a technology appropriation process with farmers to transition towards a more sustainable and resilient agricultural system.

The results highlight the relevance of rice variety selection as a fundamental strategy for reducing GHG emissions in cultivation systems. Specifically, it was observed that certain commercial varieties and heat-resistant genotypes can play a significant role in CH_4 emission mitigation when grown under intermittent irrigation systems. This observation underscores the importance of carefully choosing rice varieties as a first step towards reducing the environmental footprint in agriculture. Additionally, it highlights the need to continue developing advanced strategies and technologies to improve further environmental sustainability and the adaptability of agricultural systems to changing climate challenges.

In summary, this research provides a solid foundation for promoting more sustainable agricultural practices and mitigating GHG emissions in rice production in Colombia. The findings highlight the innovation of adopting a comprehensive and collaborative approach to addressing environmental and agricultural challenges in the region. This innovative approach not only aims to reduce GHG emissions but also seeks to improve long-term agricultural sustainability and productivity. These results are essential for enhancing the food system's resilience against climate change, demonstrating the transformative potential of innovative strategies in the agricultural sector.

1.4 Document structure

This document is composed of structured chapters, in addition to the introduction, organized to detail the progression of our research:

Section 2 delves into a comprehensive analysis of CH_4 and N_2O concentrations and yields, emphasizing the urgency of mitigating emissions from rice cultivation under AWD water management technology.

Section 3 explores the impact of rice cultivar selection on GHG emissions, specifically focusing on CH_4 and N_2O.

Section 4 examines the implications of intermittent irrigation, considering the specific characteristics of rice systems in Colombia.

Section 5 expands the research to evaluate genotypes adapted to extreme conditions that can reduce emissions while maintaining productive sustainability. Each section contributes to building a comprehensive understanding of sustainable rice cultivation practices.

2 Chapter I: Evaluating Greenhouse Gas Mitigation through Alternate Wetting and Drying Irrigation in Colombian Rice Production[1]

This chapter contains the results that were previously publish in the Journal of Agriculture, Ecosystems and Environment, titled " Evaluating Greenhouse Gas Mitigation through Alternate Wetting and Drying Irrigation in Colombian Rice Production (Loaiza et al., 2024). The results presented in this section highlight the potential for greenhouse gas emissions reduction through the adaptation of AWD technology to the local context of Colombia. Using a closed static chamber, the percentage reduction of CH_4 and N_2O achieved by this technology without affecting yields was evaluated, compared to a traditional irrigation system in the Tolima region. The monitoring extended over two years, covering two planting seasons (dry and wet periods), allowing us to determine that the adaptation of AWD technology significantly reduced CH_4 and N_2O emissions without negatively impacting yields. This finding represents a significant advancement, as AWD technology in its global form has yet to achieve this efficiency level. The commercial implementation of this adaptation ensures the potential for emission reduction without compromising the sustainability of rice cultivation systems.

2.1 Keywords

Alternate wetting and drying, Greenhouse gas emissions, Methane (CH_4), Nitrous oxide (N_2O), Global warming potential, GHG mitigation, Water management, Grain yield.

2.2 Highlights

- AWD Irrigation in Colombian Rice: Reducing Water Usage and GHG Emissions
- AWD used 19-56% less water than the conventional system with minimal impacts on yield
- AWD reduced methane emissions by 72-100% and nitrous oxide emissions by 12-70%
- AWD decreased global warming potential by 25-73% suggesting policy and economic support could improve it as a GHG mitigation practice for this region

2.3 Abstract

Rice demand in Latin America is increasing rapidly, but few studies have identified management practices to reduce water demand and soil greenhouse gas (GHG) emissions for irrigated rice systems in this region. Therefore, we tested the hypothesis that alternate wetting and drying (AWD) irrigation could maintain crop yields while mitigating global warming potential (GWP) compared to a conventional system with recommended irrigation and nutrient management practices for tropical rice in Colombia. Over four consecutive growing seasons, we monitored CH_4 and N_2O emissions, grain yield, and water consumption for two AWD treatments (AWD_{5cm} and AWD_{10cm} - where water drained to depths of 5 and 10 cm below the soil surface, respectively) and a control, in which the field was drained multiple times during fertilizer applications and then continuously flooded until harvest. The control had the highest water use across all rice seasons, with values ranging from 9260 to 16559 m^3 ha^{-1} $harvest^{-1}$. Implementation of

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[1] Chapter I of this thesis contains results that were previously published in [Journal of Agriculture, Ecosystems and Environment], titled " Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production" (Loaiza et al., 2024). https://doi.org/10.1016/j.agee.2023.108787

AWD reduced cumulative water use by 19-56%, especially in dry seasons. Both AWD treatments significantly reduced cumulative CH_4 emissions by 72-100%, which is consistent with previous research. A new finding is that AWD also decreased N_2O emissions by 12-70%, which was attributed to management of soil moisture during fertilizer application events. In total, AWD reduced GWP by 25-73% compared to the control, with minimal impacts on crop productivity. Rice yields ranged from 5.2-8.2 Mg ha^{-1}, with no significant difference among treatments in three of four seasons. This study shows that AWD saves irrigation water while greatly reducing GWP with little agronomic penalty, suggesting this technology could be a promising strategy for GHG mitigation in tropical rice in Colombia. Because there are important barriers to AWD adoption, future work should explore challenges at the farm-level as well as changes in policy, irrigation infrastructure, and institutional arrangements to understand the potential for broader implementation.

2.4 Introduction

Rice is the third most important cereal crop in the world after wheat and maize, with a global production level of 515 million tons in 2022 (OECD/FAO, 2020). Rice is a staple supply of calories for half of humanity, with more than 3 billion people depending on this crop as their main source of energy and livelihood. However, much of rice cultivation takes place under flooded conditions, with around 79 million irrigated hectares worldwide, leading to serious sustainability challenges (Wassmann et al., 2019). It is estimated that agriculture consumes about 70% of the world's freshwater supplies (Campbell et al., 2017), of which approximately 30-40% is used for rice cultivation (Bouman et al., 2007; FAOSTAT, 2020; Surendran et al., 2021). Due to CH_4 production in flooded soils, rice accounts for nearly half of GHG emissions from global croplands (Carlson et al., 2017). Most rice is produced in Asia, but population growth and changing diets in Latin America and the Caribbean (LAC) are rapidly increasing the demand for rice. Recent work suggests the LAC region has great potential for future agricultural expansion (Méndez, 2020), however this could lead to a corresponding increase in freshwater consumption and elevated GHG emissions. Colombia is the third largest rice producing country in LAC after Brazil and Peru, with a total production of 2.5 million tons per year (ENAM, 2021; World Agricultural Production, 2022). Competition for water use among different sectors in this region, combined with growing threats of climate change (increasing variability in rainfall and hotter, drier periods) currently makes it difficult for farmers to have enough water in the right place at the right time. To address these challenges, rice management practices that reduce water use and CH_4 emissions without negatively impacting crop productivity are needed.

Rice cultivation is an important source of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions (IPCC, 2014). Carbon cycling in flooded rice soils is controlled by anaerobic decomposition (methanogenesis) and CH_4 exchange between the soil and atmosphere, primarily via plant transport (Bhattacharyya et al., 2019). The two biochemical processes responsible for the production of N_2O are nitrification and denitrification, which are regulated by environmental and biological factors such as temperature, water level, oxygen concentration, pH, and carbon and nitrogen substrate availability (Tian et al., 2020). When considering the relative impact of each gas on GWP (CH_4 + N_2O = GWP), the vast majority of GWP is CH_4 emissions caused by continuous flooding (Linquist et al., 2012). Therefore, GHG mitigation efforts are often focused on water management such as non-continuous flooding or alternate wetting and drying (AWD) irrigation to introduce atmospheric O_2 into soil (Liao et al., 2021). Soil drainage not only promotes aerobic conditions which quickly inhibits methanogenesis and stimulates oxidation of CH_4 (methanotrophy), but also increases sulphate and ferric iron concentrations which delays subsequent CH_4 production when soils are re-flooded (Ratering and Conrad, 1998). However, N_2O emissions may increase at AWD due to periodic drying cycles during the growing season that increase the redox potential of the soil. This increased redox potential can promote nitrification, resulting in N_2O emissions under subsequent aerobic conditions. In addition, when the soil is re-flooded, denitrification processes may prevail, potentially further contributing to N_2O emissions (Balaine et al., 2019; Oertel et al., 2016).

From an irrigation perspective, AWD is a widely researched water-saving technology for rice cultivation (Carrijo et al., 2017; Lampayan et al., 2015). However, whether N_2O increases due to drainage events more than the decrease in CH_4 emissions will determine if AWD supports a net reduction in GWP. Lagomarsino et al. (2016) found that AWD reduced water use by 70% and CH_4 emission by 97%, but increased N_2O emissions fivefold in soils with a clay texture. Abid et al. (2019) reported that N_2O emissions were higher under AWD than under permanent flooding, while Islam et al. (2018) showed that AWD reduced seasonal CH_4 emissions but increased N_2O emissions by 23%. Colombia is one of the first countries in LAC where AWD was tested in 2015 and 2016, with CH_4 emissions decreasing by 69% but N_2O emissions being higher than flooded rice (Chirinda et al., 2017). In general, previous work has found that AWD reduces GWP despite higher N_2O emissions (Jiang et al., 2019), but an important consideration is that most studies compare AWD with a continuously flooded control, emphasizing the benefits of CH_4 relative to N_2O mitigation. In contrast, little work has evaluated the performance of AWD in the context of non-continuous flooding, which is an increasingly common agronomic practice. For example, recommended water and nutrient management practices for rice production in Colombia include multiple drainage events early in the season during the timing of N fertilizer application (Fedearroz, 2017). These wet-dry cycles could trigger higher N_2O emissions, while also decreasing the overall magnitude and importance of CH_4 emissions compared to a continuously flooded system. Thus, considering AWD is increasingly promoted in different contexts, an important knowledge gap is how additional wet-dry cycles under AWD influence net GHG mitigation compared to a non-continuously flooded system as the representative management practice for a region.

Changes in crop productivity under AWD can be variable, especially when implemented in different soil-climate combinations with different severities of soil drying (Carrijo et al., 2017). Rice is sensitive to drought stress, which significantly affects grain yield (Ahmad et al., 2021). While some studies show no impact on yield (Carrijo et al., 2018; Leon et al., 2021; Setyanto et al., 2018), other studies show an increase or decrease in productivity (Carrijo et al., 2017; Djaman et al., 2018; Yang et al., 2017). Mild-drought stress can reduce rice yield by 31%–64%, while severe stress reduced it by 65%–85% compared to normal conditions (Kumar et al., 2008). Considering this, the frequency and depth of field drainage events are important factors to investigate when adapting AWD practices to a region, especially in soils with a high percentage of sand as they are likely to dry out more quickly. While the general recommendation for AWD in Asia is to irrigate once water levels reach 15 cm depth below the soil surface (Lampayan et al., 2015), most research has occurred in lowland fields with higher clay content. Given that average yield reductions can be >20% due to water stress under AWD (Carrijo et al., 2017), research is needed to identify appropriate drainage depths in soils with high sand content to achieve GHG mitigation without negatively impacting grain yield.

In the present study, we investigated CH_4 and N_2O emissions, grain yield, and water use under two levels of AWD (5 and 10 cm drainage depth) compared with recommended management practices for tropical rice in Colombia. The control included direct seeded rice with straw removal, and flood irrigation except for drainage events to facilitate multiple fertilizer application events during the first two months of crop development. We hypothesized that implementing AWD could reduce not only water consumption and CH_4 emissions, but also N_2O emissions without affecting crop yield compared to the control by allowing soil to dry slightly more during fertilizer application events. In a two-year field experiment covering four rice growing seasons, the specific objectives were to: i) quantify seasonal CH_4 and N_2O emissions, ii) determine water use and grain yield, and iii) evaluate GWP for each treatment.

2.5 Methodology

2.5.1 Site information and experimental design

From 2018-2020, a two-year experiment was conducted at the Experimental Center "Lagunas" of the Colombian Rice Federation (Fedearroz, Spanish acronym) (3° 55' 59" North, 75° 1' 1" West) in the city of Saldaña (Tolima, Colombia). In Saldaña, the direct income of the agricultural sector depends 100% on rice farming, which comprises 60% irrigated rice and 35% dry rice. This activity generates 7.8 - 8.4% of the gross value added at the national level (Dane, 2023). At an altitude of 305 meters, the climate is characterized by pronounced dry seasons and bimodal rainfall (Feb - Jun) and (Sep - Dec). The average annual rainfall is 1099 mm, and the average annual temperature is 29 °C. Corresponding to the two rainy seasons, there are usually two rice sowing seasons per year, from April to June in the first semester and from October to December in the second semester (Fedearroz, 2021). Soils at the trial site are classified as shallow to moderately deep, well to moderately well drained, low in organic carbon, slightly acidic, and moderately fertile. The soil texture was a sandy loam (59% sand, 29% silt, and 12% cay) with the following selected properties: 1.58 g cm^{-3} bulk density, 0.85% total organic C, and pH of 6.50 for the 0-10 cm depth. The field trial was designed as a randomized complete block (RCBD) design with four replicates per treatment. Each plot covered an area of 170 m^2. Experiments were conducted during four consecutive rice growing seasons (seasons I and II in 2019 and 2020). Details of crop management including sowing, fertilizer application, irrigation, and harvest dates for each season are shown in Table 2-1. All plots were planted with the rice cultivar Fedearroz 67, a widely used commercial variety characterized by rapid initial growth and high tillering ability (Ospina et al., 2022). Dry rice was sown directly with a drill at 120 kg ha^{-1}. Fertilizer application was divided into 4-5 dates depending on the climatic conditions during the production cycle (Table 2-1). Weather conditions for each season are reported in the results.

Three water management treatments were implemented: two AWD treatments and a control (C). In the control group, the soil remained continuously flooded, except during the fertilizer application dates when the plots were briefly drained, as described below. After the fertilization period, typically within the first 40-60 days of crop development, depending on the growing season, the rice fields were consistently flooded to a depth of about 5 cm until harvest. During this period, two AWD levels were employed: AWD_5cm, considered moderate AWD, involved lowering the water level to 5 cm below the soil surface before irrigation, and AWD_{10}cm, considered more intensive AWD, lowered the water level to 10 cm below the soil surface before irrigation. To regulate the water level below the soil surface for both treatments, we utilized a piezometer constructed with a 30 cm long PVC pipe with a 15 cm diameter, buried 15 cm below the soil surface, and equipped with side perforations to allow for free water movement in each treatment. These levels were selected to prevent plant stress, as the soil was expected to drain quickly due to a high sand content and low soil organic matter.

Water management was similar in both the control and AWD treatments during the first two months of the season, where plots were drained to facilitate fertilizer application (Fedearroz, 2017). However, AWD soils were allowed to dry a greater extent during each fertilizer application event, targeting soil moisture near field capacity instead of remaining close to saturation. In each growing season, the two AWD treatments differed slightly in irrigation dates, with water levels typically dropping to 10 cm below the soil surface in AWD_{10cm} a few days after AWD_{5cm}. In addition, the number of irrigation events varied between growing seasons due to differences in rainfall, crop demand, and the extent of soil drying (Table 2-1). In 2019, AWD treatments were irrigated twice in the first growing season, and 9-10 times in the second growing season. In 2020, AWD treatments were irrigated 3-4 times in both growing seasons. In order to maintain the desired water levels for the AWD_5 and AWD_{10} treatments, a systematic approach was employed. Piezometers were strategically installed in the soil at specific locations within the experimental plots. These piezometers serve as monitoring devices to measure the water depth continuously.

Table 2-1: Crop management events during the 4 growing seasons of rice from 2018-2020. Treatments included the control, AWD$_{5cm}$ (moderate drying to 5 cm depth), and AWD$_{10cm}$ (more intensive drying to 10 cm depth). Fertilizer sources included a combination of urea (U) – 46% N, ammonium sulfate (AS) – 21% N and 24% S, and MicroEssentials (ME) – 12% N, 40% P_2O_5, 10%S, 1% Zn.

Agronomic practices	Growing season I	Growing season II	Growing season III	Growing season IV
Sowing date (dd/mm/yy)	18/12/18	29/05/19	03/12/2019	11/05/2020
Germination date (dd/mm/yy)	26/12/18	07/06/19	12/12/2019	22/05/2020
Fertilizer N rate (kg N ha^{-1})	170	176	152	175
# Fertilizer splits	4	5	4	5
Fertilizer application dates (dd/mm/yy)	05/01/19 (0 days) 16/01/19 (11 days) 28/01/19 (23 days) 13/02/19 (39 days)	20/06/19 (0 days) 08/07/19 (18 days) 22/07/19 (32 days) 05/08/19 (46 days) 20/08/19 (61 days)	08/01/20 (0 days) 20/01/20 (12 days) 04/02/20 (27 days) 18/02/20 (41 days)	2/06/20 (0 days) 16/06/20 (14 days) 1/07/20 (29 days) 21/07/20 (49 days) 4/08/20 (63 days)
Fraction of N dose (kg N ha^{-1})	05/01/19→23 (U+ME) 16/01/19→45 (U+AS) 28/01/19→45 (U+AS) 13/02/19→56 (U+AS)	20/06/19→41 (U+ME) 08/07/19→34 (U+AS) 22/07/19→45 (U+AS) 05/08/19→34 (U+AS) 20/08/19→23 (U+AS)	08/01/20→35 (U+ME) 20/01/20→34 (U+AS) 04/02/20→50 (U+AS) 18/02/20→34 (U+AS)	2/06/20→35 (U+ME) 16/06/20→34 (U+AS) 1/07/20→50 (U+AS) 21/07/20→34 (U+AS) 4/08/20→23 (U+AS)
Irrigation dates (dd/mm/yy)	**AWD$_{5cm}$** 04/02/19 04/03/19 **AWD$_{10cm}$** 05/02/19 05/03/19	**AWD$_{5cm}$** 28/06/19 04/07/19 15/07/19 30/07/19 12/08/19 27/08/19 05/09/19 11/09/19 17/09/19 23/09/19 **AWD$_{10cm}$** 29/06/19 05/07/19 01/08/19 14/08/19 29/08/19 06/09/19 18/09/19 24/09/19	**AWD$_{5cm}$** 15/01/20 27/01/20 12/02/20 04/03/20 **AWD$_{10cm}$** 17/01/20 11/02/20 03/03/20	**AWD$_{5cm}$** 11/06/20 26/06/20 11/07/20 03/08/20 **AWD$_{10cm}$** 30/06/20 13/07/20 01/08/20
Harvest date (dd/mm/yy)	08/04/19	17/10/2019	04/04/2020	09/09/2020

2.5.2 Greenhouse gas emissions

Gas sampling was performed using the static closed chambers technique described by Chirinda et al. (2017), with precautions taken in chamber design, on-site gas sampling, and gas analysis to improve data accuracy. Polyethylene chambers (114 L in volume and 80 cm in height) were used in conjunction with custom-made chambers bases (40 cm in height and 38 cm in diameter) that were sunk 5 cm into the soil immediately after planting and were required to remain in equilibrium for at least three days before sampling. A total of 12 static chambers were installed in each of the plots ($170m^2$) in the center of the growing area during the sampling season to avoid disturbance and edge effects. During each gas sampling event, the chambers were closed for 45 minutes, and four gas samples were collected at regular intervals (0, 15, 30, and 45 min). A system of vents was installed in the static chambers to avoid pressure differences between the interior and exterior of the chamber during gas sampling. A battery-powered fan was installed to ensure homogeneity of the sample in the chamber before gas sampling. Gas samples of 15 mL were collected with a propylene syringe and filled with positive pressure into a pre-evacuated 5-mL glass Exetainer® vial (Labco Ltd., Buckinghamshire, UK). Wooden walkways were placed in the rice field prior to flooding periods to prevent soil disturbance during sampling.

The measurement periods were the following: In the first growing season, measurements were taken from January 5 to April 5, 2019; for the second growing season, from June 20 to September 24, 2019; in the third growing season, from January 8 to March 20, 2020; and in the fourth growing season from June 2 to August 7, 2020. During each growing season, gas sampling focused on fertilization events, with measurements taken one day before fertilization and three consecutive days after fertilization, and when irrigation was based on water levels that fell 5 or 10 cm below the soil surface. After the fertilization period which lasted the first 40-60 days of each season, measurements were taken approximately weekly until harvest weather permitting. All samples were collected between 8:00 and 11:00 a.m., when soil temperature was expected to be equal to the average daily values (Arenas, 2016). The total number of sampling events for the first, second, third, and fourth growing seasons was 20, 37, 23, and 27, respectively.

Concentrations of CH_4 and N_2O were determined by gas chromatography (GC) using a Shimadzu GC -2014 with a ^{63}Ni electron capture detector (ECD) for N_2O and a flame ionization detector (FID) for CH_4. The detection range was 0.1ppm for N_2O and 0.061 ppm for CH_4. Gas samples were analyzed within four weeks of collection. Gas concentrations were converted to fluxes based on the duration of chamber closure (45 minutes) combined with the ideal gas law equation and measured temperature and volume of the chamber. Cumulative fluxes for the growing season were calculated by linear interpolation between sampling dates. The total length of GHG monitoring was 59, 96, 56, and 66 days for the first, second, third, and fourth growing seasons, respectively. We calculated N_2O emissions in units of N and CH_4 emissions in units of C. To calculate total GWP we first multiplied CH_4-C and N_2O-N emissions by 16/12 and 44/28, respectively, to convert to units of CH_4 and N_2O and then multiplied by the 100-year GWP values of 273 for N_2O and 27.2 for CH_4 to convert each gas to CO_2 equivalents (IPCC, 2021). Total GWP is reported as the sum of N_2O and CH_4 in units of kg CO_2 eq. ha^{-1}.

2.5.3 Rice grain yield, aboveground biomass, water use, and soil moisture

During each growing season, aboveground biomass was sampled at two main phenological phases (flowering and harvest). Samples were collected by randomly placing 0.25 m^2 quadrants within treatment plots and cutting all aboveground biomass (including stems, leaves, and panicles). Biomass samples were dried in a convection drying oven (Colres industrial) at 70 °C for 24 hours until constant weight (Yepes et al., 2011). Rice grains were harvested at physiological maturity from a 20 m^2 area within each plot. The grains were dried in an oven at 70 °C for 72 hours. Grain yield is reported at 14% grain moisture content.

Water use was measured for each irrigation event using a Parshall flume. The Parshall flume is an open channel in which water flows horizontally, so the water flow rate (Q in m^3 $harvest^{-1}$) can be determined by the water level in the Parshall flume (H in cm), assuming shallow and horizontal water movement (Takeda et al., 2019). The water level was measured using a level gage attached to the sidewall of the Parshall Channel. Seasonal irrigation volumes were calculated by summing the values obtained over the growing season. The number of irrigation events during each season is shown in Table 2-1. Soil matric potential (kPa) was measured using electrical resistance sensors from WATERMARK (Irrometer Company Inc., California USA). This provided an indication of soil moisture during field drainage periods for fertilization and irrigation events.

2.5.4 Statistical analysis

To investigate treatments effects, the following statistical tests were conducted using R statistical software (RStudio Team, 2020) with the significance level set at $p < 0.05$. Analysis of variance (ANOVA) was performed for cumulative fluxes of CH_4 and N_2O emissions, GWP, water use, and grain yield using a randomized complete block design model. When results violated the assumptions of homogeneity of variance and normality of the ANOVA test, they were transformed accordingly using log10 or power functions. Due to significant interactions between treatment and season, results were analyzed separately for each season.

2.6 Results

2.6.1 Weather conditions

Air temperature and precipitation data for each season are shown in Fig. 2-1. Average daily temperatures during this period ranged from 24-34°C for season one (Jan. – Apr. 2019), 27-34°C for season two (Jun. – Sep. 2019), 26-36°C for season three (Jan. – Mar. 2020), and 23-30°C for season four (May. – Aug. 2020). Seasons one, two, and four recorded 39, 30, and 31 precipitation days, respectively, while season three had only 15 precipitation days. In growing seasons one and two, cumulative precipitation was 650 and 111 mm, respectively, while in seasons three and four it was 83 and 209 mm, respectively. The precipitation distribution was uniform in growing periods one and four. While precipitation was concentrated in the early stages of plant development in growing period two, it was concentrated in the phenological growth stages of tillering and flowering in the third season.

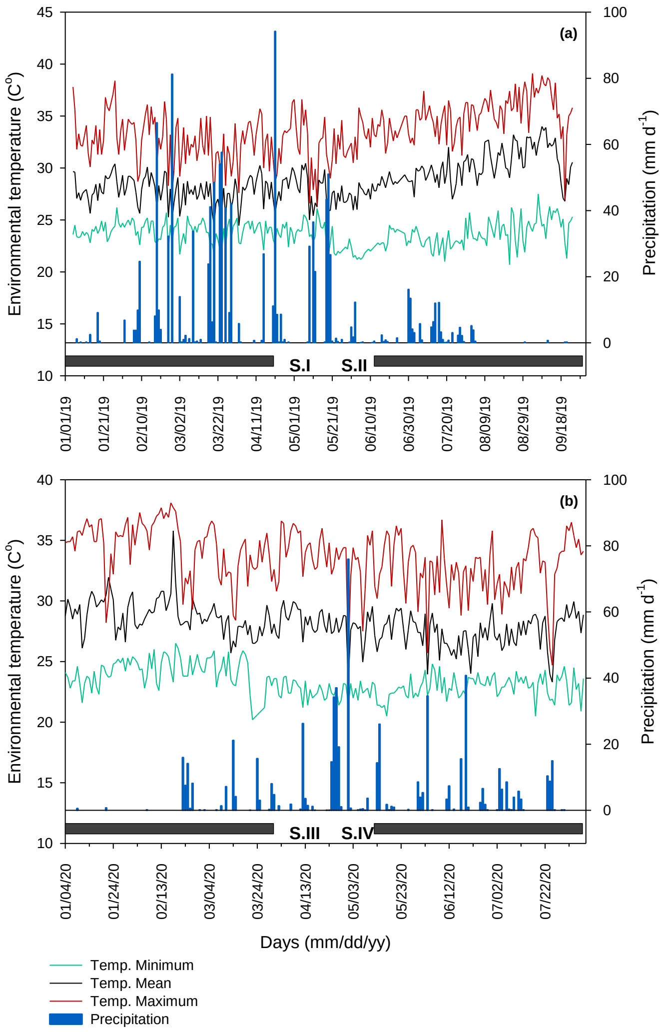

Fig. 2-1. Minimum, mean, and maximum air temperatures and daily precipitation over four rice growing seasons between 2019 and 2020. Horizontal gray bars represent growing seasons (S.I – S.IV). (a) Season I (January – April 2019) and season II (June – September 2019) and (b) season III (January – March 2020), and season IV (May – august, 2020).

2.6.2 Rice grain yield, biomass, and water consumption

Rice grain yields were highest in the second and fourth growing seasons, ranging from 7.25 to 8.15 Mg ha^{-1} (Table 2-2). In three of four growing seasons (I, III, and IV seasons), there were no significant differences in yield among treatments (*P* > 0.05). Only the yield of AWD$_{5cm}$ was significantly reduced by 11% in the second season compared with the control. In other seasons, the control treatment had a slightly higher numerical yield compared to AWD treatments, but this did not translate to statistical differences. In the third and fourth seasons, aboveground biomass differed at the flowering stage in both seasons but only at the harvest stage in the third season. At the two growth stages evaluated, aboveground biomass was higher for the second season of 2019 than in the other seasons for all treatments (Table 2-3), which resulted in a greater grain yield.

The control had the highest water consumption in all seasons compared to the treatments with AWD, ranging from 9260 to 16559 m^3 ha^{-1} $harvest^{-1}$ (Fig. 2-2). Among the four growing seasons, water use for the control was lowest in the first season, which was due to high rainfall and lower irrigation demand. In this season, water use was lower by 33% for AWD_{5cm} and 50% for AWD_{10cm} treatments compared to the control. In the second season, water use was lower by a similar amount for both AWD treatments (34% for AWD_{5cm} and 35% for AWD_{10cm}). In the third season, irrigation use was 33% lower for AWD_{5cm} and 19% lower for AWD_{10cm} compared to the control. The climatic conditions of the third season indicate that it was a drier semester. The water level in the treatment at AWD_{10cm} was dropped to 10 cm below the soil surface, and this indicates that it has fewer irrigation events, but more water had to be added compared to the other semesters to reach the sheet of water. In the fourth season, AWD decreased water use more than any other season, resulting in a 50% reduction for AWD_{5cm} and 56% reduction for AWD_{10cm}. Water consumption was generally reduced more by AWD_{10cm} than AWD_{5cm} across seasons.

Table 2-2: Effect of irrigation treatments on rice grain yield (Mg ha^{-1}) in four growing seasons. Within each column, values followed by the same letter are not significantly different at $p < 0.05$.

Seasons	**2019**		**2020**	
	I	**II**	**III**	**IV**
Treatments	**Rice grain yield (Mg ha^{-1})**			
Control	6.23 ± 0.42a	8.15 ± 0.27 a	6.90 ± 0.63 a	7.61 ± 0.16 a
AWD_{5cm}	5.93 ± 0.20a	7.25 ± 0.36 b	5.82 ± 0.77 a	7.51 ± 0.47 a
AWD_{10cm}	5.16 ± 0.38a	7.48 ± 0.13 ab	6.25 ± 0.23 a	7.43 ± 0.49 a

Table 2-3: Rice aboveground biomass at flowering and harvest growth stages in four rice production seasons. Within each column and sampling date, values followed by the same letter are not significantly different at $p < 0.05$.

Seasons	2019		2020		2019		2020	
	I	II	III	IV	I	II	III	IV
	Aboveground biomass (Mg ha^{-1})							
Treatments	Flowering stage				Maturity stage			
Date (mm/dd/yy)	3/8/2019	9/13/2019	3/7/2020	8/15/2020	4/8/2019	10/17/2019	4/4/2020	9/9/2020
Control	6.50 ± 0.59 a	10.68 ± 0.84 a	7.05 ± 0.25 a	7.25 ± 0.20 a	14.77 ± 1.16 a	17.35 ± 1.26 a	9.59 ± 0.25 a	12.00 ± 3.61 a
AWD$_{5cm}$	6.18 ± 0.13 a	9.92 ± 2.08 a	4.63 ± 0.29 b	5.96 ± 0.30 a	15.84 ± 0.73 a	17.76 ± 0.24 a	8.57 ± 0.11 ab	10.18 ± 2.47 a
AWD$_{10cm}$	6.12 ± 0.42 a	8.76 ± 1.28 a	4.47 ± 0.13 b	5.70 ± 1.20 b	14.61 ± 1.17 a	15.79 ± 4.56 a	7.63 ± 0.70 b	9.93 ± 0.55 a

Table 2-4: Cumulative CH_4 - C and N_2O – N emissions from three irrigation treatments and total GWP (kg CO_2 eq. ha^{-1}). Within each column, values followed by the same letter are not significantly different at 0.05 level.

Seasons	2019						2020					
	I			II			III			IV		
Treat-ments	CH_4 - C (kg ha^{-1})	N_2O - N (kg ha^{-1})	GWP	CH_4 - C (kg ha^{-1})	N_2O - N (kg ha^{-1})	GWP	CH_4 - C (kg ha^{-1})	N_2O - N (kg ha^{-1})	GWP	CH_4 - C (kg ha^{-1})	N_2O - N (kg ha^{-1})	GWP
Control	0.64 ± 0.09 a	1.01 ± 0.03 a	458.15 a	25.25 ± 9.39 a	1.04 ± 0.24 b	1361.71 a	4.49 ± 0.77 a	0.58 ± 0.01 a	410.82 a	3.35 ± 0.86 a	1.04 ± 0.41 a	565.92 a
AWD$_{5cm}$	0.06 ± 0.02 b	0.39± 0.12 b	169.62 b	6.51 ± 0.47 b	0.64 ± 0.04 b	511.81 a	0.86 ± 0.70 b	0.36 ± 0.07 b	185.25 b	0.95 ± 0.02 b	0.91 ± 0.08 a	425.01 ab
AWD$_{10cm}$	- 0.20 ± 0.04 c	0.31 ± 0.10 b	123.67 b	3.05 ± 0.47 b	1.99 ± 0.34 a	963.19 a	0.46 ± 0.32 b	0.35 ± 0.03 b	166.66 b	-0.32 ± 0.36 b	0.46 ± 0.06 a	187.66 b

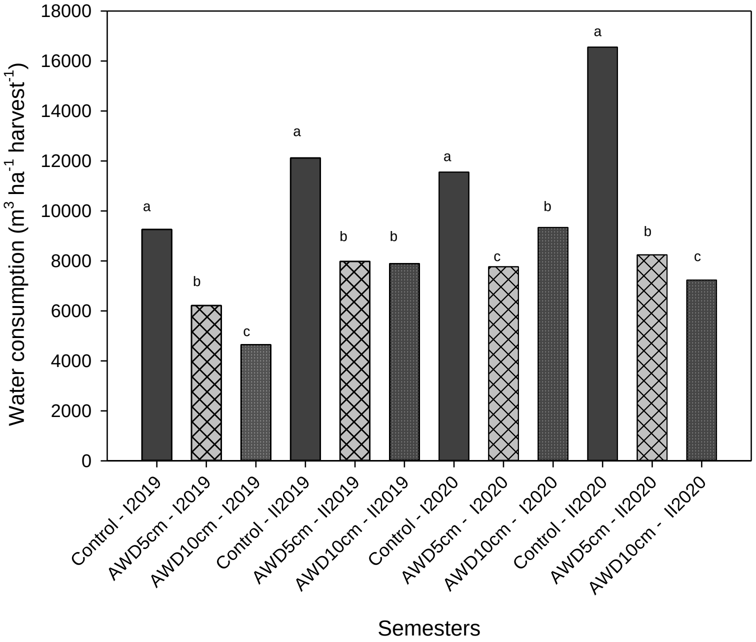

Fig. 2-2: Water consumption for the control and two AWD treatments across four rice cropping seasons. Season I (January – April 2019); season II (June – September 2019); season III (January – March 2020), and season IV (May – august, 2020).

2.6.3 Daily GHG fluxes and soil moisture

The daily fluxes of CH_4 and N_2O emissions were different for each rice growing season evaluated (Fig. 2-3, 2-6). Daily CH_4 fluxes between treatments showed high variability, with emissions ranging between -5.79 to 6.22 mg CH_4 - C m^{-2} d^{-1} for the first season; -1.56 to 104.69 mg CH_4 - C m^{-2} d^{-1} for the second season; -2.08 to 154.70 mg CH_4 - C m^{-2} d^{-1} for the third season, and -0.82 to 27.28 mg CH_4 - C m^{-2} d^{-1} for the fourth season. In the control, an increase in CH_4 emission was generally observed in the second half of the growing season near to the finish of the flowering stage when the fertilizing was finished, and the water level was constant (flooded). In the first season, daily CH_4 emissions were relatively low at < 6.22 mg CH_4 - C m^{-2} d^{-1} compared with the other seasons (Fig. 2-3a). In the second season, the increase in daily CH_4 emissions began after about 62 days in all treatments (Fig. 2-4a). The increase in daily CH_4 emissions in season two is likely due to a higher number of irrigation events after the flowering stage owing to dry conditions that increased water demand. The highest emissions occurred toward the end of the growing season on days 77-96 in the control treatment (101.95 ± 15.17, 104.59 ± 2.79, 56.20 ± 16.9, and 94.43 ± 7.61 mg CH_4 - C m^{-2} d^{-1} on days 77, 89, 95, and 96, respectively). The variation in CH_4 emissions between the AWD treatments and the control was lower in the third season except for one sampling date (Fig. 2-5a). Among treatments there were no notable changes until day 13, yet high CH_4 emissions (154.70 ± 1.95 mg CH_4 - C m^{-2} d^{-1}) were observed for the control 14 days after germination, while for AWD treatments the changes in CH_4 emissions were minor. In the fourth growing season, an increase in daily CH_4 emissions was observed 49 days after seeding following the third fertilization event in the control treatment (Fig. 2-6a), with soil matric potential mostly at saturation levels. Weather and soil matric potential did not correlate directly with CH_4 emissions, except for the third season, where precipitation was positively correlated with CH_4 emissions and soil matric potential was negatively correlated with CH_4 emissions ($P < 0.05$). This season was drier than the other seasons evaluated (83 mm).

The pattern of N_2O emissions recorded was not consistent, with peak fluxes sometimes occurring earlier and sometimes later each growing season (Fig. 2-3b, 2-6b). Importantly, N_2O emissions following chemical fertilizer application events during vegetative rice growth tended to be higher under the control than AWD treatments, although there was often variation between treatments in different seasons. In the first season (Fig 2-3b), the highest N_2O peaks occurred after the first fertilization in the control and AWD_{5cm} treatments where soil matric potential was 12 and 27 kPa (Fig. 2-3c), respectively, and after the last fertilization dose (41 days) in the control treatment (0 kPa). In contrast, the high peaks of N_2O in season II occurred 2-4 days after the last fertilizer application for the AWD_{10cm} treatment (61 after seeding) (Fig. 2-4b). In season III, emissions reached their highest levels 15 days after fertilization and 55 days after the AWD_{10cm} treatment, but AWD_{5cm} and the control also showed elevated emissions during the second half of the season (Fig 2-5b). The highest N_2O emission peaks during season IV were 2 days after the second fertilizer application for the control and AWD_{5cm} treatments (Fig 2-6b). No correlations were observed between weather and soil matric potential and N_2O emissions in any season.

Soil matric potential increased sharply during field drainage events in the AWD treatments, albeit with a different magnitude among seasons (Fig. 2-3c, 2-6c). The values of sandy loam soil matric potential typically varied across treatments, ranging from near saturation (0 to 10 kPa) to field capacity (10 to 36 kPa), or even drier under AWD management between irrigation events (> 36 kPa usual margin for irrigation). While season one had high rainfall and only a few drainage events with moderate soil drying, season two had the lowest precipitation, which resulted in frequent and more severe soil drying events and the highest number of irrigations (Fig. 2-3c and 2-4c). Seasonal patterns of soil matric potential were more similar in seasons three and four, especially between irrigations in AWD (Fig. 2-5c and 2-6c). Despite flood irrigation being practiced in the control except during fertilizer applications, it was not always possible to keep the soil saturated due to the high sand content and hydraulic conductivity, especially in years with lower rainfall. The difficulty of retaining water in fields in dry years is typical of conventional farming practices in the study region, meaning these results are relevant to local production systems. As soil in the AWD treatments was allowed to dry further than the control, matric potential in AWD treatments either reached around field capacity during fertilizer applications (season one), or lower soil moisture in years with less precipitation (seasons two-four). The fluctuation in soil matric potential explains the large changes in soil N_2O emissions and reduction in CH_4 emissions during the fertilization period across the four growing seasons.

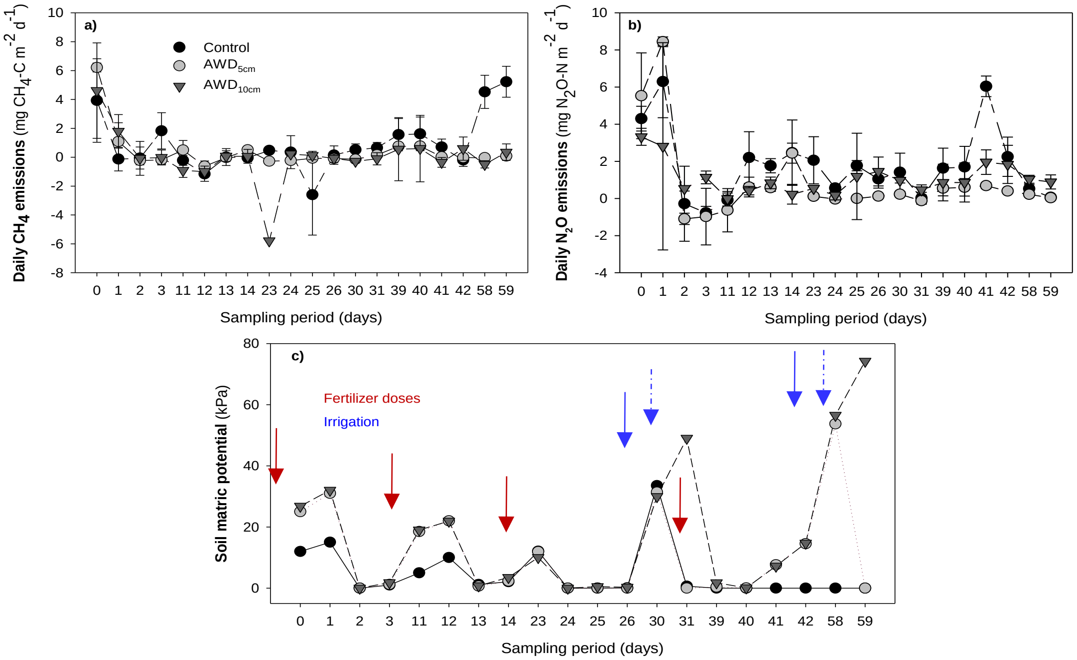

Fig. 2-3: Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season I (2019). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for AWD_{5cm}, and blue dash-dot arrows show irrigation events for AWD_{10cm}. Error bars indicate ± 1 SE (n=3).

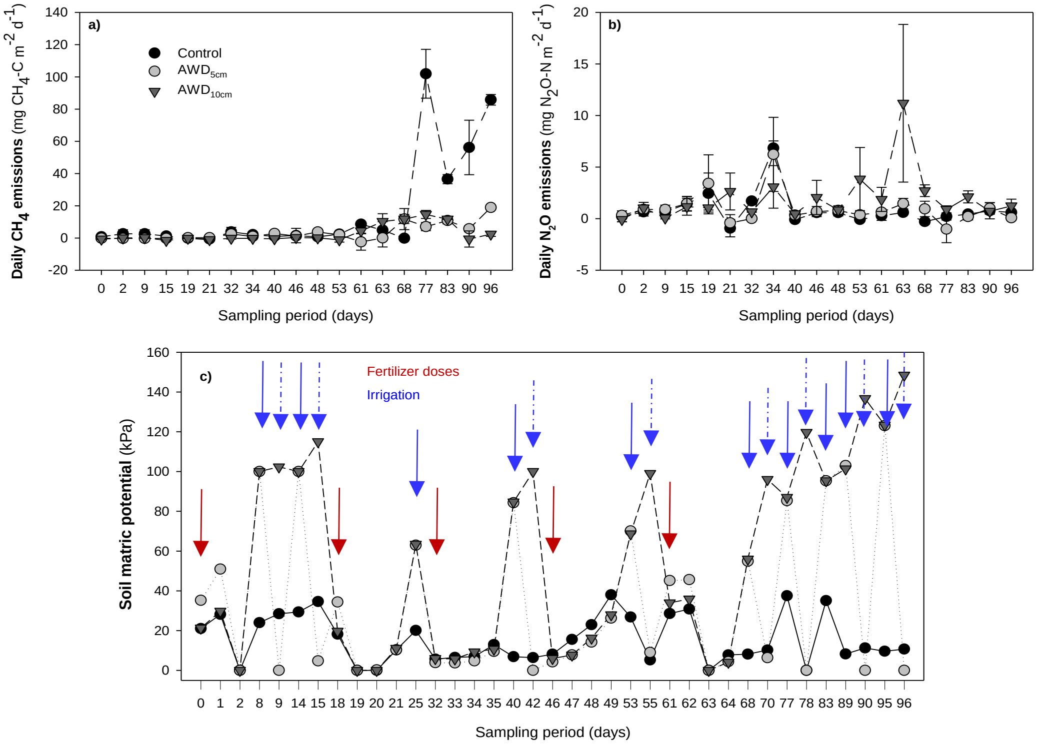

Fig. 2-4: Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season II (2019). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for AWD_{5cm}, and blue dash-dot arrows show irrigation events for AWD_{10cm}. Error bars indicate ± 1 SE (n=3).

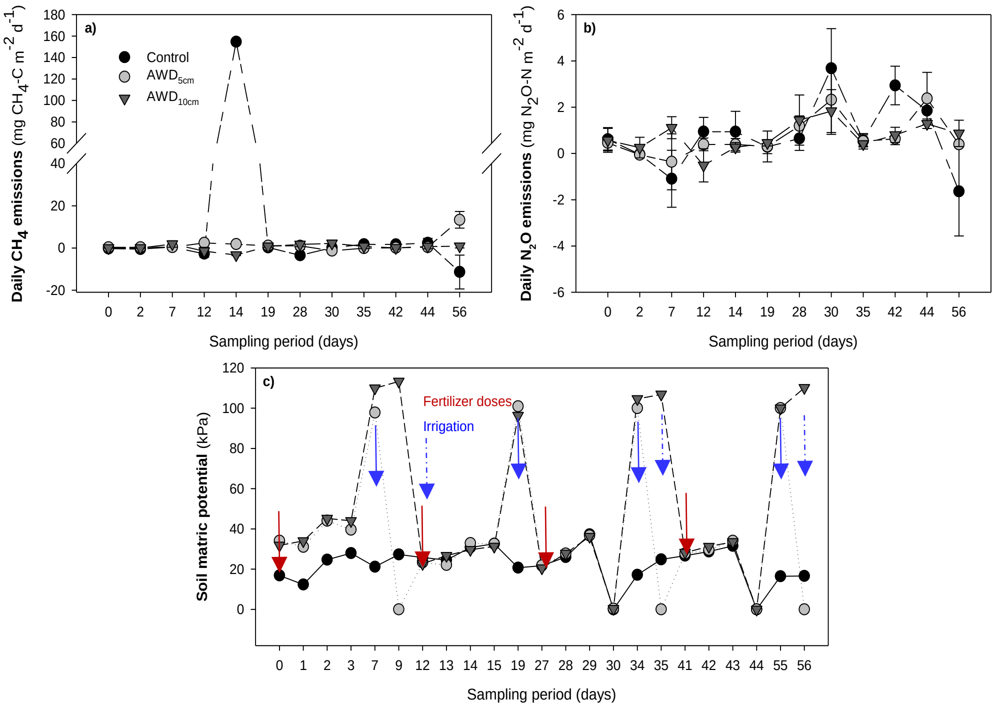

Fig. 2-5: Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season III (2020). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for AWD_{5cm}, and blue dash-dot arrows show irrigation events for AWD_{10cm}. Error bars indicate ± 1 SE (n=3).

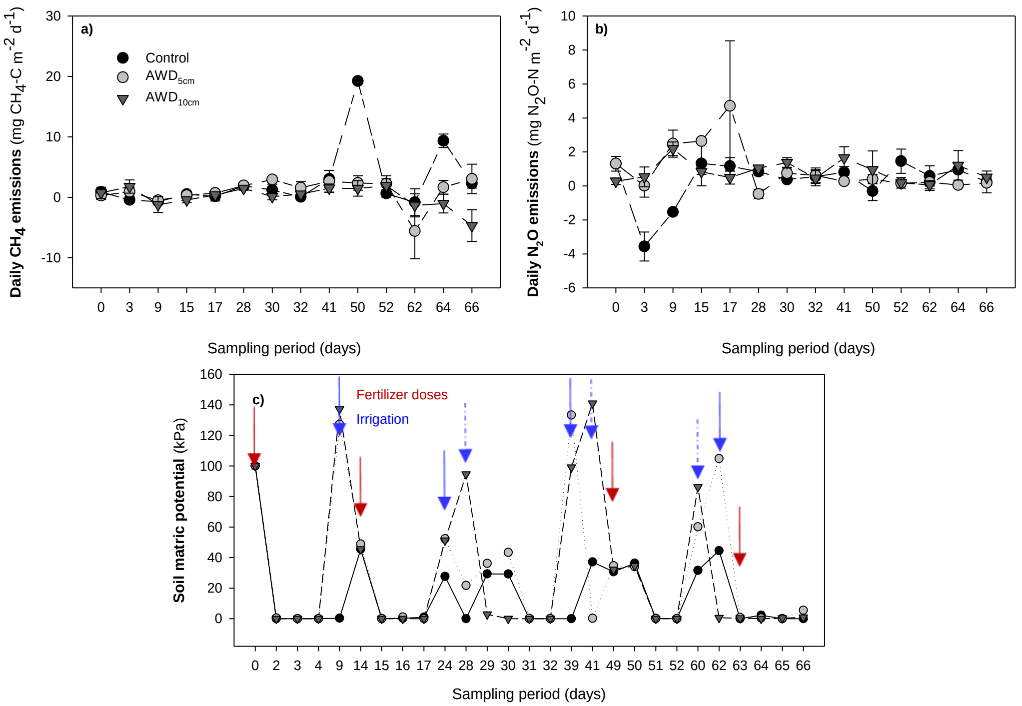

Fig. 2-6: Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season IV (2020). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for AWD_{5cm}, and blue dash-dot arrows show irrigation events for AWD_{10cm}. Error bars indicate ± 1 SE (n=3).

2.6.4 Cumulative GHG emissions and GWP

The AWD treatments significantly reduced CH_4 emissions compared to the control in every growing season (Table 2-4). For the control, CH_4 emissions were lowest in season I, highest in season II, and similar in seasons III and IV. The CH_4 mitigation achieved by AWD_{5cm} and AWD_{10cm} was 91 and >100%, respectively, in season I, 74 and 88% in season II, 81 and 90% in season III, and 72 and 100% season IV. Cumulative N_2O emissions significantly differed by treatment in three of the four growing seasons studied, except in the fourth season. Comparing AWD treatments to the control, cumulative N_2O emissions were reduced by 12 to 70% across seasons. However, in the second season, the AWD_{5cm} treatment showed a 91% increase in N_2O emissions. Cumulative N_2O emissions were highest in the second season (reaching over 3 kg N_2O ha^{-1}), and similar in range for the other seasons (0.48 to 1.63 kg N_2O ha^{-1}).

On a 100-year time horizon, GWP was significantly higher in the control than both AWD treatments in each of the four seasons evaluated (Table 2-4). The highest GWP was found in season II, which presented minor precipitation events, due to both elevated CH_4 and N_2O emissions compared to other seasons. Across seasons the GWP of AWD was 25–73% less than that of control, owing to a 72-100% reduction in cumulative CH_4 emissions and a 12-70% decrease in cumulative N_2O emissions in both wet and dry seasons. The average contribution of N_2O to GWP across the three treatments was 58-100%, while for CH_4 emissions it ranged from 0-42%. In general, the relative contribution of N_2O to GWP increased with increasing soil drying (control < AWD_{5cm} < AWD_{10cm}), whereas it decreased for CH_4 emissions. There was no apparent tradeoff between CH_4 and N_2O mitigation in AWD treatments. In fact, there was a synergy with treatments that achieved the highest reduction in CH_4 emissions also showing the highest reduction in N_2O emissions.

2.7 Discussion

2.7.1 Yields and water use

In this experiment, AWD significantly reduced water use without negatively affecting yield in three of four growing seasons. This is consistent with a large number of studies showing that AWD can decrease water inputs by around 25–70% without causing a reduction in yield (Ishfaq et al 2020). The lack of an agronomic penalty could be due to the fact that water management was relatively similar in the AWD and control during vegetative growth (Carrijo et al., 2017). During the fertilization period early in the season (ending approximately 40-60 days after sowing, depending on season), fertilizer was applied in 4-5 doses. Each time soil drainage occurred in the AWD treatments, soil matric potential decreased to somewhere between field capacity or greater, while matric potential in the control was between saturation and field capacity (sometimes with a small amount of standing floodwater). Due to the relatively shallow drainage depth (5 or 10 cm) where the soil matric potential reached the margin of irrigation, water stress may not have occurred during these events. This could explain the similar biomass observed between treatments at flowering during most growing seasons. Moreover, later in the season during rice reproductive growth, the period of soil drying between irrigation events in AWD treatments was relatively short before irrigation was triggered. This was due to the combination of high temperatures and high evaporative demand by the plants, as well as rapid drainage in the sandy loam soil, which typically resulted in only 1-3 days of soil drying time in AWD treatments. A recent global analysis found that the number of unflooded days in a rice growing season was among the strongest factors influencing rice yield under AWD compared to other soil and climate variables (Bo et al., 2022). Therefore, the relatively short periods of drainage likely allowed soil water availability to be maintained below 5 or 10 cm depth, providing roots sufficient access to water, and helping avoid drought stress that would normally result in yield loss (Carrijo et al., 2018).

Previous studies suggest that AWD applied only during the early growing season (45 to 65 days) or when the water table does not fall >15 cm below the soil surface when practiced throughout the season does not reduce yield (Carrijo et al., 2017; Zhou et al., 2017). Other studies show there is often no yield reduction when AWD irrigation is applied compared to continuous flooded rice systems (Oo et al., 2018a; Setyanto et al., 2018), while others have documented a small yield loss (Liao et al., 2021). Although soil matric potential increased to over 100 kPa at points in our study, this did not impact yield, similar to findings from Kukal et al. (2005). These results suggest it may not be necessary to continuously irrigate or saturate the soil throughout the vegetative growth season of rice because rice growing under continuous flooding conditions can adapt to intermittent flood irrigation (Jiang et al., 2019). In some cases, increasing air exchange into the soil with AWD can provide sufficient oxygen to the root system to facilitate the mineralization of soil organic matter, thereby increasing soil fertility and enhancing rice production (Oo et al., 2018b).

Our results may differ from studies reporting a yield decline with AWD for several reasons. Much work in Asia is based on promoting drainage 15 cm below the soil surface or more (Lampayan et al., 2015), which may take longer in clay soils and increase the risk of crop water stress. On the other hand, soil properties such as pH and organic carbon also affect rice yield under AWD management. In particular, while some research suggests that the most substantial yield losses occur in soils with a pH greater than 7 or a carbon content less than 1% (Carrijo et al., 2017), it is worth highlighting that our experimental site record pH values of 6.5 and carbon content of 0.85%, respectively. By presenting slightly acidic pH conditions, it prevents the formation of impermeable soil layers that can potentially obstruct root development in AWD treatments (Carrijo et al., 2017; Huang et al., 2017; Ishafaq et al., 2020).

The control had the highest water use across seasons that included both irrigation and precipitation. Since rice production requires more water than most other crops (Mekonnen and Hoekstra, 2011), identifying practices that can reduce both water use and GHG without affecting yields is an attractive option for sustainable intensification. Despite the relatively shallow drainage depths of 5 or 10 cm evaluated for the sandy loam soil in this study, corresponding to relatively short periods of non-flooded conditions, water savings were still significant (19-56% across seasons). In general, evaluation of AWD in tropical, subtropical, and temperate regions has shown great potential for non-continuous irrigation to reduce water use (Bo et al., 2022). In our study this was particularly noteworthy in seasons with lower precipitation and higher irrigation demands (e.g. AWD decreased water use by around 35% in the second season and more than 50% in the fourth season). The ability to save irrigation water is becoming increasingly important in Colombia due to water scarcity and climate change. These findings are supported by the literature which indicates that the application of AWD under different climatic and soil conditions decreases water use by 20-44% (Hasan et al., 2016; Liang et al., 2016), with grain yield remaining the same or even increasing compared to continuous flooding (Djaman et al., 2018; Xu et al., 2020). To ensure Colombia's food security and access to freshwater, our results suggest rice production can be optimized through AWD management to maintain rice yields while increasing water productivity.

2.7.2 Daily and cumulative GHG emissions

This study is unique because AWD was tested in a non-continuously flooded system which is typical for tropical rice in Colombia and increasingly elsewhere due to water shortages, providing new insights on the CH_4 and N_2O mitigation potential under these conditions. While the daily pattern of CH_4 fluxes differed among the four rice seasons studied (Fig. 2-3a, 2-6a), cumulative CH_4 emissions for the control were low compared to continuously flooded systems reported elsewhere (Jiang et al, 2019; Linquist et al., 2012; Wu et al., 2022). Daily CH_4 emissions remained low in the control until later in the season, which can be attributed to drainage events implemented during the first 40-60 days of crop development to facilitate 4-5 fertilizer applications. Drainage increases soil aeration, reducing methanogenic activity and decreasing the survival rate of methane-producing archaea (Ratering and Conrad, 1998; Sahrawat, 2006). Even when control plots were continuously flooded during reproductive growth, emissions were still below 160 mg CH_4 - C m^{-2} d^{-1} in all seasons studied. Short drainage events early in crop development have been shown to inhibit CH_4 emissions throughout much of the growing season for several reasons. Oxygen availability in soil stimulates methanotrophic activity (oxidation of CH_4), while also increasing sulphate and ferric iron concentrations which continue to inhibit CH_4 production even when soil redox potential drops to low levels following re-flooding (Malyan et al., 2016; Nazaries et al, 2013; Ratering and Conrad, 1998; Sahrawat, 2006; Souza et al., 2021). In addition, rice plants may develop fewer aerenchyma due to less anoxic conditions during early crop development, decreasing CH_4 transport to the atmosphere despite high CH_4 production in soil later in the season (Le Mer and Roger, 2001; Islam et al., 2018). Ammonium sulfate was also used as an N fertilizer source and straw from the previous season was removed from the field, decreasing carbon substrate for methanogenesis, and causing soil redox to drop more slowly (Gao et al., 2002; Sander et al., 2014).

Despite low CH_4 emissions in the control, the two AWD treatments further reduced CH_4 emissions by 72-100% across seasons (Table 2-4). Although the conditions for implementing the AWD technology were generally different from those in our study, the mitigation potential is well-documented with many other experiments showing that soil drainage significantly reduces CH_4 emissions (Bo et al., 2022; Carrijo et al., 2017; Islam et al., 2020; Jiang et al., 2019; Oo et al., 2018a; Setyanto et al., 2018; Zhang et al., 2011). In our study, the additional introduction of dry periods beyond the first two months of the growing season to 5 and 10 cm drainage depth under both AWD treatments appeared sufficient to increase oxygen penetration into the soil, causing soil organic carbon to be oxidized to CO_2 instead of CH_4, effectively suppressing CH_4 emissions compared to the control. Tariq et al. (2017) and Islam et al. (2018) reported that early and mid-season drainage reduced cumulative CH_4 emissions by 88 to 91% compared to continuous flooding. Chirinda et al. (2017) found similar results in a study conducted in the same study area under traditional AWD management (15 cm below ground level) compared to continuous flooding. Sometimes it can be challenging to maintain aerated soil conditions in AWD due to high rainfall volumes during wet seasons in tropical climates. Despite frequent rainfall occurring in the two wettest seasons of this study (I and IV), the high hydraulic conductivity of the sandy loam soil supported rapid drainage and sufficient soil drying between irrigations (Fig 2-3c, 2-6c), maintaining the effectiveness of AWD for CH_4 mitigation in both seasons. Since rice farmers in Colombia are used to draining fields during fertilizer applications as conventional practice, they may be able to extend the AWD management practice throughout the growing season.

For all seasons, N_2O emissions showed high variability after N fertilization events and during transient dry periods (Fig 2-3b, 2-6b). An important finding is that despite multiple drainage events occurring in all treatments during the first two months prior to fertilizer applications, N_2O emissions remained relatively low during these wet-dry cycles in all treatments (less than 20 mg N_2O - N m^{-2} d^{-1}). In contrast to other studies, the control had slightly higher cumulative N_2O emissions than the AWD treatments across three growing seasons, except in season two when AWD_{10cm} produced significantly higher emissions (Table 2-3, 2-4). This is because most research has evaluated AWD compared to continuous flooding, thus N_2O emissions in the control are extremely low due to anaerobic conditions in submerged soils causing complete denitrification, and any drainage tends to increase N_2O losses. For example, in a meta-analysis Jiang et al. (2019) found that CH_4 emissions were reduced by 53% but N_2O emissions increased by 105%. Another meta-analysis by Wu et al. (2022) found that drainage decreased CH_4 emissions by 58% but increased N_2O emissions by 150%. However, in the present study the control and AWD treatments both experienced non-continuous flooding during fertilizer applications in the first two months of the season, with soil moisture remaining close to saturated in the control but drying to field capacity or lower levels in the AWD treatments. As denitrification processes tend to increase as soil approach saturated conditions (Wang et al., 2021), it is likely that the enhanced soil drying in AWD during fertilizer applications helped limit N_2O losses compared to the control. These results highlight that management of soil moisture during drainage events can avoid a tradeoff in N_2O emissions for AWD management compared to a non-continuously flooded control.

Despite relatively high N inputs and multiple drainage events, cumulative N_2O emissions were relatively low across seasons, generally ranging from 0.5-1.6 kg N_2O ha^{-1} (Table 2-4). According to several studies (Kritee et al., 2018; Lagomarsino et al., 2016; LaHue et al., 2016), N_2O emissions may be low under AWD management if the amount of mineral N in soil at the time of field drainage to support fertilizer application is low. Thus, applying fertilizer to moist soils between field capacity and optimal moisture depending on soil texture (Chapuis-Lardy et al., 2007) helps ensure that the applied N fertilizer is absorbed by roots and therefore little mineral N remains in the soil, limiting nitrification and denitrification processes that trigger N_2O emissions. In addition, the type of N fertilizer, in conjunction with soil moisture at the time of application, can affect N_2O emissions. Urea and ammonium sulfate were used in this study which provides plant-available NH_4^+-N, limiting nitrification and subsequent denitrification transformations in submerged soils while also preventing NO_3^-- N leaching (Rahman and Forrestal, 2021). Fertilization with ammonium sulfate has been shown to mitigate methane emissions by increasing methane oxidation and stimulating sulfate-reducing bacterial populations. This suggests that competition for mineral nitrogen between rice roots and microbes in the rhizosphere plays a critical role in modulating microbial activity (Ali et al., 2012; Bodelier et al., 2000a, b; Rath et al., 2002; Sahrawat, 2006).

2.7.3 GWP and relevance of AWD in this region

According to several AWD studies, it is possible to reduce CH_4 emissions, but this typically results in higher N_2O emissions which represents a tradeoff (Kraus et al., 2022; Lagomarsino et al., 2016; Wang et al., 2021; Wu et al., 2022). When water and N inputs are not properly managed during field drainage events, elevated N_2O emissions can partially or fully offset the reductions in GWP. Our study provides new insights into how this tradeoff can be resolved while reducing both CH_4 and N_2O emissions through changes in water management during the timing of N fertilization, leading to consistent reductions in GWP. Due to lower CH_4 emissions from the non-continuously flooded control, N_2O emissions represented a greater proportion of total GWP (Table 2-4), which is uncommon in flooded rice systems. This places increased importance on avoiding higher N_2O emissions during wet-dry irrigation cycles. As mentioned earlier, draining to field capacity during fertilizer applications may have helped AWD maintain lower N_2O emissions compared to the control which remained close to saturated soil conditions. This suggests that effective GWP mitigation can be achieved by focusing on the combined management of N fertilizer and soil moisture during irrigation events, promoting nutrient availability early in the season during rapid vegetative growth while reducing both N_2O and CH_4 emissions in a non-continuously flooded system.

The effects of AWD on GWP are variable in the literature, as N_2O emissions are not always higher. Prangbang et al. (2020) reported that AWD could reduce annual CH_4 emissions by 32%, while yield and N_2O emissions remained the same. Meanwhile, Lahue et al. (2016) observed no increase in N_2O emissions under AWD, while Cuevas and Ardila. (2018) found that maintaining soil moisture near field capacity can help reduce both CH_4 and N_2O emissions. Yagi et al. (2020) showed that multiple drainage events generally increased N_2O emissions but the combined impacts on GWP were 29% lower. Similarly, Bo et al. (2022) found that non-continuous flooding increased N_2O emissions by 92%, but the substantial reduction in CH_4 emissions (54%) still reduced total GWP by 47% in a recent global analysis. Our work helps address an important knowledge gap because it is not only one of the first studies for tropical rice in Latin America, but as noted by Bo et al. (2022), many rice systems are switching to some sort of intermittent irrigation and the effectiveness of AWD in this context remains uncertain. Given the promising results for AWD compared to non-continuously flooded rice observed here, agronomic practices focused on managing soil moisture during field drainage events should be evaluated elsewhere in future research, ideally with other strategies to further reduce GHG emissions. For example, AWD can be combined with efficient rice varieties that have high crop N requirements, further reducing the risk of N_2O production and keeping N_2O emissions low. This is an opportunity that should be explored in future research under different climate and soil conditions in Colombia.

AWD is a technology that, if properly applied, has the potential to benefit both rice farmers and the environment by reducing overall production costs (depending on water pricing) while maintaining rice yields and reducing GHG emissions. However, there are important barriers to adoption that have been explored in other works (Enriquez et al., 2021; Pearson et al., 2018). For example, farmers need the ability to have level fields and reliable access to irrigation water to quickly irrigate field, when necessary, but this is not always possible in a smallholder context (Islam et al. 2018). When evaluating the feasibility of this type of water management in Colombia, it is important to keep in mind that current irrigation fees are based on rice area cultivated as there is not yet a policy that charges for actual water use, which does not provide an economic incentive for farmers to reduce the number of irrigations. In the absence of incentives for farmers to reduce GHG emissions, implementing this type of management could face challenges. Therefore, changes in agricultural policy, irrigation infrastructure, and institutional arrangements are likely needed to facilitate AWD adoption more broadly (Enriquez et al., 2021). In the short-term, considering that implementing field drainage events while controlling soil moisture during the early season fertilization period is a common practice for farmers in Colombia, it could make it easier for farmers to implement this version of AWD throughout the growing season to achieve environmental benefits. Such an approach would allow for the reduction of GHG emissions and water use without compromising farmer yields and profitability.

2.8 Conclusions

We quantified water use, grain yield, and GHG emissions in response to two AWD irrigation treatments compared to the conventional management regime of tropical rice in Colombia. We found that both CH_4 and N_2O emissions significantly decreased under AWD management with little difference in rice yields in three of four seasons. Our findings are consistent with our hypothesis: that AWD treatments with drainage depths of 5 or 10 cm can help reduce CH_4 and N_2O emissions in the Colombian context without reducing yields by maintaining soil water content at levels that do not induce crop water stress compared to the control. An important aspect of this study is that AWD was compared against a non-continuously flooded control, which is becoming a more common management practice due to water scarcity. The significant reduction in water use and CH_4 emissions is aligned with the large body of evidence on AWD irrigation. However, the simultaneous reduction in N_2O emissions is an important contribution because many AWD studies report an increase in N_2O emissions. We attribute the reduction in N_2O emission to optimal water management at the time of fertilization events early in the season to achieve a soil moisture near field capacity for AWD treatments, whereas this differs from conventional rice management where the soil is maintained at near saturation conditions. Thus, fine tuning water management during drainage events may be the key to lowering GHG emissions without reducing productivity in non-continuously flooded systems where N_2O emissions represent an important contribution to GWP. Future work should explore whether the control treatment could produce similar results if soil water content continued to be maintained near field capacity after fertilization to avoid water stress. Our results suggest implementation of AWD can be a low GHG emission, climate-resilient practice for Colombian rice farmers because it ensures yields and food security and improves water use efficiency during dry and wet seasons.

2.9 Acknowledgments

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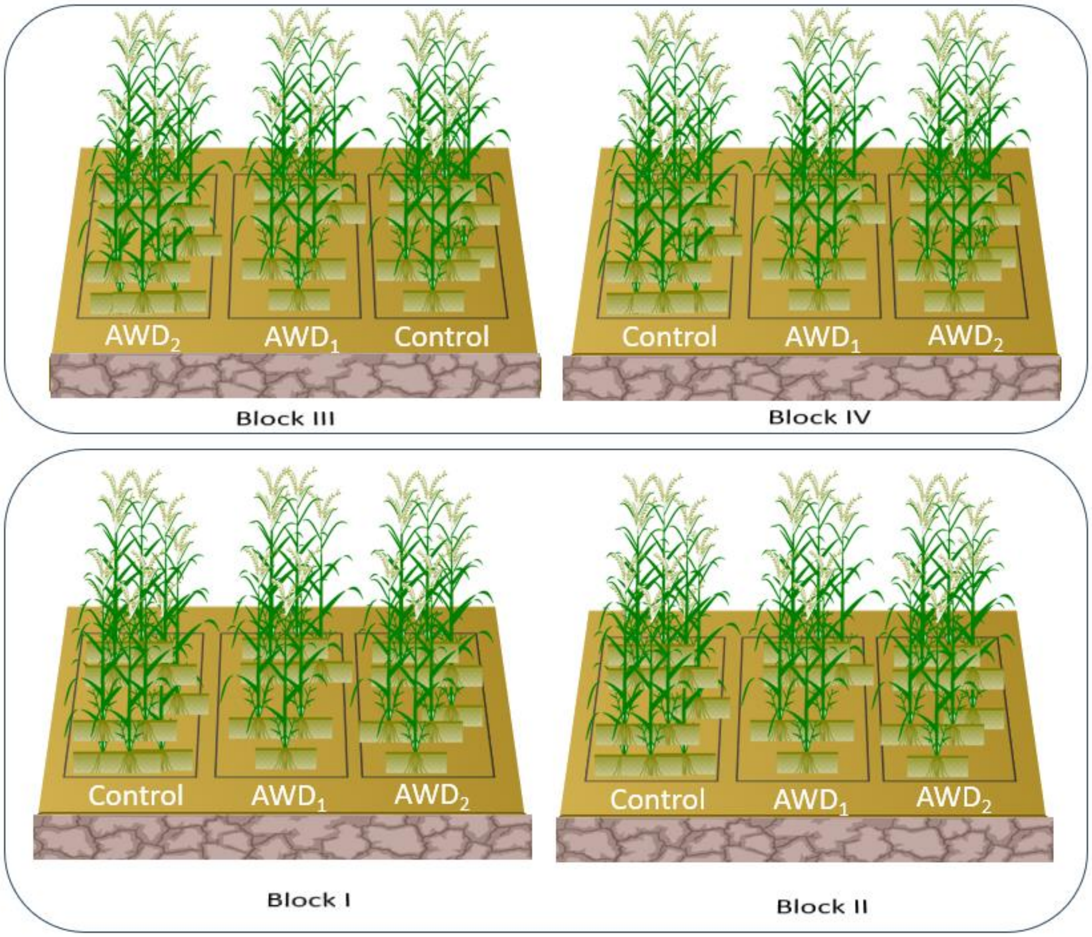
2.11 Annex

Annex A: Schematic representation of the experimental design.



3 Chapter II: Identifying rice varieties for mitigation of methane and nitrous oxide emissions in two regions of Colombia.

After thoroughly examining the impact of AWD irrigation on GHG emissions and rice productivity, our focus now shifts to understanding how rice variety selection can further mitigate these emissions. In Chapter II, titled "Identifying Rice Varieties for Methane and Nitrous Oxide Emission Mitigation in Two Regions of Colombia", findings from a study previously submitted to the Journal of Field Crops Research (Loaiza et al., 2024). This study, aimed at addressing environmental challenges in rice cultivation, evaluates the mitigation potential of various commercial rice cultivars under intermittent irrigation practices. Specifically, we analyze how different rice varieties can reduce CH_4 and N_2O emissions, key greenhouse gases contributing to global warming. By elucidating the efficacy of rice variety selection in emission reduction, this research significantly advances our understanding of sustainable agricultural practices and their role in climate change mitigation strategies.

3.1 Keywords

Greenhouse gas emissions, Grain yield, Global warming potential, Rice varieties, climate change

3.2 Highlights

- Yield and GHG emissions evaluated for four rice varieties over two seasons in two locations
- Intermittent irrigation resulted in low CH_4 emissions and high N_2O emissions
- CH_4 and N_2O emissions represented 27 and 73% of global warming potential, respectively
- Different varieties provided 32-69% GHG mitigation across locations, primarily by reducing N_2O emissions

3.3 Abstract

Cultivar selection offers a promising strategy to mitigate methane (CH_4) and nitrous oxide (N_2O) emissions from rice systems without compromising food security goals. However, there is limited research on the GHG mitigation potential of different rice varieties in Latin America, particularly under non-continuously flooded irrigation. The objective of this study was to examine CH_4 and N_2O emissions, grain yield, and global warming potential (GWP = CH_4 + N_2O) of 4 four commercial rice cultivars grown under intermittent irrigation during two seasons (2020 and 2021) in two rice-growing regions of Colombia (Tolima and Casanare). Results show that crop productivity did not differ among rice varieties during the wet season but F-68 in Tolima and F-Itagua significantly reduced yields in the dry season in Casanare. Across varieties, CH_4 emissions and GWP were relatively low due to frequent field drainage periods supporting soil oxidation (0.9-18.4 kg CH_4 ha^{-1} and 349-4704 kg CO_2-equivalents ha^{-1}, respectively). As a result, N_2O emissions contributed the majority of GWP (73% on average across locations). The varieties F-67 in Tolima and F-Itagua in Casanare significantly reduced GWP by 32-61% across seasons, primarily by reducing N_2O emissions. Contrary to previous work focusing on CH_4 mitigation in rice systems, our study highlights the role of rice variety selection in reducing N_2O emissions under non-continuously flooded irrigation, a practice which is increasingly being implemented for global rice systems in the face of climate change and water scarcity.

3.4 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 approximately 6-22% of CH_4 (Smartt et al., 2016; Smith et al., 2021) and 11% of N_2O on a global level (Zhang et al., 2021; 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 100-year time horizon (IPCC, 2021), greenhouse gas (GHG) emissions from rice cropping systems represent a severe concern for climate change (Wassmann et al., 2000; Van Groenigen et al., 2011; Zhang et al.,2019a). Although 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 need for climate-smart approaches to boost the yields of current rice production systems. Hence, developing practical pathways for reducing GHG emissions from rice systems to mitigate climate change without negatively affecting rice yields and compromising food security is an urgent priority.

Cultivar choice can strongly influence GHG emissions, especially CH_4 production and release from rice fields (Setyanto et al., 2004; Ma et al., 2010; Qin et al., 2015). Soil CH_4 production is due to the anaerobic decomposition of soil organic matter and plant carbon inputs, with the rice plant acting as the primary pathway for the transport of CH_4 from soil to the atmosphere (Conrad, 2007). Differences in rice biomass production, root development, aerenchyma, and grain yields all influence how much carbon is captured and incorporated into plant biomass and how much enters the soil, which in turn becomes substrate for CH_4 emissions (Denier van der Gon et al., 2002; Gutierrez et al., 2013; Jiang et al., 2017). Due to contrasting growth habits, root exudates, internal physiology, and cultivar-specific effects on soil methanotrophic communities, previous research has shown large variation in seasonal CH_4 emissions among different cultivars (Ma et al., 2010; Simmonds et al., 2015; Zheng et al., 2014). For example, Japonica varieties tend to emit less GHG 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 cultivars, with Li et al. (2022) reporting grain yield increases of 19–94% between the 1960–2010s, while CH_4 emissions decreased by 9–41% compared to 1950s. Variety replacement over several decades in China has also generated a large yield increase with substantial GHG reduction (Zhang et al., 2019b).

Soil N_2O emissions are produced through microbial nitrification and denitrification reactions depending on available carbon, inorganic N substrate, soil O_2 concentration, pH soil and temperature (Markfoged et al., 2011; Signor & Cerri, 2013; Song et al., 2019). Thus, different rice cultivars may also influence N_2O emissions by altering these microbial processes, for example due to different root characteristics influencing O_2 and organic carbon availability in the rhizosphere (Chunmei et al., 2020; Firestone & Davidson, 1989; Xiong et al., 2021). Moreover, cultivars 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 Japonicas varieties in relation to CH_4 while N_2O emissions were similar. Other studies reported the main driving forces influencing N_2O emissions in rice soils include inorganic NO_3-N concentration, soil organic carbon content, and cultivar differences in root dry weight, shoot dry weight, root length, stomatal conductance, and transpiration rate (Baruah et al., 2010; Firestone & Davidson, 1989; Gogoi and Baruah, 2012; Gorh and Baruah, 2019).

Rice production in Colombia is a crucial sector that plays a significant role in ensuring food security and promoting rural development. Colombia is one of the largest rice producers in Latin

America, trailing only behind Peru and Brazil (Statista Research Department, 2022; FAOSTAT, 2023). The country's rice production is mainly characterized by three water management systems: irrigated, flooded, and rainfed production. Rice is grown in five regions, with the Llanos and Centro regions accounting for the most significant production. Various rice varieties are cultivated, including commercial varieties such as Fedearroz 67 (F-67) and Fedearroz 2000 (F-2000), bred from a panel of intercrosses with indica materials. Average rice yield is around 5 Mg ha^{-1}, although yield levels may differ based on the production system and variety used (DANE, 2023). Currently, there is no information available regarding the impact of different varieties on GHG emissions.

Due to rice being a staple food crop and economic livelihood for small farmers, it is important to identify varieties that can increase or maintain yield while reducing global warming potential (GWP = CH_4 + N_2O emissions). Other studies have found that selecting rice varieties with specific traits, such as high photosynthetic efficiency or resistance to environmental stressors, can increase grain yield while reducing GWP (Li et al., 2022; Zheng et al., 2021). These studies have generally 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 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 may influence CH_4 and N_2O emissions differently due to distinct underlying mechanisms, the net impacts on GWP under non-continuously flooded conditions remain unclear.

Further research in Latin America is necessary to promote the cultivation of high-yielding, sustainable varieties that can help meet the increasing demand for rice while also reducing the environmental impact of rice production related to GHG emissions. This experiment was conducted to assess the effects of different rice varieties on crop yield, CH_4 and N_2O emissions, and GWP in both dry and wet seasons across two regions in Colombia (Tolima and Casanare).

3.5 Methodology

3.5.1 Experimental site and design

Field experiments were conducted at two representative sites in Colombia (Tolima and Casanare). The Tolima region is primarily irrigated rice while Casanare has both irrigated and rainfed rice. The study was conducted during two cropping seasons: the dry season covering the end of 2020 (season I) and 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 provided irrigation water. In Casanare, the experiment was located in the municipality of Aguazul, specifically at the "La Primavera" farm (5° 28' 54" North, 72° 38' 8" West), in a piedmont plains environment where rice crops were established under rainfed conditions (relying solely on rainfall for water – wet season) and under an irrigation system supplied by water from the Charte River under dry season.

The top layer of soil (0-10 cm) at the Tolima site is classified as Typic ustorthents (IGAC, 1997), soil with loam texture, low organic matter (1.47%), slightly acidic (pH: 5.81), and moderately fertile characterized by low cation exchange capacity (6.36 cmol kg^{-1}), 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, 2012). The top 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: F-2000, F-67, F-70, and F-68 for Tolima and F-2000, F-67, F-70 and FL Fedearroz Itagua (F-Itagua) for Casanare. Rice varieties were chosen based on their commercial relevance and agronomic characteristics for each region. The variety F-Itagua was selected because it is more representative than F-68 for the Casanare rice-growing area. Plot size was 50 m^2. In Saldana, the rice was sown using a mechanized method with a seeding density of 100 kg ha^{-1} in a laser-levelled basin. In Casanare, the soil was prepared with two harrow passes and micro-sorting with a grader, and the seed was sown by hand in the furrow at a density of 135 kg ha^{-1}.

Irrigation was different for each site according to standard practice for each region. In Saldaña, 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. Afterward, irrigation resumed. Following rice flowering, the soil was kept under a small layer of continuous water until physiological maturity was reached. In Casanare, irrigation management varied between the dry and wet seasons, following conventional practice. In the dry season, irrigation was conducted intermittently, as described above, which involved alternating wet and dry periods throughout the growing season until the flowering stage. Following this phase, the soil was maintained under a thin layer of continuous water until reaching physiological maturity. In the wet season (Season II), the irrigation depended on the intensity and frequency of rainfall events, which adequately met the crop's water requirements without additional water application. Irrigation practices varied based on regional standards for each site. The aim was to achieve greater N fertilization efficiency by integrating soil moisture control and proper timing of fertilization. Table 3-1 provides further details of the agricultural practices, such as the planting and harvesting dates and fertilizer application information. Moisture levels were monitored using soil tension sensors in Tolima and piezometers in Casanare.

Table 3-1: Rice crop management events during the two seasons evaluating four commercial varieties in Tolima and Casanare. Fertilizer sources included a combination of 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, respectively.

Agronomic practices	**Season I : Irrigation**	**Season II: irrigation**	**Season I: Irrigation**	**Season II: rainfed**
Regions	**Tolima**		**Casanare**	
Experimental locations	**Saldaña**		**Aguazul**	
Commercial varieties	F-67; F-68, F-70 and F-2000		F-67; F-70; F-2000 and F-Itagua	
Sowing date (dd/mm/yy)	15/10/20	17/06/21	1/10/20	12/06/21
Germination date (dd/mm/yy)	24/10/20	4/07/21	13/10/20	22/06/21
Application dates (dd/mm/yy), Fertilizer sources, and Fraction of dose (kg ha-1)	05/11/20→ **296** (U+KCl+ME+V+SF) 17/11/20→ **200** (U+KCl+SAM+SCM) 30/11/20→ **225** (U+KCl+SAM) 17/12/20→ **200** (U+KCl+SAM+SM)	14/07/21→ **321** (U+KCl+ME+V+SF) 27/07/21→ **250** (U+KCl+SAM+Active3+SM) 10/08/21→ **275** (U+KCl+SAM+Active3+SM) 24/08/21→ **175** (U+KCl+SAM)	28/10/20→ **200** (TS) 04/11/20 →**200** (TS) 11/11/20 →**200** (TS) 25/11/20 → **100** (TS)	06/07/21→ **200** (TS) 13/07/2 → **200** (TS) 21/07/21→ **200** (TS) 23/08/21 → **75** (U)
Nitrogen applied (**kg N ha^{-1}**)	U+ME+V → **37** U+SAM→ **34** U+SAM→ **50** U+SAM →**13**	U+ME+V → **48** U+SAM+Active 3→ **37** U+SAM+Active 3→ **58** U+SAM →**45**	TS → **48** TS → **48** TS → **48** TS → **24**	TS → **48** TS → **48** TS → **48** U → **35**
Harvest date (dd/mm/yy)	9-12/02/21	20-26/10/21	29/01/21	06/10/21

3.5.2 GHG Sampling and Global Warming Potential

The GHG sampling in the rice systems was performed using the closed static chamber technique (Chirinda et al., 2017). See Loaiza et al. (2024) for a full description of methodology. In brief, the chambers were composed of two parts, a base (40 cm height) and a lid (114 liters, 80 cm height) made of polyethylene. 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, and each 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 for temperature recording, and iv) a gas sampling port.

Sampling was conducted approximately weekly 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 events. Subsequently, weekly monitoring was conducted until harvest. Gas samples were collected between 8 and 11 a.m. Each chamber was enclosed for 45 minutes, and four samples were removed (t0, t15, t30, and t45) using 20 ml propylene syringes with an adapted 3-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 temperature, atmospheric pressure, and volume of the chamber. The seasonal cumulative fluxes for CH_4 and N_2O emissions (kg ha^{-1}) were calculated by linear interpolation between sampling dates. The global warming potential of each gas was calculated as 27.2 for CH_4 and 273 for N_2O according to the 100-year time frame (IPCC, 2021).

3.5.3 Rice grain yield and aboveground biomass

The aboveground rice biomass was sampled in both regions during three phenological stages: Floral primordium, maximum tiller, 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 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 hours. The grain yield is reported at 14% grain moisture content.

3.5.4 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 interaction on GHG emissions and rice yields were analyzed using analysis of variance (ANOVA) with repeated measures on 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 HSD test for mean separation.

3.6 Results

3.6.1 Climatic conditions during crop development

The average minimum and maximum daily temperatures in Tolima ranged from 23.3 to 31.8°C for season I and from 22.9 to 32.5°C for season II (Fig. 3-1). Cumulative precipitation reached 371 and 633 mm for seasons I and II, respectively. Similarly, in Casanare, the average minimum and maximum daily temperatures ranged from 22.5 to 32.2°C for season I and 22.5 to 30.7°C for season II. The cumulative precipitation was 363 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. 3-2).

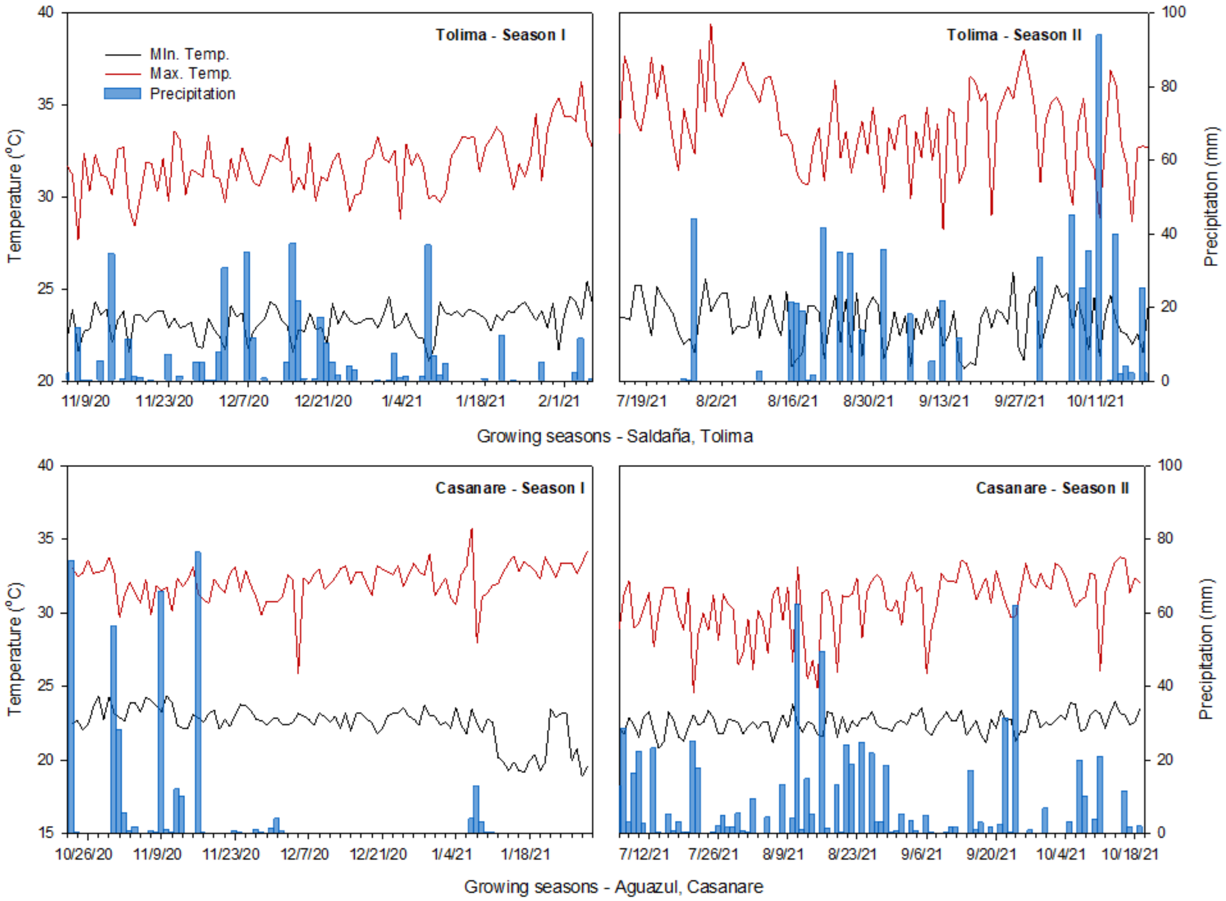


Fig. 3-1: Minimum and maximum temperature and precipitation in the experimental field in Saldana – Tolima and Aguazul – Casanare during the rice growing seasons in 2020 and 2021 (I and II season).

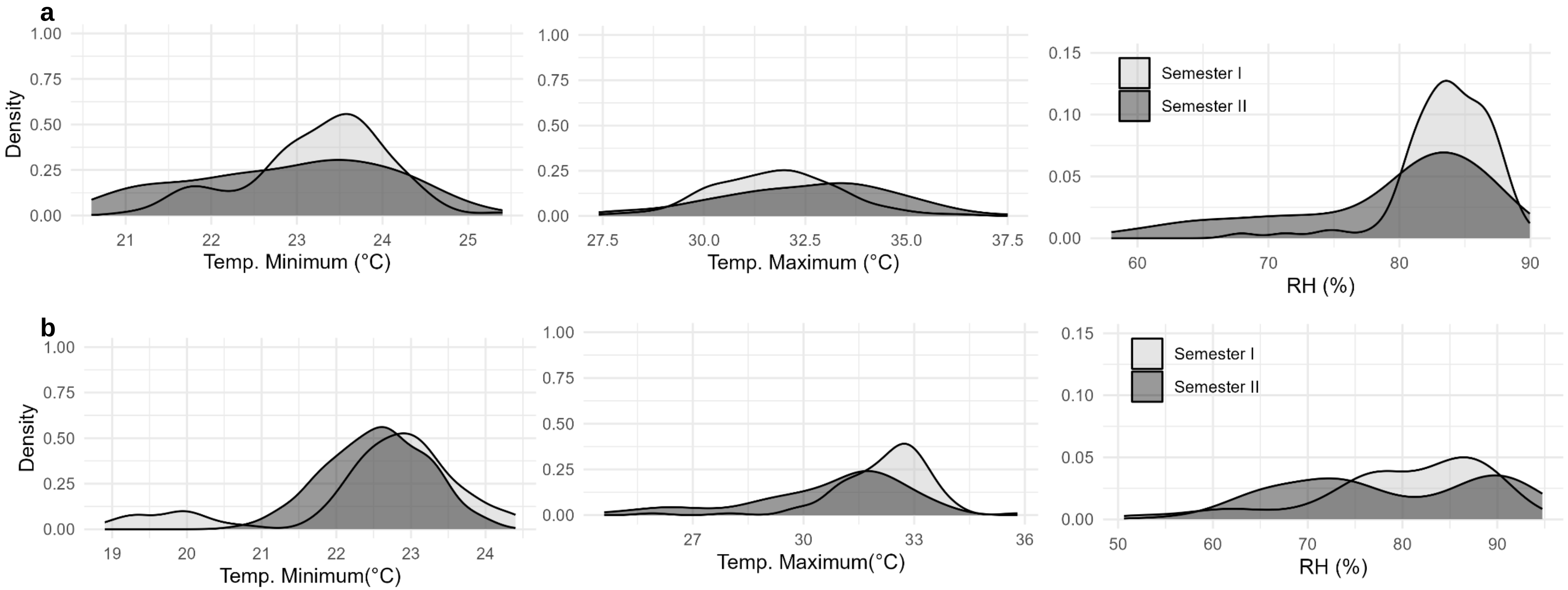


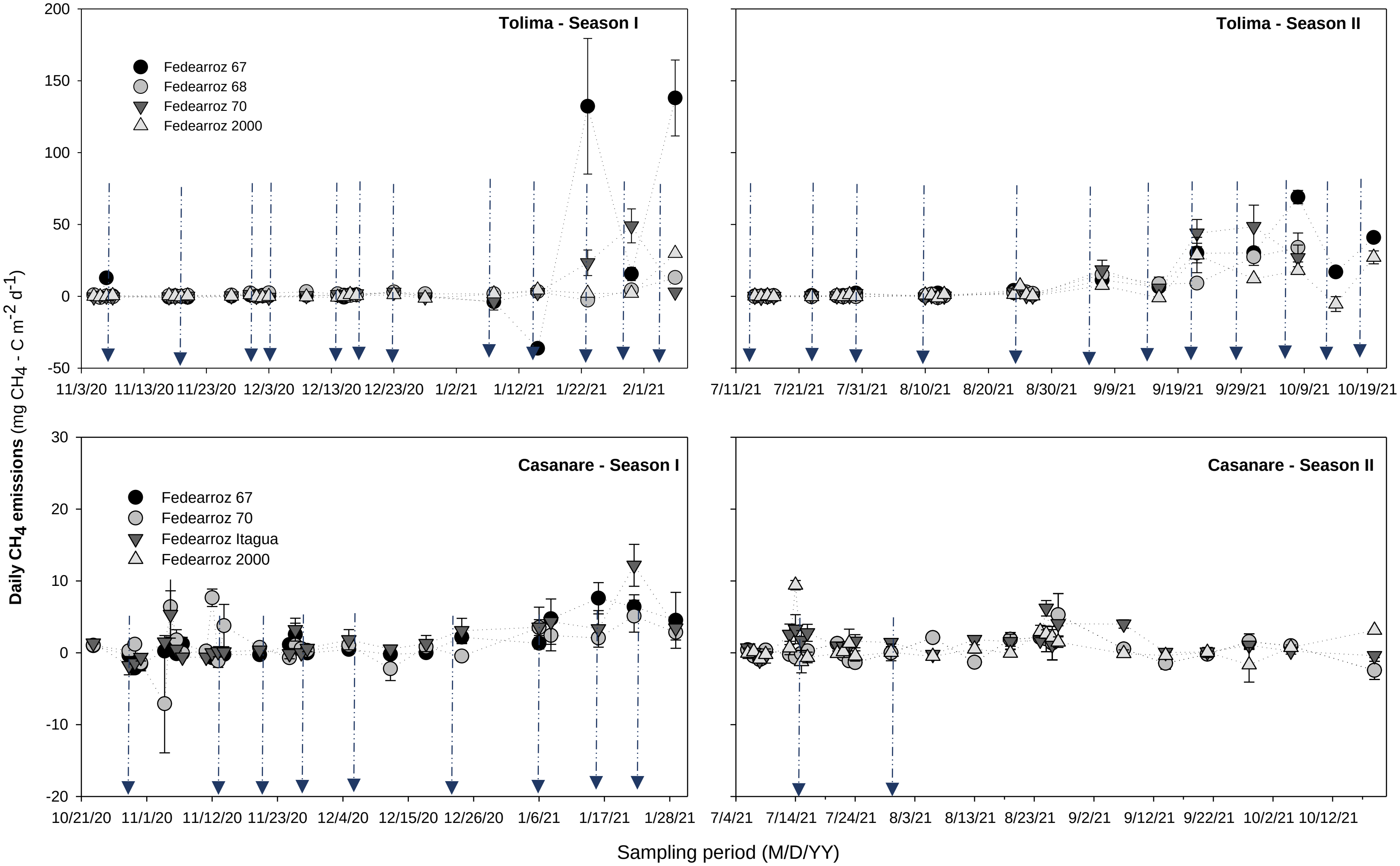
Fig. 3-2: Frequency distribution for climatic variables such as minimum temperature, maximum temperature, and relative humidity for seasons I and II of Tolima (a) and Casanare (b).

3.6.2 Daily CH_4 and N_2O emissions

The pattern of CH_4 and N_2O emissions was different across locations and for the first compared to the second season (Fig 3-3). Higher CH_4 emissions were observed at Tolima than Casanare, with the highest two peaks occurring for F-67 (138 and 69 mg CH_4 - C m^{-2} d^{-1} in season I and II, respectively), and considerably lower peaks for F-2000 in Casanare (16 and 9 mg CH_4 - C m^{-2} d^{-1} in season I and II, respectively). In contrast, higher N_2O emissions were found at Casanare, particularly during the first growing season. In Casanare, F-70 and F-2000 produced the highest N_2O fluxes during season I and II, respectively (90 and 11 mg N_2O - N m^{-2} d^{-1}, respectively), while lower N_2O peaks occurred each season in Tolima for F-68 and F-2000 (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 when there was less precipitation. However, precipitation and temperature did not have a significant correlation with daily CH_4 and N_2O emissions in either region ($P > 0.05$).

Daily CH_4 fluxes in Tolima exhibited a similar variation across different varieties throughout the 60 first days of both growing seasons. However, CH_4 emissions for F-67 and F-70 increased during the flowering stage when a constant layer of water was maintained on the soil until physiological maturity. For F-67, these CH_4 peaks during flowering contributed approximately 50-90% of total emissions in seasons I and II. 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 regions, but there was variation regarding the timing of emissions and variety effects (Fig. 3-3). For example, three days after the second fertilization in the first season in Tolima, N_2O emissions increased for all varieties. In the second season, the main N_2O peak was observed for F-2000 three days after the fourth fertilization. In Casanare, the peak N_2O flux was for F-70 in the first growing season following the third fertilizer dose, and for F-2000 in the second growing season following the first fertilizer dose. Generally, N_2O emissions remained below 5-10 mg N_2O - N m^{-2} d^{-1}, except in Casanare where high emissions were observed for several sampling events early in season I.



Tolima - Season I
Tolima - Season II
Casanare - Season I
Casanare - Season II
● Fedearroz 67
○ Fedearroz 68
▼ Fedearroz 70
△ Fedearroz 2000
● Fedearroz 67
○ Fedearroz 70
▼ Fedearroz Itagua
△ Fedearroz 2000
Daily CH$_4$ emissions (mg CH$_4$ - C m^{-2} d^{-1})
200
150
100
50
0
-50
30
20
10
0
-10
-20
11/3/20
11/13/20
11/23/20
12/3/20
12/13/20
12/23/20
1/2/21
1/12/21
1/22/21
2/1/21
7/11/21
7/21/21
7/31/21
8/10/21
8/20/21
8/30/21
9/9/21
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9/29/21
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11/1/20
11/12/20
11/23/20
12/4/20
12/15/20
12/26/20
1/6/21
1/17/21
1/28/21
7/4/21
7/14/21
7/24/21
8/3/21
8/13/21
8/23/21
9/2/21
9/12/21
9/22/21
10/2/21
10/12/21
Sampling period (M/D/YY)

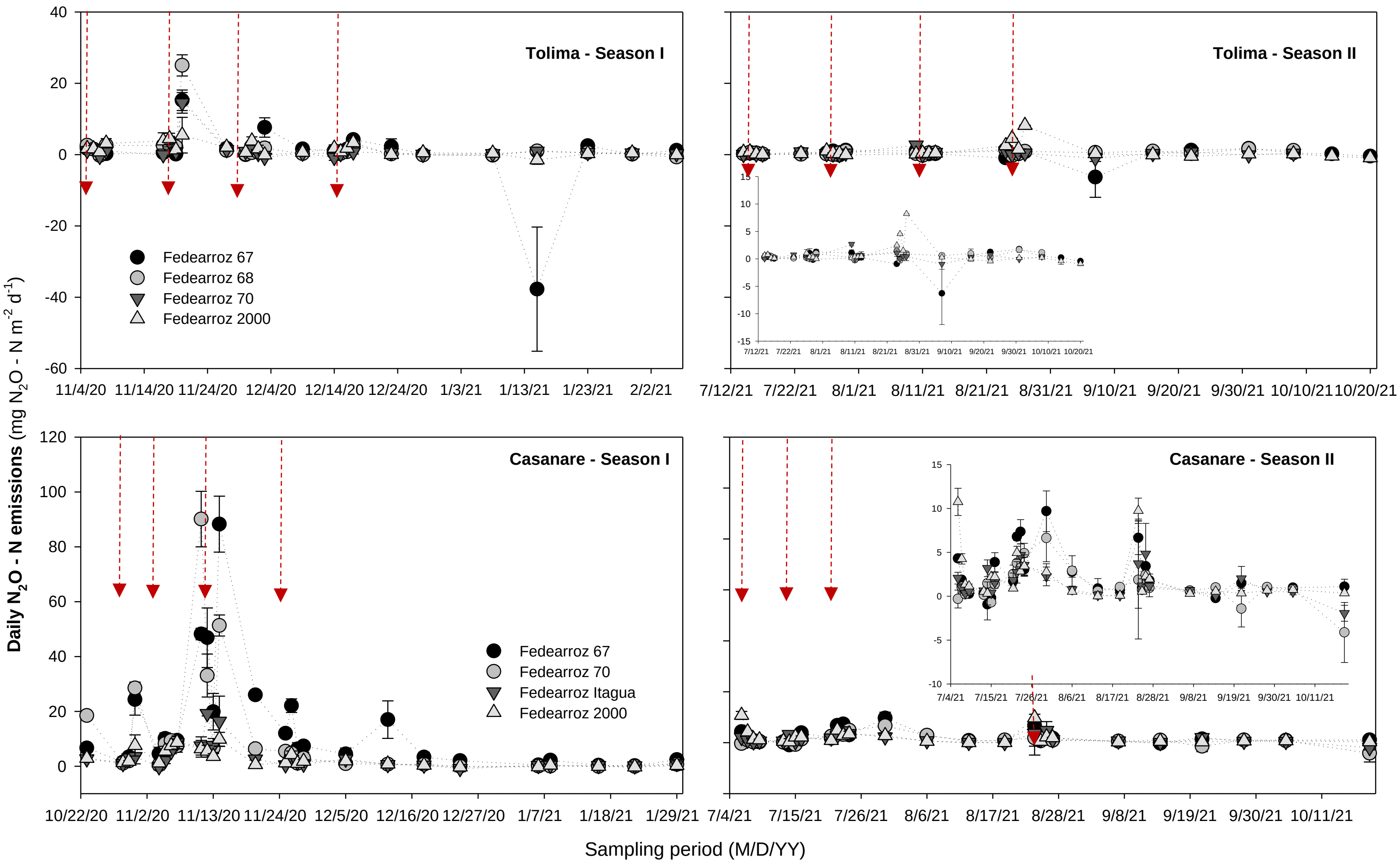

Fig. 3-3: Daily CH_4 and N_2O fluxes from four rice commercial varieties during sampling in two seasons between 2020 and 2021 in Tolima and Casanare. Daily CH_4 - C emission - I and II season; Daily N_2O - N emission - I and II season. Error bars indicate ± SE (n=3). The red arrow denotes fertilizer events, while the blue arrow signifies irrigation events

3.6.3 Grain yield and aboveground biomass

Significant differences in rice grain yields were observed among rice varieties during the first season under dry weather conditions (Table 3-2). In Tolima, yields for F-68 were 26 and 30% lower than F-2000 and F-70, respectively, whereas F-67 was not significantly different from F-68. Meanwhile, F-Itagua exhibited a 12-17% lower yield compared to F-67, F-70, and F-2000 in Casanare. However, no yield differences occurred in the second season under wet weather conditions. Generally, higher yields were observed for the second compared to the first season in Tolima, whereas productivity levels were similar in both seasons at Casanare.

Several differences in aboveground biomass varieties were also observed for different phenological stages (Table 3-2). In Tolima, F-2000 had lower biomass at primordium during season I, while F-68 and F-70 had lower biomass at primordium and F-67 at flowering in season II. In Casanare, only F-70 had lower biomass at maximum tillering in season II. However, none of the in-season biomass differences translated into lower grain yields. Comparing the two seasons at Tolima, relatively higher biomass was observed for primordium and maximum tillering during season II but not season I. Biomass at different phenological stages was similar for both seasons in Casanare.

3.6.4 Cumulative GHG emissions and Global Warming Potential.

In Tolima, GWP ranged from 537-809 and 349-605 kg CO_2 equivalents ha^{-1} for season I and II, respectively (Table 3-3). There was a significant effect of variety on CH_4, N_2O, and GWP. The varieties with among the highest GWP were F-68 and F-70 in seasons I and II, respectively. Relative to this, the other two varieties (F-67, F-2000) all had lower GWP in season I and II, whereas only F-67 had significantly lower GWP in season II. F-67 exhibited reduced N_2O emissions in both seasons, particularly because of negative fluxes in season II. However, F-67 also produced the highest CH_4 emissions in both seasons. Meanwhile, F-2000 had lower CH_4 emissions with moderate to high N_2O emissions compared to other cultivars. In the second season, all cultivars showed higher CH_4 emissions and lower N_2O emissions (Table 3-3), 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% of GWP, respectively (31 and 69% across varieties). During the wet season, CH_4 and N_2O emissions contributed approximately 40-100 and 0-60% of total GWP (62 and 38% across varieties).

In Casanare, GWP ranged from 926-4704 and 544-935 kg CO_2 equivalents ha^{-1} for season I and II, respectively. There was a significant effect of variety on CH_4, N_2O, and GWP. The variety with among the highest GWP in both seasons was F-67. Relative to this, F-70, F-2000, and F-Itagua all had lower GWP in season I, while only F-Itagua had lower GWP in both seasons. F-Itagua had the lowest N_2O emissions in both seasons and among the lowest CH_4 emissions.

Emissions of both gases were lower in the second than in the first season. No significant correlations were observed among soil GHG emissions, yield, above-ground bio-mass, and meteorological conditions. During the dry season, CH_4 and N_2O emissions contributed approximately 1-27 and 73-99% of GWP, respectively (9 and 91% across varieties). During the wet season, CH_4 and N_2O emissions contributed approximately 3-9 and 91-97% of total GWP (5 and 95% across varieties).

Table 3-2: Rice aboveground biomass for different growth stages and grain yield in two regions. Values followed by the same letter are not significantly different within each column at $p < 0.05$.

Seasons	**I**				**II**			
	Tolima							
	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**	
Fedearroz 67	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
Fedearroz 68	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
Fedearroz 70	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
Fedearroz 2000	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	**I**				**II**			
	Casanare							
	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**	
Fedearroz 67	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
Fedearroz 70	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
Fedearroz 2000	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
Fedearroz 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 3-3: Cumulative CH_4 and N_2O emissions from four rice commercial varieties and the corresponding Global Warming Potential (kg CO_2 equivalents ha^{-1}). Values are mean ± SE. Within each column, values followed by the same letter are not significantly different at the 0.05 level.

Seasons	**Tolima**						**Casanare**						
	I - 2020			**II – 2021**			**Varieties**	**I - 2020**			**II - 2021**		
Varieties	**CH_4 (Kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 e)**	**CH_4 (Kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 e)**		**CH_4 (Kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 e)**	**CH_4 (Kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP (kg CO_2 e)**
F-67	17.6 ± 3.1 a	0.5 ± 0.2 c	**631 b**	18.4 ± 0.6 a	-0.5 ± 0.1 c	**349 b**	F-67	2.3 ± 0.2 b	17.0 ± 0.7 a	4704 a	1.0 ± 0.01 bc	3.3 ± 0.5 a	935 a
F-68	2.6 ± 0.1 b	2.7 ± 0.1 a	809 a	8.9 ± 1.0 b	1.1 ± 0.1 a	540 a	F-70	1.7 ± 0.2 b	10.8 ± 0.5 b	2994 b	1.5 ± 0.3 b	2.9 ± 0.2 ab	828 ab
F-70	6.7 ± 0.3 b	1.6 ± 0.2 b	633 b	14.4 ± 1.6 a	0.8 ± 0.1 b	605 a	F-2000	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-2000	2.5 ± 0.2 b	1.7 ± 0.05 b	**537 b**	7.8 ± 0.9 b	1.2 ± 0.1 a	**534 a**	**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**

3.7 Discussion

3.7.1 Grain yield

The rice varieties evaluated here produced moderate to high grain yields, ranging from 4.2-7.3 Mg ha^{-1} during the study period (Table 3-1). Rice variety selection plays a significant role in cropping system yield potential, due to varying morphological, physiological, and biochemical responses under different weather conditions (Laenoi et al., 2018; Luo et al., 2019). An important finding is that yield reductions were observed for several varieties in the dry season at both locations, but not the wet season. Interestingly, this result occurred despite weather differences between regions in the dry season (Figures 3-1 and 3-2). For example, while total precipitation was similar at both sites (363-371 mm), 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. 3-2).

Peng et al. (2004) and Qiong et al. (2023) demonstrated that heat stress can reduce crop yields by approximately 7-10% for every degree C rise above the average temperature. Thus, in Tolima the increase in minimum temperature by more than 5°C combined with high humidity levels between 80-90% during reproductive growth may explain the larger yield reduction for F-68 observed at this location. Thermal stress and high relative humidity may cause spikelet sterility due to reduced pollen production and increased respiration rates (Matsui, 2009; Mohammed & Tarpley, 2010). In addition, by shortening the growth period before reaching physiological maturity, seed production and grain yield can be lowered as a result of shortened embryo and endosperm development (Sanwong et al., 2023).

The intermittent irrigation program implemented during vegetative growth may have also contributed to crop water stress in the dry season. Research has shown important benefits of correctly managed intermittent irrigation coupled with fertilizer application, helping reduce water use by around 20-40% or more while increasing fertilizer efficiency (Bo et al., 2022; Thakur et al., 2014; Materu et al., 2018; Qiu et al., 2022). However, this approach requires greater control over irrigation timing and management of soil moisture compared to flooded rice systems, which may increase the risk of water stress during field drainage events (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 availability depended on the ecological flow of the Charte River.

Water stress during the early reproductive and flowering stages negatively impacts yield (Boonjung & 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 the observed decrease in aboveground biomass during rice development in the dry season, particularly during maximum tillering and flowering (Table 3-1). 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 implemented 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 cultivars. However, it is likely 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 12-17 and 26-30% at Casanare and Tolima, respectively (Table 3-1).

Yields for the wet season were generally 2-3 Mg ha^{-1} higher in Tolima but not Casanare. Torres & Henry (2018) and Noor et al. (2019) also reported higher rice yields for wet compared to dry seasons because 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 F-67, F-70, and F-2000 have intermediate to late growth periods, good temperature change resistance, and high grain yield capacity (Fedearroz, 2009; Fedearroz, 2000a; Fedearroz, 2000c). Additionally, these varieties have intermediate to high tiller number with a similar N requirement (24 kg N Mg^{-1}). The absence of yield effects among varieties during the wet season in both locations is consistent with previous studies on intermittent irrigation, which generally show small changes in yield or yield benefits (Carrijo et al., 2017; Feng et al., 2021; Wang et al., 2016a-b; Wang et al., 2018). Together 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.

3.7.2 CH_4 and N_2O emissions

Overall 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 low compared to prior studies for irrigated rice systems (Table 3-3). 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 around 94% of total GWP (Qian et al., 2023). In 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; Dubey, 2005; Singh et al., 2018). Our findings align with 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. 3-3). 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 concentration, favoring emissions transported through the rice plant to the atmosphere in waterlogged soils (Ma et al., 2010; Humphreys et al., 2019; Gar'kusha et al., 2023). Our finding 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.t, 2023; Malayan et al., 2016). Compared to Tolima, CH_4 emissions remained at a lower levels for both seasons in Casanare. The successful adaptation of rice varieties to the local climatic conditions combined with early season management of water resources may have helped the rice plants develop constitutive aerenchyma, which promoted oxygen diffusion into soil without experiencing notable abiotic stress (Yamauchi & Nakazono, 2022).

Soil N_2O emissions generally occurred during vegetative growth due to repeated flood-drain cycles for intermittent irrigation and fertilizer application (Fig. 3-3). 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 3-17 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 & 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 (Jiang et al., 2019). Evidence for this was the relatively low CH_4 emissions but high N_2O emissions in Casanare, resulting in a 4-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 have been that the applied N fertilizer was ammonium sulfate. Hence, the NH_4^+ had to undergo nitrification and then denitrification processes before it was susceptible to atmospheric losses, allowing better NH_4^+ capture by plants while also reducing nitrate leaching in the soil (Delaune et al., 1998; Mazzeto et al., 2020; Rahman & Forrestal, 2021). Another factor was likely 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 nitrification and denitrification processes contributing to N_2O emissions (Braker & Conrad, 2011; Chapuis-lardy et al., 2007; Loaiza et al., 2023). 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 processes, 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 increase denitrification rates (Arce et al., 2018; Congreves et al., 2018).

3.7.3 Effect of rice varieties on GWP mitigation

This research identified two different varieties that displayed promising GHG mitigation in Tolima and Casanare. Notably, these effects were primarily achieved through a reduction N_2O emissions rather than CH_4 emissions, resulting in an overall decrease in GWP. In Tolima, F-67 reduced N_2O but not CH_4 emissions, while only F-Itagua reduced N_2O emissions in Casanare but had mixed effects on CH_4 emissions (Table 3-3). The importance of N_2O mitigation for lowering

GWP in rice systems is a new finding compared to previous work, which has mostly occurred under flooded conditions and focused on CH_4 reductions (Qian et al., 2023). Relatively little research has focused on the mechanisms by which varieties can reduce N_2O emissions under intermittent irrigations. Some studies show it can be due to the release of carbon substrates from roots that fuels denitrification (Gu et al., 2017; Van Groenigen et al., 2015). Others have reported it may be related to a variety of effects on soil inorganic N dynamics (Firestone & Davidson, 1989; Kim et al., 2021; Zhou et al.t, 2020). For example, F-67 in the current study may have had 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 F-2000 having the lowest and F-67 having the highest CH_4 emissions in Tolima. This difference is possibly related to variation in the morphology and physiology of the rice plant, such as the presence of aerenchyma, which can influence the transport of CH_4 from the roots to the atmosphere (Kim et al., 2018; Iqbal et al., 2021; Yuan et al., 2023). It is conceivable that F-2000 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; Gutiérrez et al., 2014; Jiang et al., 2017). In contrast, F-67 might exhibit an inducible aerenchyma, providing more resistance to air diffusion under abiotic stress conditions, indicating this variety is more susceptible to adverse weather conditions (Colmer & Voesenek, 2009; Yamauchi & 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, illustrating that different varieties can affect soil microbial communities, the supply of C substrates, and gas transport pathways through roots and plant tissues (Soremi et al., 2023). 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. In 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 was primarily due to changes in belowground CH_4 production and oxidation among varieties. 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, likely by increasing CH_4 oxidation potential, highlighting the importance of variety effects on microbial communities. Future research must take an integrated approach to investigate variety effects on CH_4 emissions as the net outcome of multiple mechanisms related to CH_4 production in soil, as well as subsequent CH_4 oxidation within the rice rhizosphere or plant-mediated gas transport to the atmosphere, recognizing these steps and their interactions will differ among varieties in response to environmental and management factors (Bhattacharyya et al., 2019; Simmonds et al., 2015).

3.7.4 Broader implications

The findings of this study underscore the potential for mitigating GHG emissions through the selection of rice cultivars in Colombia. Previous studies have compared varieties in rice-producing regions outside of Latin America to highlight differences in CH_4 emissions (Bhattacharyya et al., 2019; Simmonds et al., 2015; Susilawati & Setyanto, 2018; Yu et al., 2022; Zhang et al., 2021). However, it is essential to note that practices like cultivar selection have yet to be extensively studied or recognized as GHG mitigation strategies in Latin America, as reported by Chirinda et al. (2018). By selecting cultivars with favorable emission profiles and implementing intermittent irrigation with appropriately timed N fertilizer application events, we found that GWP mitigation can be achieved by 32-61%. Recent studies elsewhere have 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 finding is that N_2O needs to be recognized as a pathway for GWP mitigation in non-continuously flooded 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 contexts. Water shortages are increasing around the world and there is interest in intermittent irrigation to reduce the water footprint and associated GWP of rice (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. 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 from soil (Yan et al., 2000), indicating different mechanisms may be more or less desirable depending on the irrigation regime.

3.8 Conclusions

Results from this study demonstrate considerable potential for mitigating GHG emissions in Colombian rice systems without sacrificing food security by strategically selecting rice cultivars. Yield differences were not observed in the wet season, but several varieties produced lower yields in the dry season at both locations, likely due to water stress during soil drainage periods. Meanwhile, in the Tolima region, F-67 and Casanare, FL-Itagua, showcased reductions in GWP by 1-42% and 9-80%, respectively, compared to other varieties, primarily achieved through a decrease in N_2O emissions. The Tolima site had lower GWP (ranging from 349-809 kg CO_2 ha^{-1}) compared to the Casanare site (544-4704 kg CO_2 equivalents ha^{-1}). The higher GWP in Casanare was largely driven by high N_2O emissions observed in F-67 and F-70 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, an important finding is the major contribution of N_2O to GWP under intermittent irrigation in this study, ranging from 24-99% in the dry season and 35-97% in the wet season across sites. These results highlight the need for rice variety development focusing on low N_2O emissions 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.

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4 Chapter III: Evaluating Intermittent Irrigation Strategies for rice production to Mitigate Greenhouse Gas Emissions and Preserve yields in Contrasting Environments.

Building upon the knowledge acquired from our previous experiments, which examined the efficacy of AWD irrigation systems in reducing water consumption and mitigating CH_4 and N_2O emissions without compromising yield, and subsequent identification of commercial rice varieties under traditional irrigation systems, the idea of developing a proposal for an intermittent irrigation system emerged. This system integrates the benefits of traditional irrigation techniques recognized in rice-growing areas with AWD technology. This innovative approach optimizes water usage and minimizes greenhouse gas emissions while maintaining crop productivity. The preliminary work established by these initial experiments provided the momentum for the research project presented in Chapter III.

In Chapter III, we delve into the results previously submitted to the Journal of Agriculture-Climate Interactions in Tropical Regions, where they underwent editorial review. The submission was titled "Evaluating Intermittent Irrigation Strategies for Rice Production to Mitigate Greenhouse Gas Emissions and Preserve Yields in Contrasting Environments" (Loaiza et al., 2024). This chapter highlights the potential for reducing CH_4 and N_2O emissions and the associated GWP with the proposed intermittent irrigation system. It evaluates the impact of different rice varieties on gas emissions. These varieties were selected based on their performance under traditional irrigation systems, with some showing reductions in one or both gases. This research contributes to a deeper understanding of how rice variety selection can further enhance emission mitigation strategies in rice cultivation systems. New rice management practices are also analyzed, including intermittent irrigation and precise fertilizer application, enabling soil moisture monitoring and irrigation adjustment during growth stages to mitigate water stress and enhance nutrient absorption. This system is a scalable and cost-effective alternative that leverages farmers' practical knowledge and accessible technologies for implementation.

4.1 Keywords

CH_4, N_2O, Grain yield, Global warming potential, Flooded, intermittent irrigation, sustainability.

4.2 Highlights

- The oxidation process in intermittent irrigation reduces cumulative CH_4 emissions by 100% compared to flooded systems
- Cumulate N_2O emissions also decrease by 54-78% in Tolima, 6-46% under the rainfed system, and 100% under the irrigation system in Casanare
- The use of intermittent irrigation had no adverse impacts on crop productivity

4.3 Abstract

The emission of methane (CH_4), a major greenhouse gas (GHG), from flooded systems is generally reduced by implementing intermittent irrigation. Additionally, nitrous oxide (N_2O) emissions resulting from inorganic fertilizer application and fertilizer type are mitigated by controlling soil moisture, a common agronomic practice in Colombia. However, such practices are not widely adopted in rice-growing regions in Colombia. Consequently, the comprehensive effects of intermittent irrigation on CH_4 and N_2O emissions, as well as rice grain yield, have yet to be extensively investigated in Colombia. The objectives of this study were examining the differential impacts of water management strategies, specifically intermittent irrigation versus flooded irrigation, on GHG emissions in two rice-growing regions in Colombia: Tolima and Casanare. Our analysis includes CH_4 and N_2O emissions, global warming potential (GWP), and crop yields using randomized block designs for two commercial rice varieties. The results demonstrate that transitioning from flooding to intermittent irrigation has significant environmental benefits. In particular, such a switch enables a drastic reduction in CH_4 emissions, which were reduced by almost 100% in Tolima and Casanare. Notably, a 54% to 78% reduction in N_2O emissions is observed in Tolima, 6% to 46% in rainfed systems, and 100% in irrigated systems with soil moisture maintained near field capacity during fertilization in Casanare. Crop yield shows no significant differences in both regions. Intermittent irrigation reduced GWP by 62% to 85% in Tolima, 14% to 62% in rainfed systems, and 100% in the irrigated system in Casanare. This study concludes that shifting from flooded to intermittent irrigation minimizes rice production's GWP and greenhouse gas emissions while preserving yields. Optimized water management contributes to reduced N_2O emissions.

4.4 Introduction

Rice cultivation is crucial in global food security, providing sustenance for approximately half of the world's population (Dorairaj et al., 2023; Fukagawa et al., 2019; Mohidem et al., 2022). However, associated emissions of greenhouse gases (GHGs), mainly methane (CH_4) and nitrous oxide (N_2O), pose significant environmental challenges (Boateng et al., 2017; Chirinda et al., 2018; Gupta et al., 2021; Kritee et al., 2018; Mboyerwa et al., 2022; Nguyen, 2002; Yao et al., 2017; Qian et al., 2023). Despite extensive research on global GHG emissions in rice paddies, there remains a critical gap in understanding the implications of intermittent irrigation, particularly regarding its effects on N_2O emissions. It is recognized that intermittent irrigation improves water management efficiency during the production cycle, ensuring a reduction in CH_4 emissions ranging from 20% to 100%, depending on the system type, varieties (Feng et al., 2021), and climatic conditions (Cowan et al., 2021; Loaiza et al., 2024a; Sapkota et al., 2020; Wang et al., 2020). Soil aeration during the rice growing cycle suppresses the growth of methanogenic microorganisms while increasing methanotrophic populations (Ma & Lu, 2011). In addition, intermittent irrigation reduces aerenchyma development which limits CH_4 transport through rice plants (Iqbal et al., 2021; Yuan et al., 2023). However, it is essential to note that soil aeration also enhances N_2O formation as an intermediary in nitrification and denitrification reactions (Jiang et al., 2019; Maris et al., 2016; Zschornack et al., 2016).

Assessing intermittent irrigation methods for rice farming is crucial for tackling the twin challenges of cutting GHG emissions while maintaining crop yields, particularly in varied environmental conditions. The efficacy of intermittent irrigation hinges on its capacity to regulate soil moisture levels, thereby curtailing methane emissions from inundated fields and reducing N_2O releases linked with inorganic fertilizers. However, there remains to be scientific ambiguity surrounding the specific effects of intermittent irrigation on both crop output and GHG dynamics across different agricultural settings. Our study aims to clarify these mechanisms and uncertainties, offering valuable insights into sustainable rice farming techniques. Intermittent irrigation could increase emissions because the wet-dry cycles could trigger microbial N_2O production, and there is no longer a flood layer preventing N_2O release from the soil surface (Kritee et al., 2018; Zhou et al., 2020). At the same time, Intermittent irrigation has the potential to mitigate emissions by regulating soil water levels, thereby minimizing the occurrence of drastic shifts between aerobic and anaerobic conditions near the soil surface. This regulation fosters microaerophilic conditions, which can effectively reduce emissions, including N_2O. Studies by Islam et al. (2020a) and Riya et al. (2017) support this notion by highlighting the role of intermittent irrigation in maintaining stable soil conditions and consequently reducing N_2O emissions. For both CH_4 and N_2O emissions, one of the biggest sources of variation is different varieties. Considering that C dynamics influence CH_4 while N dynamics influence N_2O, it is possible that some varieties are better at CH_4 mitigation but worse at N_2O mitigation (Iqbal et al., 2023; Loaiza et al., 2024b). Current knowledge concerning GHG emissions under intermittent irrigation largely stems from global studies. Nevertheless, the specific characteristics of Colombian rice systems, influenced by diverse climatic conditions, varieties, socioeconomic conditions of producers, and agronomic practices, may introduce nuances that deviate from established knowledge. This requires dedicated exploration to identify potential emission pattern variations and assess intermittent irrigation's effectiveness in mitigating GHG emissions.

Reducing GHG emissions in Colombia's intermittent and flooded irrigation systems is crucial for developing sustainable strategies and mitigating environmental impact. Research has identified that implementing mitigation practices, such as intermittent irrigation known as Alternate Wetting and Drying (AWD), with water depth control below 15 cm from the soil surface, can reduce CH_4 emissions and increase N_2O emissions during planting periods under extreme drought conditions. This significantly reduces the net global warming potential (GWP) due to decreased CH_4 emissions (Chirinda et al., 2017). However, Loaiza et al. (2024a) found that the optimal soil tension for AWD implementation in water depth management (5 and 10 cm below the soil surface) and fertilizer application under soil moisture conditions between saturation and field capacity is the appropriate way to reduce CH_4 and N_2O emissions without affecting yields. This contributes to the reduction of the net GWP, unlike flooded systems. However, there needs to be more knowledge about how these specific intermittent irrigation systems affect emissions in the Colombian context without reaching the soil tension achieved by AWD. Knowing more about the factors influencing emissions in intermittent and flooded irrigation systems would allow the design of more efficient and sustainable agricultural practices adapted to local conditions for more relevant adoption. This knowledge would not only provide environmental benefits by reducing GHG emissions. However, it could also enhance the agricultural sector's resilience to climate change challenges and promote food security in the country.

Rice production is crucial in Colombia, a vital sector for ensuring food security and fostering rural development. The country ranks as one of the leading rice producers in Latin America, standing in third place after Peru and Brazil (Statista Research Department, 2022; FAOSTAT, 2023). Colombian rice production uses three water management systems: irrigation, flooding, and dry farming. In flooded systems, prevalent across Colombian rice fields, water consumption averages between 13,000 to 20,000 m^3 per hectare per harvest (Min Agricultura, 2022). While these systems have historically sustained production, their significant water demands underscore the need for exploring alternative practices. The Llanos and Central regions are the most prominent in terms of production. Although the average rice yield reaches around 5 tons per hectare, it can vary depending on the production system, the variety used, and the region, as indicated by DANE (2023). There has yet to be any available information in Colombia directly addressing the impact of intermittent irrigation systems on yield. Despite this, various global studies (Carracelas et al., 2019; Cowan et al., 2021; Wu et al., 2017) suggest that intermittent irrigation may lead to a significant decrease in yield compared to a flooded system. On the other hand, it has also been observed that it could either increase or maintain yields (de Avila et al., 2015; Lan et al., 2020; Massey et al., 2014). These findings have indicated that the specific characteristics of intermittent irrigation systems can have a notable effect on crop production, emphasizing the need to fully delve into the analysis of this relationship to understand its influence on Colombian agriculture. Identifying efficient intermittent irrigation systems that boost or maintain yield and reduce GWP is essential, expressed as the GWP (CH_4 + N_2O emissions).

Further research is needed in Colombia to promote efficient intermittent irrigation systems that can help conserve water resources, meet the growing demand for rice, and reduce environmental impact with GHG emissions. This experiment was conducted to assess the environmental impact of implementing an efficient intermittent irrigation system considering optimal soil moisture conditions for fertilizer application and water depth renewal on yield, GHG emissions, and GWP under two production systems: irrigation and dry farming in two regions of Colombia (Tolima and Casanare). Overall, the study aims to directly contribute to filling the existing knowledge gap and advancing our understanding of sustainable rice cultivation practices in Colombia. This research aligns with several United Nations Sustainable Development Goals (SDGs), particularly SDG 13 on climate action and SDG 12 on responsible production and consumption. By investigating the environmental impact of intermittent irrigation systems in Colombian rice cultivation, we contribute to SDG 13 by exploring strategies to mitigate greenhouse gas emissions. Additionally, our study supports SDG 12 by promoting sustainable agricultural practices that optimize resource efficiency and reduce environmental harm.

4.5 Methodology

4.5.1 Experimental site and treatments

The experimental trials were conducted in two representative regions of rice cultivation in Colombia: Saldaña at the Lagunas Experimental Center (3° 55' 59" North, 75° 1' 1" West) in the Tolima region and in Aguazul at the La Primavera Experimental Station (5° 28' 54" North, 72° 38' 8" West) in the Casanare region. Tolima represents the central region, which is primarily irrigated rice production. For our field experiment, irrigation water was sourced from the Saldaña River Irrigation District during the first semester of 2022. Casanare represents the plains region, which consists of both rainfed and irrigated rice systems. In our field experiment, rice was grown under rainfed conditions in the first semester of 2022 and under irrigation in the second semester between 2022-2023, with irrigation water sourced from the Charte River.

In the Tolima experiment, soil conditions in the top 10 cm layer revealed a sandy loam texture with 1.47% organic matter content. Additionally, the soil exhibited slight acidity with a pH of 5.81, a low cation exchange capacity of 6.36 cmol kg^{-1}, and a high iron content of 147.98 mg kg^{-1}, available phosphorus of 33.23 mg kg^{-1}, copper of 4.32 mg kg^{-1}. Soil volumetric moisture values are 21% for field capacity, 42% for saturation, and 17% for permanent wilting point. On the other hand, in the Casanare experiment, the soil displayed a sandy texture with lower organic matter content (1.20%). The soil was acidic, with a pH of 4.83, a cation exchange capacity of 8.3 cmol kg^{-1}, and low nitrogen content (0.06%). Furthermore, a high phosphorus content of 56 mg kg^{-1} and an elevated iron content of 261.66 mg kg^{-1} were recorded in the experimental area. Soil volumetric moisture values are 35-36% for field capacity, 39% for saturation, and 20% for permanent wilting point.

Field experiments at both sites followed a factorial design, where the effects of two irrigation systems, continuous and intermittent, on the growth of two plant varieties were investigated. The rice varieties used in the Tolima region were Fedearroz 67 (F-67) and Fedearroz 2000 (F-2000), while in the Casanare region, FL Fedearroz Itagua (F-Itagua) and Fedearroz 70. The assignment of varieties to each irrigation treatment was randomized, allowing for the examination of individual and interactive effects of irrigation type and plant variety. The total experimental area covered 1200 m^2, with individual plot sizes of 50 m^2. In both regions, the implementation of intermittent irrigation treatment, fertilizer application, and water replenishment occurred with soil moisture levels maintained near or above field capacity. It is important to note that soil moisture levels during fertilizer application ranged from 29% to 37% for the intermittent irrigation treatment in Tolima, while in Casanare, the corresponding soil moisture levels were between 35% and 38%. However, the production system in the Tolima region predominantly relies on irrigation. Conversely, in the Casanare region, characterized by diverse climatic conditions and water resource availability, two distinct production systems are observed: irrigation and rainfed. Notably, in the rainfed system, the intermittent irrigation treatment was tailored to depend solely on rainfall, eliminating the need for supplemental irrigation. Consequently, achieving the intermittent irrigation regimen entailed draining surplus water only during fertilizer application to sustain soil moisture levels proximal to field capacity.

4.5.2 Agronomic management

For soil preparation during the rice growing season in Tolima and Casanare, two passes with a 24-inch disc plow (harrow) were conducted, followed by two passes of a Micro-grader. Subsequently, a 14-point furrower was used to create planting furrows spaced 0.17 m apart in the test area. Climatic data for each region were obtained from climate stations located at the experimental centers in the Tolima and Casanare regions, where the trials were conducted. Data encompassing temperature, precipitation, and other pertinent climatic parameters were meticulously gathered from these climate stations. Table 4-1 provides further details of the agricultural practices, including planting and harvesting dates, fertilizer type and application.

Table 4-1: Crop Management Practices in Rice Seasons: Saldaña, Tolima (Under Irrigation System) and Aguazul, Casanare (Under Rainfed and Irrigation Systems).

Agronomic practices	**Season I**	**Season I: Rainfed**	**Season II: Irrigation**
Regions	**Saldaña - Tolima**	**Aguazul - Casanare**	
Commercial varieties	F - 67 and F - 2000	F - Itagua and F - 70	
Sowing density (kg ha^{-1})	100	130	
Type of sowing	Mechanized planting	Manual	
Sowing date (dd/mm/yy)	31/05/22	03/05/22	01/11/22
Germination date (dd/mm/yy)	11/06/22	13/05/22	11/11/22
Total fertilizer amount (kg ha^{-1} season $^{-1}$)	971	483	654
Application dates (dd/mm/yy), Fertilizer sources, and Fraction of dose (kg ha^{-1})	21/06/22 → **NX**+**SP**+**V**+**SZ**+**ME** → 296 06/07/22 → **NX**+**SP**+**SAM**+**SM** → 175 19/07/22 → **SAM**+**NX**+**SP**+**SM** → 175 09/08/22 → **SAM**+**NX**+**SP**+**SM** → 175 23/08/22 → **SAM**+**U**+**KCl** → 150	24/05/22→ **TS**→ 67 04/06/22→ **TS**→ 133 15/06/22→ **TS**→ 133 05/07/22→**SAM**→ 150	30/11/22→ **Nit**→ 66 14/12/22→**Nit+Ab**→ 207 19/12/22→**Nit+Ab**→ 207 03/01/23 →**Nit+Ab**→174
Nitrogen applied (kg N ha^{-1})	162	119	117
Harvest date (dd/mm/yy)	5/10/2022	19/08/22	9/03/23

Fertilizer sources -Tolima: Nitro Xtend (**NX**) :40% N, 6% S (nitrification inhibitor)
Sol Potasio (**SP**): 3% K_2O, 90% SiO_2.
Ammonium sulfate (**SAM**):21% N (ammoniacal nitrogen) and 24% S.
Urea (**U**): 46% N (ureic nitrogen)
Sulfazinc (**SZ**): 5.51% CaO,4.39% S, 8.85% Zn, 36 % SiO_2, 3% P_2O_5.
MicroEssentials (**ME**): 12% N (amoniacal nitrogen), 40% P_2O_5, 10% S, and 1% Zn.
Sol – Max (**SM**): 4% P_2O_5, 20% MgO, 42% CaO, 8% SiO_2
Sulfazinc (**SZ**): 5.51% CaO,4.39% S, 8.85% Zn, 36 % SiO_2, 3% P_2O_5.
Vicor (**V**): 3% N (ureic nitrogen), 15% Ca, 5% MgO, 3% S, 0.02% Cu, 1% B, 0.02% Mn, 0.005% Mo, 2.5% Zn.
Fertilizer sources Casanare: Third State (**TS**): 24% N (1.6% ammoniacal nitrogen; 22.4% ureic nitrogen) and 12% K_2O.
Ammonium sulfate (**SAM**):21% N (ammoniacal nitrogen) and 24% S.
Nitroazu (**Nit.**): 27% N (15% ammoniacal Nitrogen, 12% ureic nitrogen), 6% P_2O_5, 6% K_2O, 1% MgO, 2% CaO, 3% S.
Abotec (**Ab.**): 15% N (6.7% nitric nitrogen, 8.3 ammoniacal nitrogen), 4% P_2O_5, 23% K_2O.

4.5.3 GHG Sampling

The closed static chamber technique was used to determine CH_4 and N_2O emissions, as described by Chirinda et al. (2017). See Loaiza et al. (2024a) for a full description of methodology. Each chamber consisted of two parts: a base with a height of 40 cm, a lid with a volume of 114 liters, and a height of 80 cm. Both parts were made of polyethylene. Before sowing rice seeds, one base was inserted into the soil in each plot, covering nine or twelve rice seedlings. The lids had fans for air mixing, a steel thermometer for temperature recording, and a gas sampling port. Four gas samples were collected from each chamber using a polyethylene syringe at 15-minute intervals during early morning hours between 8 and 10 am throughout the rice growing season. Immediately after collection, the gas samples were transferred to pre-evacuated 5.9 ml glass

Exetainer vials (Labco Ltd.), and the sampling period covered approximately 80% of the growing rice season in both regions to obtain accurate and reliable data on CH_4 and N_2O emissions.

The concentrations of each gas were determined using gas chromatography (Shimadzu GC-2014) with a Flame Ionization Detector (FID) for CH_4 and a ^{63}Ni Electron Capture Detector (ECD) for N_2O. The detection limit was 0.060 ppm for CH_4 and 0.100 ppm for N_2O. The gas fluxes were calculated based on the linear increase in the gas concentration observed throughout the sampling period using the following equation:

$$F = \frac{\Delta C}{\Delta t}\frac{VM}{AV_m} \quad (1)$$

where F (mg m^{-2} h^{-1}) is the CH_4 or N_2O flux, $\Delta C/\Delta t$ (ppm h^{-1}) is the linear change in CH_4 or N_2O concentration observed over time, M is the relative molecular mass (16 for CH_4 and 44 for N_2O), V (m^3) and A (m^2) are the chamber volume and the Vm is molar volume of gas (L mol^{-1}) is determined through the ideal gas law. The seasonal cumulative fluxes for CH_4 and N_2O emissions (kg ha^{-1}) were calculated by linear interpolation between sampling dates. The global warming potential was calculated in terms of carbon dioxide equivalent (kg CO_2 equiv. ha^{-1}) over a 100-year time frame using the intergovernmental panel on climate change (IPCC) guidelines and radiative forcing potentials of 27.2 for CH_4 and 273 for N_2O (IPCC, 2021).

4.5.4 Rice biomass and grain yield

Aboveground rice biomass in both regions was assessed at various phenological stages, including primordium, tiller, and flowering. Sampling involved randomly placing 0.25 m^2 quadrants within the treatment plots and collecting all aboveground biomass components, such as stems, leaves, and panicles. These biomass samples dried at 70 °C for 24 hours until a constant weight was achieved, following the methodology outlined by Yepes et al. (2011). At physiological maturity, a 20 m^2 area was harvested from each plot to determine rice grain yields. The harvested grains were dried in an oven at 70 °C for 72 hours, and the reported grain yield reflects a moisture content of 14%.

4.5.5 Statistical analysis

The statistical analyses were conducted using R Studio software, with the ADE4 and Agricolae libraries employed for data processing. The normality of datasets was assessed based on sample size, employing the Shapiro-Wilk test for datasets with less than 50 observations and the Kolmogorov-Smirnov test for datasets with more than 50 observations, both at a 5% significance level. Parametric data underwent one-way and two-way ANOVA, followed by Tukey's HSD post-hoc tests for group comparisons. Non-parametric datasets, such as daily emissions, underwent Kruskal-Wallis tests, followed by Dunn's test for post-hoc analysis.

The relationships between daily CH_4 and N_2O emissions and climatic conditions were analyzed through multivariate principal component analysis (PCA), co-inertia analysis, and permutation Monte Carlo tests to compare production systems and assess the climate's effect on emissions. These analyses were conducted using the R Studio environment and the ADE4 library (Posit team, 2023; Thioulose et al., 2018).

4.6 Results

4.6.1 Climate conditions

During the June to September 2022 growing season in Tolima, 363 mm of rainfall accumulated in 47 events. In the vegetative phase (60 days after germination), 33 events yielded 275 mm. Transitioning to the reproductive phase (35 days later), five events contributed to 63 mm. The maturation phase (30 days after reproductive) saw eight events with 25 mm accumulation. The daily average temperature held steady at 27°C, with max/min of 30°C/24°C (Fig. 4-1a). Relative humidity averaged 81%, peaking at 84% in vegetative and dropping to 76% later (Fig. 4-1b). Solar energy varied: 408 cal cm^{-2} d^{-1} (vegetative), 439 cal cm^{-2} d^{-1} (reproductive), and 445 cal cm^{-2} d^{-1} (maturation).

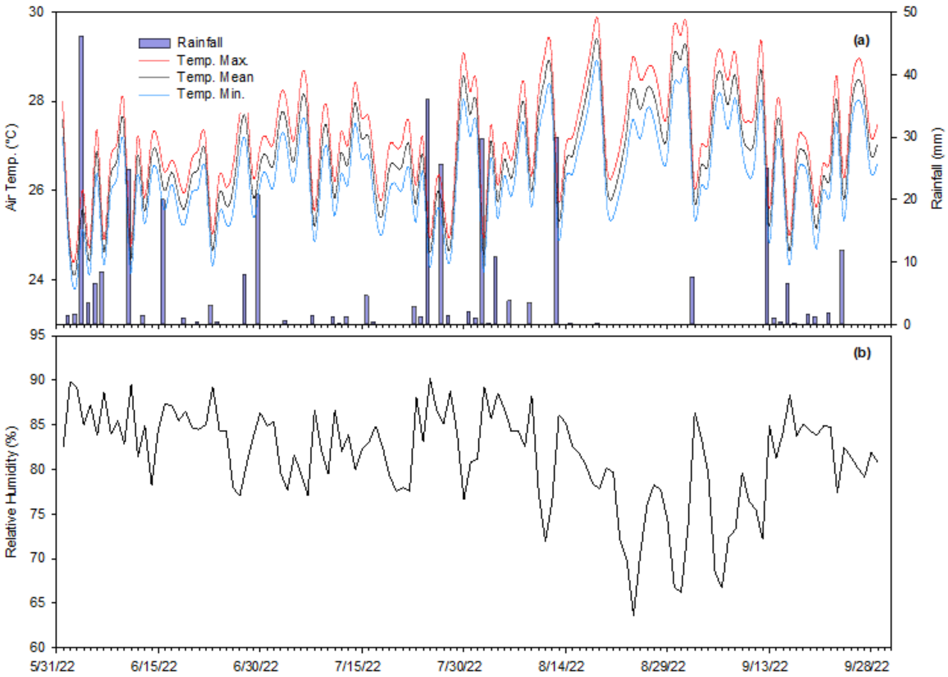
In Casanare's rainfed system production, the first semester of 2022 saw 1283 mm across 72 events. Vegetative phase: 776 mm (61 events); reproductive phase: 425 mm (35 events); maturation: 82 mm (13 events). Daily average temperature was 25°C, max/min of 29°C/22°C (Fig. 4-1c). Daily average relative humidity was 91%, holding in vegetative/reproductive and dropping to 88% in maturation (Fig. 4-1d). Solar energy averaged: 308 cal cm^{-2} d^{-1} (vegetative), 362 cal cm^{-2} d^{-1} (reproductive), 405 cal cm^{-2} d^{-1} (maturation). In the second semester of irrigated rice planting, 61 mm of precipitation came in 9 events. Vegetative phase: 49 mm (5 events); maturation: 12 mm (4 events). Average temperature: 26°C, max/min of 29°C/24°C (Fig. 4-1e). Average daily relative humidity was 79%, reaching 82% in vegetative and 75% in both reproductive and maturation phases (Fig. 4-1f). Average solar energy: 403, 464, and 370 cal m^{-2} d^{-1} for vegetative, reproductive, and maturation phases, respectively.

4.6.2 Daily CH_4 and N_2O fluxes

In Tolima, continuous flooding resulted in the highest CH_4 emissions, peaking 59 days after germination, spanning both rice varieties' reproductive and maturation phases. In contrast, intermittent irrigation consistently resulted in emissions below 10 mg m^{-2} d^{-1}, with no significant differences observed between varieties for either treatment ($p > 0.05$). N_2O emissions notably increased during the fourth fertilization, 70 days after germination, near the maturation phase under continuous flooding. The intermittent irrigation treatment effectively mitigated N_2O emissions for both varieties on the same date, with significant differences observed between varieties for both treatments ($p < 0.05$). Specifically, F-67 exhibited the highest emissions under flooded conditions, whereas F-2000 demonstrated higher emissions under intermittent irrigation (Fig. 4-2)

For Casanare, CH_4 emissions peaked at 76 days after germination under continuous flooding during the rainfed season. The pattern was similar for both varieties in intermittent irrigation, with significant differences between varieties ($p < 0.05$). N_2O emissions were highest during the second and fourth fertilizations under continuous flooding, remaining below 4 mg m^{-2} d^{-1} with intermittent irrigation (Fig. 4-3). In the irrigated season, CH_4 emissions peaked at 43 days after germination for continuous flooding, while intermittent irrigation showed consistently negative emissions throughout the cycle. For N_2O, peaks occurred in the second and third fertilizations, with an increase under continuous flooding at each fertilization compared to consistently negative emissions with intermittent irrigation (Fig. 4-4). Significant differences ($p = 0.001$) also were observed between the two growing seasons in the Casanare region.

Both N_2O and CH_4 emissions showed significant differences between treatments ($p < 0.05$) in both regions. A direct relationship was identified between CH_4 emissions, air temperature, and solar energy and an indirect relationship with relative humidity during the planting semester from May to September 2022 in both regions through principal component analysis (Annex A). The average explained variance was 70%.



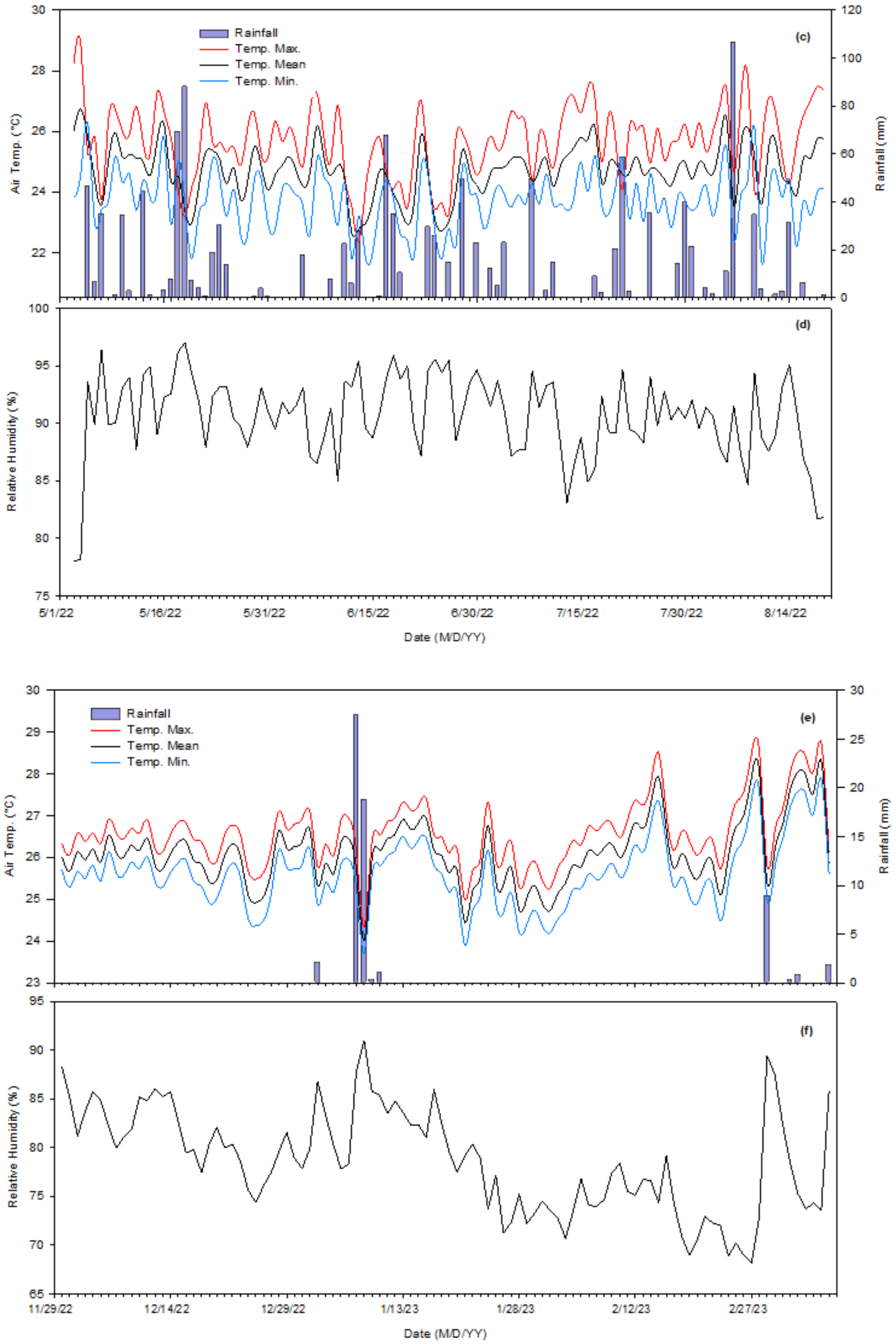


Fig. 4-1: Mean daily air temperature, minimum and maximum temperature, and rainfall (a,c,e) and Relative humidity (b, d, f) for Tolima, Casanare rainfed, and Casanare irrigated seasons.

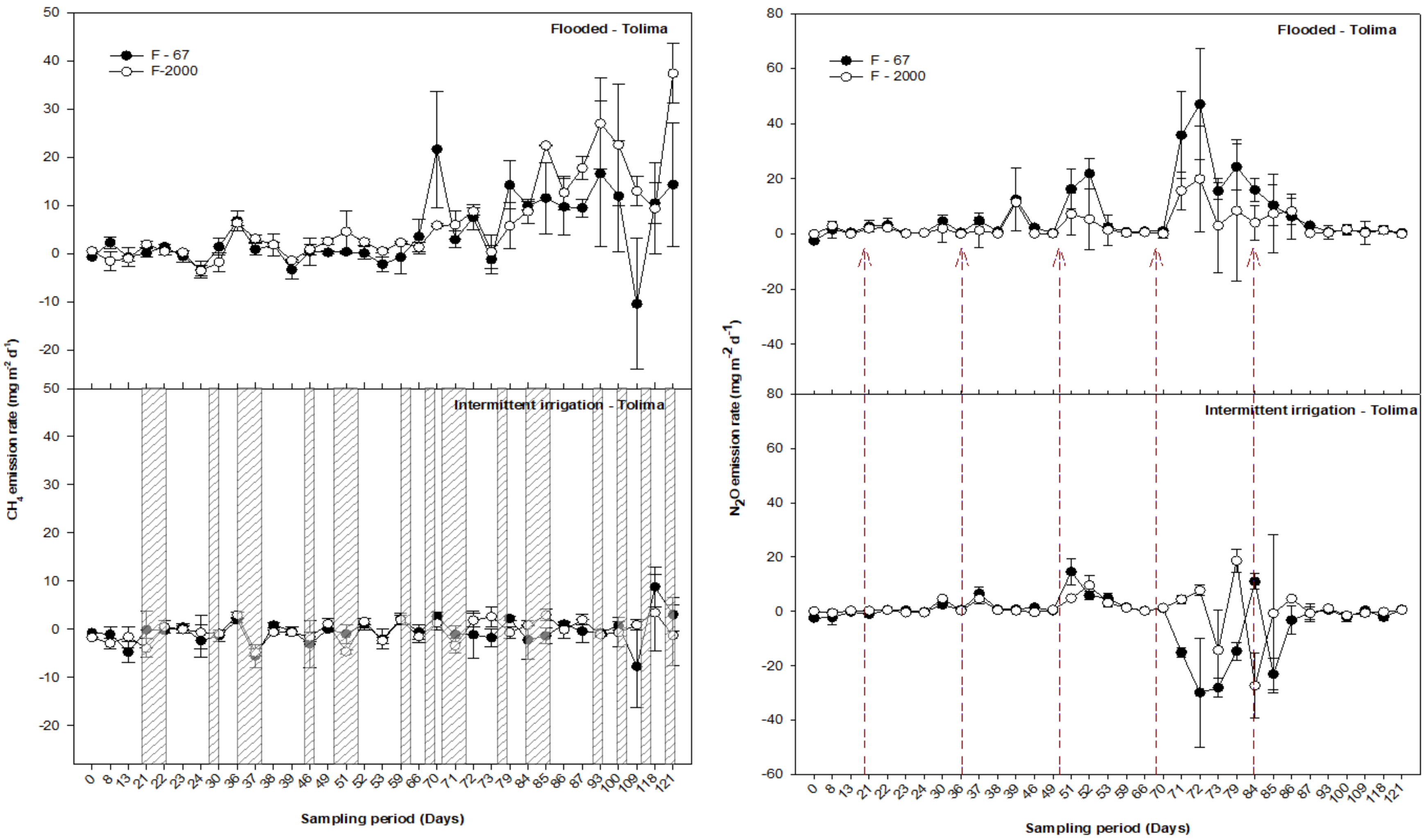


Fig. 4-2: Daily CH_4 and N_2O emissions in Tolima. Drainage periods are depicted by shading and red arrows are fertilizer events. Error bars indicate ± 1 SE (n=3).

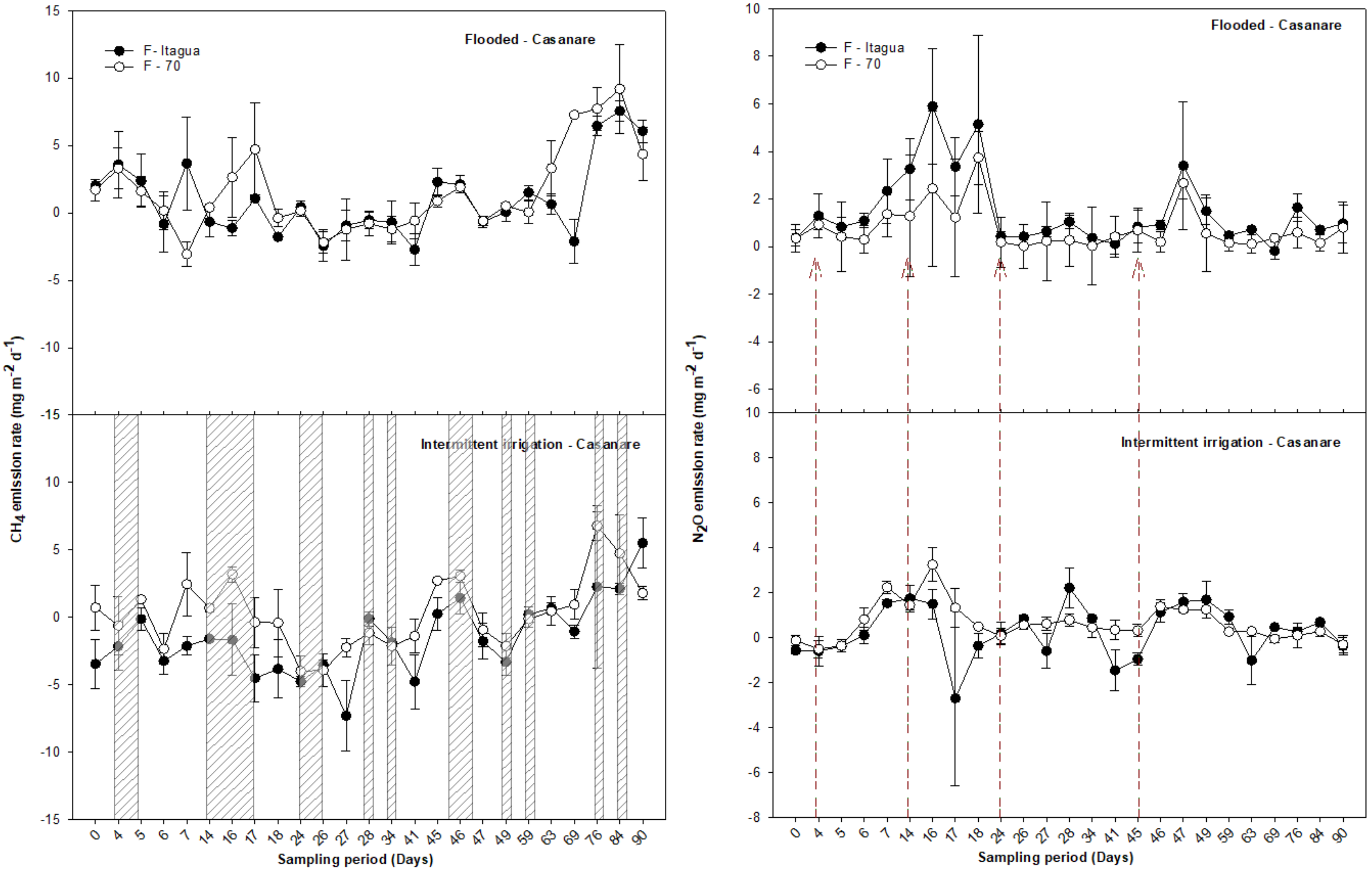


Fig. 4-3: Daily CH₄ and N₂O emissions in Casanare under rainfed system. Drainage periods are depicted by shading and red arrows are fertilizer events. Error bars indicate ± 1 SE (n=3).

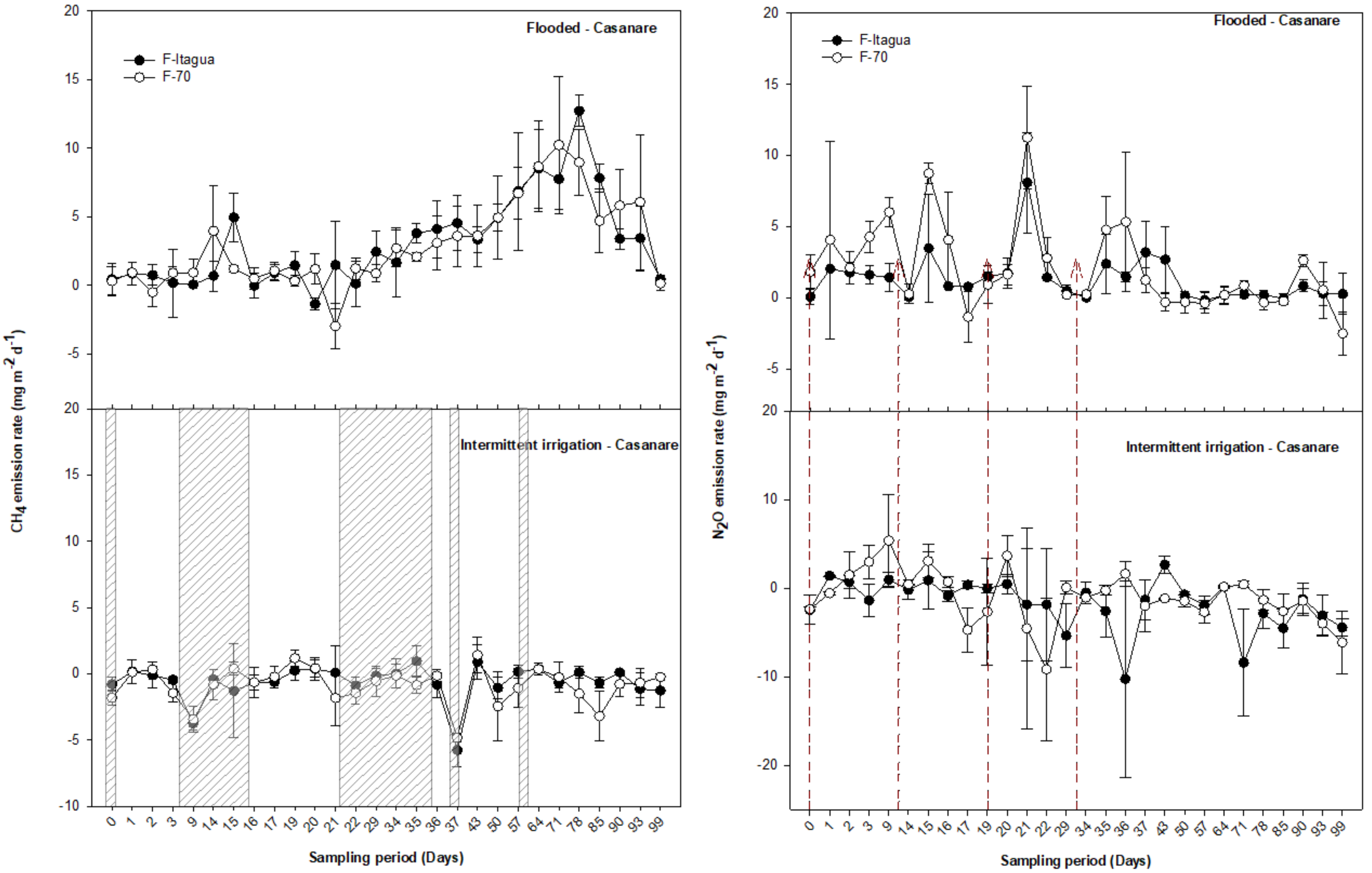


Fig. 4-4: Daily CH_4 and N_2O emissions in Casanare under irrigation system. Drainage periods are depicted by shading and red arrows are fertilizer events. Error bars indicate ± 1 SE (n=3).

4.6.3 Cumulative CH_4 and N_2O emissions and Global Warming Potential

The flood treatment consistently resulted in significantly higher cumulative CH_4 and N_2O fluxes across regions, varieties, and seasons than intermittent irrigation. One exception is that no differences were observed in Casanare during Season I with the F-70 variety, which displayed a higher emission pattern in the flood treatment. Otherwise, CH_4 reduction was 100% in both regions. Cumulative N_2O flux reduction ranged from 54% to 78% in Tolima and 6% to 46% in Casanare during the first season, reaching 100% in the second. Varieties with the most substantial N_2O reduction under intermittent irrigation were F-67 in Tolima (78%) and F-Itagua in Casanare (46%) (Table 4-2).

Flood irrigation also exhibited higher GWP values in both regions than intermittent irrigation across various regions and planting seasons, except for F-70 IN Season I in Casanare. CH_4 emissions contributed to increased GWP values in both flooded treatment varieties. In contrast, N_2O contributed to higher GWP values under intermittent irrigation in both regions, except during the second season in Casanare, where both emissions were negative. The F-2000 and F-70 varieties demonstrated the highest accumulated methane emissions under flood treatment in Tolima and Casanare. Intermittent irrigation treatment in Tolima led to an 85% reduction in GWP for F-67 and a 62% reduction for F-2000. In Casanare, a 62% reduction was observed for the F-Itagua variety and a 14% reduction for F-70 in the first season, with both varieties experiencing a 100% reduction in the second season (Table 4-2).

Table 4-2: Cumulative CH_4 and N_2O emissions from rice systems subjected to Flooded and intermittent irrigations treatments and their contribution to the Global Warming Potential. Within each column, values followed by the same letter are not significantly different at 0.05 level.

Saldaña - Tolima						
System	Irrigation					
Varieties	Fedearroz 67			Fedearroz 2000		
Treatments	**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}**
Flooded	$4.47 \pm 0.21_a$	$3.40 \pm 0.10_a$	1050_a	$6.73 \pm 0.29_a$	$3.36 \pm 0.50_a$	1100_a
Intermittent irrigations	$-1.60 \pm 0.03_b$	$0.75 \pm 0.03_b$	161_b	$-0.35 \pm 0.06_b$	$1.55 \pm 0.02_b$	414_b
Factor /Variables	**CH_4**		**N_2O**		**GWP**	
Varieties	***		NS		NS	
Treatments	***		**		***	
V x T	*		NS		NS	
Aguazul -Casanare						
Rainfed (season I)						
Varieties	Fedearroz Itagua			Fedearroz 70		
Treatments	**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}**
Flooded	$1.95 \pm 0.27_a$	$1.24 \pm 0.005_a$	392_a	$2.23 \pm 0.67_a$	$0.93 \pm 0.31_a$	314_a
Intermittent irrigations	$-1.35 \pm 0.06_b$	$0.67 \pm 0.17_b$	147_b	$1.20 \pm 0.08_a$	$0.87 \pm 0.01_a$	269_a
Irrigation (season II)						
Flooded	$4.41 \pm 1.20_a$	$0.79 \pm 0.07_a$	336_a	$5.77 \pm 0.87_a$	$0.73 \pm 0.06_a$	357_a
Intermittent irrigations	$-0.65 \pm 0.08_b$	$-2.14 \pm 0.05_b$	-603_b	$-1.09 \pm 0.06_b$	$-0.72 \pm 0.08_b$	-225_b
Factor /Variables	**CH_4**		**N_2O**		**GWP**	
Season	I	II	I	II	I	II
Varieties	NS	NS	NS	NS	NS	NS
Treatments	*	***	NS	***	NS	***
V x T	**	NS	NS	***	.	***
Seasons	NS		**		*	

4.6.4 Biomass and grain yield

The flood treatment, F-67 exhibited superior primordium-phase aboveground biomass, while F-2000, under intermittent irrigation, displayed notable tiller-phase biomass. No distinct trends were observed during the flowering phase. Despite biomass and yield variations, statistical analysis revealed no significant differences in the Tolima region (Table 4-3).

Season I in Casanare showed significant primordium and flowering stage aboveground biomass differences between treatments and varieties. F-Itagua had higher biomass in flood conditions during the primordium stage, and F-70 exhibited elevated biomass under intermittent irrigation during flowering. No significant yield differences were observed. In Season II, initial development highlighted the prominence of the primordium under flood conditions, especially in F-Itagua and F-70. The tiller stage varied, with higher values in F-Itagua - Flooded. F-Itagua - Flooded and F-70 - Intermittent irrigations had higher values during flowering. Although no significant differences were recorded, rice grain production was more pronounced in F-Itagua - Flooded. Significant differences in the Casanare region between planting periods were observed for the tiller, flowering, and yield phases, with F-Itagua excelling in the irrigated planting period and F-70 in the dryland planting semester (Table 4-3).

Table 4-3: Comparative Analysis of Phenological Variation and Rice Grain Yield Performance in Tolima and Casanare: Assessing Two Treatment Types and Varietal Differences Across Seasons. Significance Levels Indicated by Distinct Letters ($P < 0.05$), with *, **, *** Denoting Significance at $P = 0.05$, $P = 0.01$, $P = 0.001$, and $P < 0.001$, Respectively; NS Represents Non-Significance at the $P = 0.05$ Level.

Season	**I – Irrigation**			
	Saldaña - Tolima			
Stage	**Aboveground biomass (Mg ha^{-1})**			**Rice grain yield (Mg ha^{-1})**
	Primordium	**Tiller**	**Flowering**	
F-67 - Flooded	5.33 ± 0.42 $_a$	10.67 ± 0.84 $_a$	17.00 ± 0.68 $_a$	7.49 ± 0.65 $_a$
F-67 - Intermittent irrigations	4.33 ± 0.33 $_a$	11.00 ± 0.86 $_a$	17.00 ± 0.68 $_a$	7.70 ± 0.23 $_a$
F-2000 - Flooded	5.00 ± 0.45 $_a$	11.00 ± 0.68 $_a$	16.33 ± 0.33 $_a$	7.40 ± 0.37 $_a$
F-2000 - Intermittent irrigations	4.33 ± 0.33 $_a$	12.33 ± 0.61 $_a$	17.00 ± 0.45 $_a$	7.17 ± 0.68 $_a$
Varieties (V)	NS	NS	NS	NS
Treatments (T)	*	NS	NS	NS
V x T	NS	NS	NS	NS

Season	**I – Rainfed**				**II – Irrigation**			
	Aguazul - Casanare							
Stage	**Aboveground biomass (Mg ha^{-1})**			**Rice grain yield (Mg ha^{-1})**	**Aboveground biomass (Mg ha^{-1})**			**Rice grain yield (Mg ha^{-1})**
	Primordium	**Tiller**	**Flowering**		**Primordium**	**Tiller**	**Flowering**	
F-Itagua - Flooded	0.96 ± 0.19 $_a$	2.58 ± 0.19 $_a$	14.48 ± 0.51 $_a$	5.44 ± 0.20 $_a$	0.81 ± 0.04 $_a$	3.84 ± 0.16 $_a$	16.82 ± 0.89 $_a$	5.52 ± 0.24 $_a$
F-Itagua - Intermittent irrigations	0.49 ± 0.94 $_a$	3.03 ± 0.45 $_a$	13.79 ± 0.94 $_a$	5.04 ± 0.16 $_a$	0.65 ± 0.03 $_a$	3.63 ± 0.44 $_a$	15.35 ± 0.63 $_a$	5.11 ± 0.18 $_a$
F-70 - Flooded	0.64 ± 0.08 $_a$	2.55 ± 0.22 $_a$	16.62 ± 1.11 $_a$	5.23 ± 0.17 $_a$	0.81 ± 0.06 $_a$	3.64 ± 0.30 $_a$	15.60 ± 1.39 $_a$	4.98 ± 0.22 $_a$
F-70 - Intermittent irrigations	0.63 ± 0.11 $_a$	2.42 ± 0.24 $_a$	16.84 ± 0.90 $_a$	5.24 ± 0.20 $_a$	0.74 ± 0.09 $_a$	3.62 ± 0.17 $_a$	16.80 ± 1.32 $_a$	4.88 ± 0.16 $_a$
Varieties (V)	NS	NS	*	NS	NS	NS	NS	NS
Treatments (T)	**	NS	NS	NS	NS	NS	NS	NS
V x T	*	NS	NS	NS	NS	NS	NS	NS

Variables	**Primordium**	**Tiller**	**Flowering**	**Rice grain yield**
Season	NS	***	*	***

4.7 Discussion

4.7.1 CH_4 emissions

The intermittent irrigation strategy implemented here reduced daily CH_4 emissions by 31-96%, thus our results support previous findings on CH_4 emission reduction through intermittent drainage (Cowan et al., 2021; Goto et al., 2004; Meijide et al., 2017; Tirol-Padre et al., 2018). The periods of soil aeration throughout the crop cycle, within the context of intermittent irrigation treatment, may be associated with significant changes in the dynamics of water and oxygen in the soil pores. These periods allow for the introduction of sufficient oxygen (O_2), promoting the oxidation of organic carbon to CO_2 through methanotrophic bacterial activity under aerobic soil conditions (Lim et al., 2024; Sun et al., 2016), thereby reducing CH_4 emissions (Bo et al., 2022). However, during short periods of water replenishment in intermittent irrigation treatment, when soil pores are saturated, organic carbon oxidation may persist due to the presence and abundance of methanotrophic bacteria at the soil-water interface and in the rice rhizosphere (Deppe et al., 2010). Furthermore, the ability of rice plants to supply atmospheric oxygen to roots through the vascular system known as aerenchyma (Neue, 1993; Nouchi et al., 1991) facilitates root oxidation, where O_2 diffusion is a crucial factor (Bhattacharyya et al., 2016, 2019). The presence and abundance of CH_4-oxidizing bacteria in the rhizosphere also contributes to oxidation potential, favoring CH_4 reduction (Neue, 1993). On the other hand, soil aeration periods and high iron contents in both regions may promote iron oxidation, inhibiting reduction processes and thus reducing CH_4 emissions compared to continuously flooded rice production systems, which favor reduction processes. These findings are supported by Nishimura et al. (2020), who found that intermittent irrigation systems can achieve CH_4 reduction by oxidizing Fe^{2+} to Fe^{3+} during aeration periods, suppressing reduction processes.

During the rice cultivation cycle under intermittent irrigation treatment in both regions, a significant reduction in methane emissions to the atmosphere was observed, reaching average values close to -10 mg m^{-2} d^{-1}. These findings suggest that, at a regional level, there is no discernible effect on the reduction rate, indicating that despite the different regional climatic conditions, such as variations in rainfall patterns, frequency, and distribution, soil aeration periods favored the oxidation processes of soil organic carbon throughout the cultivation cycle. However, scientific literature needs more specific research on the impact of regional climatic characteristics on intermittent irrigation systems regarding CH_4 production. On the other hand, there has been a greater focus on correlating specific environmental parameters, such as temperature and precipitation, with CH_4 emissions in continuously flooded production systems. For example, Lee et al. (2023) demonstrated that in continuously flooded rice systems, temperature and total hours of sunlight have a positive effect on CH_4 emissions. Hou et al. (2023) showed that in flooded rice systems in China, a significant increase in average temperature and traditional fertilization with N, P, and K could contribute to increased CH_4 emissions. Regarding rice varieties, no significant effect was observed on daily CH_4 emissions under intermittent irrigation in both regions. This suggests that the evaluated commercial varieties were able to supply sufficient atmospheric oxygen through the aerenchyma in the rhizosphere to ensure methanotrophic processes. It has been documented that CH_4 emissions vary considerably among varieties due to the influence of plant physiology on the rate of O_2 diffusion (Baruah et al., 2010; Shang et al., 2011).

Our observations confirm that continuous irrigation leads to high CH_4 emissions, while intermittent irrigation effectively reduces these emissions. The most significant peaks in CH_4 emissions throughout the production cycle occurred during the tillering, flowering, and grain-filling stages in the flooded treatments. These stages were characterized by a significant advancement in aboveground biomass development and fully developed aerenchyma, potentially contributing to increased root exudates and thereby enhancing overall CH_4 production and transport, as highlighted by Aulakh et al. (2001), Gupta et al., (2002) and Kludze et al. (1993). The scientific literature extensively documents the intrinsic connection between aboveground biomass development and daily CH_4 emissions in rice systems (Feng et al., 2021; Huang et al., 1997; Mariko et al., 1991; Sass et al., 1990). Our study supports this relationship by observing consistent patterns during the phenological stages of cultivation in flooded and direct-seeded systems. In the early stages of the vegetative phase in the direct-seeded system, characterized by lower biomass and smaller size of aerenchyma in rice (the primary CH_4 emission pathway in flooded systems) (Van den Berg et al., 2016; Jiménez & Pedersen, 2023), where morphological structures are not fully developed, our measurements indicated that daily emission rates of CH_4 were similar between both treatments. This finding aligns with previous research indicating that limited biomass and aerenchyma development in these stages restricts CH_4 emissions through the plant by up to 27% (Iqbal et al., 2021), regardless of the emission potential of varieties or soil reduction conditions (anaerobic conditions) (Meijide et al., 2017).

In summary, our findings highlight the critical influence of the development of plant phenological stages as a relevant pathway for CH_4 emissions in flooded systems and underscore the efficacy of intermittent irrigation in mitigating these emissions. The discussion emphasizes the importance of proper water management, particularly in intermittent drainage, as a viable strategy for reducing CH_4 emissions in rice cultivation. The integration of these practices holds promise for sustainable and environmentally friendly rice production, contributing to global efforts to address greenhouse gas emissions in agriculture.

4.7.2 N_2O emissions

The daily emissions of N_2O in the continuous irrigation treatment peaked at various stages of the production cycle in the regions of Tolima and Casanare. In Tolima, these peaks were identified during the fourth fertilization event, occurring close to the maturation stage. In the case of Casanare, they occurred during the rainfed season, specifically during the second fertilization event, and during the irrigation season, between the second and third fertilization events (Fig. 4-2, 4-3, and 4-4). The observed peaks of N_2O emissions in the treatment subjected to continuous flooding could potentially be attributed to an increase in the availability of nitrogen (N) for soil microbes resulting from the application of urea and ammoniacal fertilizers during the productive cycle (Firestone & Davidson, 1989; Xu et al., 2015).

Conversely, the daily N_2O emissions in the treatment subjected to intermittent irrigation in both regions ranged between 2 and -5 mg N_2O m^{-2} d^{-1}. This behavior is likely attributable to regulating soil moisture levels during fertilizer application, either close to or above the field capacity and saturation points. Such regulation facilitated the solubilization of fertilizers, as evidenced by experiments conducted by Loaiza et al. (2024a). These findings align with prior studies by Riya et al. (2017) and Islam et al. (2020b), underscoring that fluctuations in soil water levels near the surface create microaerophilic conditions, thereby mitigating abrupt transitions between aerobic and anaerobic environments. Such conditions are pivotal for nitrification while providing the requisite substrate (e.g., nitrate) for denitrification. Alternatively, managing residual soil moisture near or above field capacity creates micro-aerophilic conditions with low oxygen levels within specific pore fractions.

The emission values obtained from our trials under intermittent irrigation were markedly lower when compared to those reported by Feng et al. (2021) in Hubei Province, China, characterized by a subtropical continental monsoon climate. Specifically, treatments employing AWD exhibited daily emissions ranging from 0.02 to 0.03 mg N_2O m^{-2} d^{-1}. Similarly, Chirinda et al. (2017) reported N_2O emissions under AWD treatment of approximately 0.55 mg N_2O m^{-2} d^{-1} in the Saldaña region, Tolima, between 2015 and 2016, under tropical climatic conditions. The same study documented emissions under continuous flooding, with average daily emissions of 1.7 mg N_2O m^{-2} d^{-1}. This underscores that our findings revealed higher emission values, ranging between 8 and 15 mg N_2O m^{-2} d^{-1} for the Casanare region and 40 mg N_2O m^{-2} d^{-1} for the Tolima region, under continuous flooding conditions.

In this study, intermittent irrigation reduced N_2O emissions compared to continuous flooding (Fig. 4-2, 4-3, and 4-4). This decrease in N_2O emissions is attributed to controlling soil moisture, maintaining it between saturation and field capacity. This strategy prevents abrupt transitions between aerobic and anaerobic soil conditions (Riya et al., 2017), during which compounds such as nitrate and nitrite are reduced to gaseous nitrogen (NO, N_2O, or N_2) in the soil denitrification process, a phenomenon common in continuously flooded rice systems (Firestone & Davidson, 1989; Peng et al., 2011). The intermittent irrigation treatment used in our trial was more frequent, allowing for the respiration of nitrates by maintaining a balance in soil moisture conditions between field capacity and saturation. This helped to keep soil aerobic and anaerobic conditions below the threshold of aerobic respiration (Sapkota et al., 2020), thereby inhibiting the exchange of N_2O between the soil and the atmosphere (Suenaga et al., 2018), possibly due to the low oxygen concentration in soil pores, which favors the complete occurrence of denitrification processes (Pan et al., 2022; Trost et al., 2013). Systems such as intermittent irrigation or AWD, which maintain soil tension and moisture levels close to the permanent wilting point or levels of water below 15 cm from the soil surface, improve soil aeration, thereby promoting the nitrification process and resulting in the release of more N_2O into the atmosphere (Liang et al., 2022).

The results of our study differ from those of several previous studies (Berger et al., 2013; Kritee et al., 2018; Xu et al., 2016; Zhou et al., 2020), which have reported that reducing water input during rice development decreases soil moisture, thus increasing the potential for oxidation-reduction and N_2O formation up to 45 times more than in flooded systems, where N_2O is reduced to N_2 due to lower oxidation-reduction potential.

Significant differences between varieties within each region were not observed. However, regional disparities were identified where the highest peaks of N_2O emissions under continuous flooding treatment were observed in the Tolima region compared to Casanare (Figures 4-2, 4-3, and 4-4). This coincided with the highest levels of applied fertilizer, indicating potentially more significant substrate contents for nitrification (Kim et al., 2021; Yao et al., 2012), which may explain the higher N_2O emissions quantified in the Tolima region under continuous flooding.

4.7.3 Grain yield

The impact of intermittent irrigation in rice production systems has shown varied outcomes. Several studies have reported yield reductions under intermittent irrigation (Chapagain & Yamaji, 2010; Feng et al., 2021; Islam et al., 2020a), while others have documented yield increases (Hassan et al., 2015; Nugroho et al., 2018; Thakur et al., 2018). Conversely, some investigations have found no yield reduction under intermittent irrigation (Bo et al., 2022; de Avila et al., 2015; Haque et al., 2016; Haque et al., 2021; Keisser et al., 2002; Linquist et al., 2015; Loaiza et al., 2024a). In our study, intermittent irrigation involved controlling soil moisture near field capacity and saturation for fertilizer application events, maintaining this criterion for water replenishment every 3 to 4 days throughout the production cycle. This approach did not result in yield penalties compared to continuous flooding irrigation (Table 4-3). These findings could be attributed to optimal soil moisture levels, avoiding water stress during plant growth (Feng et al., 2021). By avoiding water stress during critical plant development stages, proper seed formation, panicle, tiller, and root development, as well as an adequate photosynthesis rate, were facilitated (Shukla et al., 2013; Yang et al., 2004), resulting in yields equivalent to those observed under continuous flooding conditions. Bouma et al. (2007) and Carrijo et al. (2017) found that ensuring water levels in intermittent irrigation systems, such as AWD, below the permanent wilting point, around -20 kPa, can prevent yield reductions. Our study identified the optimal soil moisture threshold and proper water management, preventing yield losses.

Yields in Tolima and Casanare did not differ significantly between varieties and irrigation treatments. However, differences were observed between regions, particularly in the Casanare region, and among seasons. Disparities between regions could be attributed to climatic variations and the type of cultivated variety. Regarding climate, Tolima receives approximately 431 cal m^{-2} d^{-1} of solar energy, while Casanare receives around 358 cal m^{-2} d^{-1}, potentially explaining the regional divergence. Several studies have demonstrated the positive impact of solar radiation on plant growth and development (Deng et al., 2015; Quevedo et al., 2019; Peng et al., 2004; Tu et al., 2022), directly correlating with yields (Tao et al., 2013). On the other hand, varieties planted in Tolima, such as F-67 and F-2000, exhibited higher tillering compared to those in Casanare, such as F-Itagua and F-70, which showed an intermediate level of tillering (Ospina et al., 2024). This difference in tillering among varieties suggests that those adapted to Tolima's climatic conditions display better vegetative development than those in Casanare, elucidating the regional disparity. Seasonal differences in Casanare could be attributed to climatic conditions such as temperature, precipitation intensity, and distribution, which impact water control and soil moisture during fertilization periods between the two seasons. The rainy season solely relies on rainfall distribution and quantity, while the dry season depends on irrigation application. Increased heat during the dry season might elevate soil tension, slightly affecting yield values for this season. Numerous studies (Julia & Dingkuhn, 2013; Mittler et al., 2012; Kobayashi et al., 2010; Rang et al., 2011) have demonstrated that even a slight rise in temperatures during at least one day of heat stress can impact enzymatic efficiency, growth, and productivity, directly influencing yield.

The findings of this study contribute to the existing body of knowledge by affirming that well-designed intermittent irrigation systems can be implemented without compromising crop yields. This aligns with findings from previous studies and supports the notion that intermittent irrigation can be a sustainable and efficient alternative to flooded systems, particularly in regions prone to water scarcity or where water management is crucial for environmental conservation. While our results support the potential of intermittent irrigation, it is essential to acknowledge the challenges associated with its widespread adoption. Consistent irrigation scheduling and adequate moisture control can undermine the benefits of intermittent irrigation. Addressing these challenges requires technological solutions and policy interventions to encourage farmers to adopt and effectively manage intermittent irrigation practices.

4.7.4 Cumulative CH_4 and N_2O emissions and Global warming potential.

The cumulative net flows of CH_4 result from a balance between methanogenic and methanotrophic activities (Lee et al., 2014; Nagler et al., 2021; Zhang et al., 2023). Our results, based on the dynamics of daily emissions, demonstrate that intermittent irrigation significantly reduces CH_4 emissions compared to flooded treatments, regardless of whether it is irrigated or rainfed rice production. With intermittent irrigation, lower daily CH_4 emissions and reduced peaks during critical crop stages, such as tillering, flowering, and grain filling, contribute to lower cumulative flows. These findings are supported by similar studies (Hou et al., 2000; Mazza et al., 2016; Minamikakawa et al., 2016; Nie et al., 2023), which found an 82% reduction in CH_4 emissions in controlled irrigation systems. At the regional level, rice varieties exhibited varying impacts on CH_4 emissions. Significant differences were observed in Tolima among varieties and irrigation treatments, whereas in Casanare, distinctions were found only among irrigation treatments. Specifically, the F-67 variety demonstrated lower CH_4 values in Tolima, irrespective of the irrigation treatment. Conversely, although no significant differences among varieties were noted in Casanare, the F-Itagua variety displayed lower levels of accumulated CH_4. These findings suggest that these varieties may effectively mitigate CH_4 emissions in rice cultivation systems.

The cumulative net flows of N_2O stem from the nitrification and denitrification processes. Nitrification, involving the microbial conversion of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification, entailing the reduction of NO_3^- to N_2 (Fireston & Davidson, 1989; Hassan et al., 2022; Wang et al., 2016). Cumulative flows decreased significantly in both regions with intermittent irrigation compared to flooded treatment. The control of soil moisture during fertilization events was a key point for the significant reduction of N_2O. However, higher cumulative net flows were observed in the rainfed system in the Casanare region, where soil moisture depended on precipitation. This finding aligns with previous research (Zhan et al., 2015), suggesting that alternating wet and dry soil conditions due to frequent precipitation events can increase N_2O emissions through nitrification and denitrification processes. No significant differences were observed among the Tolima or Casanare region rice varieties across the evaluated treatments. However, during the analyzed seasons in Casanare, lower cumulative nitrous oxide fluxes were recorded during intermittent irrigation in the dry season. This phenomenon was attributed to the intermittent irrigation treatment's enhanced control of soil moisture threshold, maintaining it closer to field capacity, in contrast to rainy periods when soil drained near its water-holding capacity, solely influenced by rainfall distribution and intensity during the wet season. This threshold between aerobic and anaerobic conditions facilitated the creation of microaerobic conditions with reduced oxygen levels, enabling the complete execution of nitrification and denitrification processes, thereby diminishing N_2O exchange to the atmosphere (Riya et al., 2017; Sapkota et al., 2020)

Considering the percentage difference in the contribution of CH_4 and N_2O emissions from different rice production systems, it is essential to determine the GWP to estimate the impact of greenhouse gas emissions on the environment (Shang et al., 2011; Tariq et al., 2017). This study employed GWP to indicate the impact of CH_4 and N_2O emissions on total GHG emissions in two irrigation systems (continuous flooding and intermittent irrigation). Continuous flooding and intermittent irrigation systems, and varieties exhibited a GWP primarily attributed to N_2O emissions, which accounted for over 73% in Tolima and between 56–97% for both wet and dry seasons in the Casanare region during crop development. These findings contradict research associating positive associations between GWP in flooded rice systems and CH_4 emissions (Bayer et al., 2015; Camargo et al., 2018; Zschornack et al., 2018). Although N_2O significantly contributes to GWP under continuous flooding and intermittent irrigation, reductions in net cumulative N_2O fluxes between treatments differ significantly, with lower emissions observed in intermittent irrigation. These reductions in CH_4 and N_2O highlight that intermittent irrigation could effectively mitigate GWP, even if a slight increase in N_2O emissions slightly compensates for the reduction in CH_4. These results stem from combined actions such as controlling water stress levels, irrigation frequency, and soil moisture control (Feng et al., 2013; Loaiza et al., 2024a). These findings align with research demonstrating that intermittent flooding can reduce GWP with a significant reduction in CH_4 and a slight increase in N_2O compared to continuous flooding systems, where the proportions of CH_4 and N_2O emissions vary and can contribute significantly to GWP (Cowan et al., 2021; Sun et al., 2022; Zou et al., 2005). These results are crucial for the Tolima and Casanare regions, where rice production can increase or be sustained without a proportional increase in GHG emissions through the adoption of intermittent irrigation.

4.8 Conclusions

The study demonstrates that the method of intermittent irrigation studied here can not only reduce CH_4 emissions but also N_2O emissions without compromising the sustainability and profitability of rice systems in the Tolima and Casanare regions. Controlling soil moisture at field capacity or maintaining optimal residual moisture during fertilizer application is crucial in intermittent irrigation treatments for N_2O emission reduction in agriculture. During the physiological development of the plant, we determined that tillering, flowering, and grain filling are vital for establishing mitigation strategies in reducing CH_4 emissions, as these stages are sensitive to water stress, representing a critical juncture. These are moments when emissions increase in flooded systems due to the development of the leaf index, which enhances emission pathways.

The intermittent irrigation system exhibited a lower GWP than flooded systems, indicating significant mitigation potential. In this study, intermittent irrigation emerges as a low-cost and easily adaptable water technique for small-scale farmers. However, it is essential to emphasize that the success of this strategy is inherently linked to precise soil moisture management and strategic synchronization with critical plant development stages.

In summary, this study supports the efficacy and feasibility of intermittent irrigation as a sustainable practice for rice production, offering significant environmental benefits. The careful implementation of this technique, coupled with attention to specific plant development factors, can reduce greenhouse gas emissions and contribute to the adaptability and resilience of farmers facing climatic and economic challenges. Overall, we show in this section that this study not only highlights the effectiveness and practicality of intermittent irrigation in reducing the environmental footprint of rice cultivation, but also serves as a clarion call for a paradigm shift towards more sustainable and resilient agricultural practices worldwide. By bridging the gap between traditional methods and innovative water management strategies, together we can embark on a journey to achieve global food security in an environmentally sustainable way.

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4.10 Reference

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4.11 Annex

Annex A: Results of Principal Component Analysis (PCA) for the relationship between daily emissions of CH_4, N_2O and climatic conditions.

Table A1: Factor loadings – Tolima – Semester I.

Treatments	**F-2000 Flooded**		**F-2000 Intermittent irrigation**		**F-67 Flooded**		**F-67 Intermittent irrigation**	
Variables	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**
CH_4	-0.5988	-0.4654	0.3521	0.5538	-0.5445	-0.2870	0.2152	0.9036
N_2O	-0.5015	0.5214	-0.0445	-0.8497	-0.4649	0.4109	-0.5503	0.2613
Temp.	-0.9767	0.0881	0.9790	-0.1345	-0.9780	-0.0892	0.9816	0.0423
Rainfall	0.3142	0.7236	-0.3181	-0.3289	0.3062	-0.7988	-0.3170	0.2063
Relative humidity	0.8364	0.1673	-0.8283	-0.1631	0.8381	-0.1964	-0.8148	0.2669
Solar energy	-0.7701	0.1621	0.7924	-0.0974	-0.7627	-0.2379	0.7786	0.1376
Total variance	70%		70%		72%		70%	

Table A2: Factor loadings – Casanare – Semester I and II.

Semester I

Treatments	**F-Itagua Flooded**		**F-Itagua Intermittent irrigation**		**F-70 Flooded**		**F-70 Intermittent irrigation**	
Variables	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**
CH_4	0.5416	-0.1566	-0.6252	0.1552	0.5934	0.3634	-0.6559	-0.2213
N_2O	0.3594	0.1325	0.0399	0.5045	0.0448	-0.0398	-0.3327	0.4623
Temp.	0.8921	-0.4171	-0.8895	-0.4191	0.9108	0.3601	-0.8895	-0.4180
Rainfall	-0.5175	-0.6683	0.5252	-0.5761	-0.4951	0.6595	0.5075	-0.5702
Relative humidity	-0.9079	-0.2020	0.9045	-0.2135	-0.8921	0.2646	0.8912	-0.2269
Solar energy	0.8458	0.3450	0.2551	0.2551	0.8286	-0.4208	-0.8557	0.3205
Total variance	71%		72%		71%		73%	

Semester II

Treatments	**F-Itagua Flooded**		**F-Itagua Intermittent irrigation**		**F-70 Flooded**		**F-70 Intermittent irrigation**	
Variables	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**	**Comp 1**	**Comp 2**
CH_4	0.6289	-0.4448	0.0577	0.7399	0.4097	0.8007	0.3614	-0.5362
N_2O	-0.2748	0.6755	-0.1439	-0.1364	0.1762	-0.8422	0.3513	-0.7746
Temp.	-0.1996	-0.3191	-0.2784	-0.7394	-0.1592	0.0099	-0.2199	-0.1539
Rainfall	-0.6326	-0.4730	-0.7421	0.2353	-0.7572	0.2902	-0.7644	0.3524
Relative humidity	-0.8416	0.3419	-0.7001	0.0559	-0.7558	-0.3976	-0.6348	-0.4458
Solar energy	0.7971	0.4897	0.9273	-0.0587	0.8729	-0.2965	0.9291	0.0332
Total variance	60%		53%		63%		56%	

5 Chapter IV: Comparative Analysis of Two Commercial Varieties and Two Heat-Tolerant Genotypes: Managed Intermittent irrigation vs Flooded Irrigation under extreme climatic conditions.

Based on the results of previous research, there is a growing need to determine whether heat-tolerant rice genotypes, developed through crossbreeding with commercial varieties, possess the capability to withstand extreme climate conditions under intermittent irrigation compared to continuous flooding, thereby ensuring productivity.

In rice agriculture, addressing the imperative of sustainable production methods in light of escalating climate challenges is paramount. This chapter investigates the contrasting reactions of two commercial rice varieties and two experimental heat-resistant genotypes under varying water management strategies—specifically, intermittent irrigation and flooding—within the climatically demanding Tolima region.

The chapter presents key findings from a comprehensive examination of CH_4 and N_2O emissions, GWP, crop quality, and yield dynamics. As we delve into the complexities of genotype responses and irrigation methodologies, this chapter highlights the crucial role of scientific inquiry in maintaining the delicate equilibrium between agricultural productivity and environmental sustainability. It underscores the necessity for ongoing exploration and improvement of cultivation practices, driven by the need to secure a resilient and sustainable future for rice agriculture in the face of evolving climatic challenges.

5.1 Keywords

rice cultivars; methane emission; Nitrous oxide emissions; water management.

5.2 Highlights

- Genotypes IR 93341 and 93353 significantly reduce CH_4 emissions under both intermittent and flooded irrigation while demonstrating good grain quality
- Genotypes show low adaptation to extreme drought, affecting yield
- N_2O emissions under intermittent irrigation and high-volatilization fertilizer match those of flooded systems, showing effective volatilization suppression
- Substantial reduction in Global Warming Potential (GWP) in intermittent irrigation: variations of 12-43% in commercial varieties and 25-73% in genotypes compared to flooding

5.3 Abstract

This study aims to investigate the contrasting impact of two commercial rice varieties and experimental two heat-resistant genotypes under two water management conditions (intermittent irrigation and flooding) in extreme climatic conditions in the Tolima region. The objective was to assess methane (CH_4) and nitrous oxide (N_2O) emissions, Global Warming Potential (GWP), crop quality, and yield. The results highlight that transitioning from flooding to intermittent irrigation reduces CH_4 emissions by 74-75% in commercial varieties and 81-95% in experimental heat-

resistant genotypes under intermittent irrigation. Furthermore, an 85% reduction in CH_4 emissions for genotypes and a 61% reduction for commercial varieties were observed. No significant differences were found between cultivars and treatments regarding N_2O emissions, indicating that intermittent irrigation allows gas reduction by completing nitrification and denitrification, like flooded rice systems. It emphasizes the dependence on water resource management rather than cultivars. Commercial rice varieties exhibited higher yields than the experimental genotypes, likely due to dry conditions during the planting period, resulting in yields below the average for the Tolima region. The reduction in GWP for the intermittent irrigation treatment ranged from 12 to 43% in commercial varieties and 25 to 73% in genotypes, compared to the flooded treatment. Findings suggest that differences in genetic characteristics between cultivars and genotypes could explain the reduction in CH_4 emissions, and soil moisture control is a critical factor in reducing N_2O emissions. Despite providing a good starting point for identifying sustainable production systems with low emissions, it is crucial to assess the effect of extreme climate conditions that may affect productivity in more detail. In recognition of study limitations, future research is proposed to explore further the impact of extreme climatic conditions on the sustainability and productivity of different cultivars.

5.4 Introduction

Rice crops represent a prominent source of anthropogenic emissions of methane (CH_4) (Smith et al., 2008; Smith et al., 2021; Tian et al., 2016) and nitrous oxide (N_2O) (Akiyama et al., 2005; Malyan et al., 2016; Zhang et al., 2012). The production and emission of CH_4 are intrinsically linked to soil methanogenic processes under anaerobic conditions (Corand, 2020; Lyu et al., 2018). Previous studies have demonstrated that CH_4 emissions in rice systems are influenced by water regimes (intermittent flooding, flooded, and dryland) (Thuong et al., 2024; Yan et al., 2009; Zhang et al., 2023), the use of nitrogen fertilizers (Banger et al., 2012; Lakshani et al., 2023; Yao et al., 2012; Zhou et al., 2017), availability of organic carbon (Chen et al., 2013; Humphreys et al., 2019; Senthilraja et al., 2023), and rice varieties (Habib et al., 2023; Thuong et al., 2024; Zhang et al., 2014). Likewise, N_2O emissions are related to soil moisture and applied nitrogen (Ciarlo et al., 2007; Ju et al., 2024; Skinner et al., 2014). In continuously flooded rice production systems, N_2O emissions are generally not significant due to anaerobic conditions, where a complete reduction of N_2O to molecular nitrogen (N2) occurs (Berger et al., 2013; Mazid Miah et al., 2016).

Globally, rice production is estimated to contribute between 10% and 30% of anthropogenic CH_4 emissions and 11% of N_2O emissions (Carlson et al., 2017; Nazaries et al., 2013; Mboyerwa et al., 2022). Asia leads global production with 90%, while Latin America contributes less than 5% (Shahbandeh, 2024; World Economic Forum, 2022). Despite the difference in the extent of rice cultivation, the contribution to greenhouse gas (GHG) emissions to national inventories is significant in Latin America, making rice cultivation a strategic component in development (Parra – Peña et al., 2022). Various production systems contribute to CH_4 and N_2O emissions (Samaniego, 2009; Wong et al., 2023). Therefore, a key goal for production systems in Latin America is to optimize the use of water resources and agronomic practices, such as fertilization events, to increase rice productivity without raising GHG emissions. Methanogenic microorganisms, responsible for CH_4 production, thrive in anaerobic environments typical of flooded rice fields (Lee et al., 2014; Mahabubur Rahman & Yamamoto, 2021; Conrad, 2020). Simultaneously, methanotrophic microorganisms play a crucial role in CH_4 capture under aerobic conditions, representative of upland and intermittent flooding rice systems (Ma & Lu, 2011; Ma et al., 2013; Zhang et al., 2012). Additionally, N_2O emissions are relevant in rice contexts due to fertilization events, which depend on soil moisture conditions to facilitate the reduction of N_2O to N_2 through nitrification and denitrification (Butterbach – Bahl et al., 2013; Smakgahn, 2020; Wang et al., 2021). The transfer of CH_4 and N_2O from the soil to the atmosphere occurs through processes of molecular diffusion, ebullition, and transport facilitated by plants (Frenzel & Karofeld, 2000; Wang et al., 2017). Previous research has indicated that over 90% of GHG emissions released by rice fields occur through plant-mediated transport, utilizing plant structures such as aerenchyma under flooded conditions (Gaihre et al., 2011; Smartt et al., 2016; Timilsina et al., 2020). However, despite the significant contribution of plants in GHG emission transfer, research on variations in GHG emissions among different cultivars has been limited in Latin America.

The mitigation of climate change impacts on rice production systems has focused on agronomic management practices, addressing aspects such as fertilizer application (Hasukawa et al., 2021; Islam et al., 2022a; Lina et al., 2022; Zhang et al., 2022), agricultural waste management (Baruah & Baruah, 2015; Lehtinen et al., 2014; Li et al., 2021), and irrigation regulation (Islam et al., 2020; Islam et al., 2022b; Sapkota et al., 2020). Despite these efforts, adopting practices such as fertilization, waste management, and irrigation poses a substantial challenge for farmers, especially when lacking regulatory support and economic incentives (Chirinda et al., 2018). In this context, there is a need to seek more accessible and practical solutions for farmers, avoiding additional barriers that may impact the cost-benefit relationship of mitigation practices. A proposed strategy involves leveraging natural variation among rice cultivars regarding CH_4 and N_2O emissions. It is argued that this tactic could provide a more cost-effective alternative to reducing GHG emissions in Latin America, as associated adjustments would not entail drastic changes in existing agricultural practices or increased production costs (Chirinda et al., 2018). This approach aims to effectively address GHG emissions without imposing an additional burden on farmers. It could represent a viable solution without regulatory measures and economic incentives for rice farmers in Latin America.

Various studies (Asch et al., 2023; Gogoi et al., 2008; Islam et al., 2019; Vo, 2023) have demonstrated the existence of genotypic variations in CH_4 emissions, suggesting the potential for selecting rice varieties with reduced CH_4 emissions. However, regarding N_2O emissions, previous research (Bhatia et al., 2023; Li et al., 2023; Verma et al., 2023) has determined that reduction depends on soil moisture conditions, the type and application of nitrogen fertilizers, with less effect from the genetics of the cultivars. Meanwhile, Jiang et al. (2016) demonstrate that modifying the grain by adding photosynthate can reduce N_2O emissions by decreasing carbon input and increasing nitrogen absorption in the plant without affecting yield. There is increasing evidence that genetic improvements in cultivars can contribute to food security and reduce GHG. Gogo et al. (2008) showed that high-yielding varieties like IR-36 exhibited lower CH_4 emissions than commercial varieties in India. The reduction was associated with variation in aboveground biomass accumulation. Zhang et al. (2019) evaluated hybrids and commercial varieties in China, demonstrating inverse relationships between root morphology, physiological parameters, and CH_4 emissions, showing lower CH_4 emissions and higher yield. Quin et al. (2015) assessed different cultivars with genetic diversity in China, finding that cultivars Qihuazhan, Yexianzhan 8, and Yue'erzhan are suitable for promoting low-carbon agriculture and high yields. Li et al. (2015) demonstrated that it is possible to identify cultivars with CH_4 mitigation potential and high yields based on the number of tillers <15, a harvest index >0.43, and leaf nitrogen assimilation <40. These studies underscore the potential impact of genetic differences in rice varieties on CH_4 emissions, providing valuable information for sustainable agricultural practices and climate change mitigation.

Evidence from Latin America has been presented in two studies conducted in Colombia. First, Loaiza et al. (2024) successfully identified specific commercial rice varieties from two rice-growing regions. They indicated that the varieties Fedearroz 67, Fedearroz-2000, and Fedearroz Itagua could potentially reduce CH_4 and N_2O emissions under intermittent irrigation systems without affecting the average yield of the regions. This ensures a reduction in GWP without compromising the food security of the regions. Second, Soremi et al. (2023) observed significantly higher CH_4 emissions in rice hybrids compared to a breeding line and a homozygous variety, noting that these differences are linked to root characteristics and aboveground biomass. They suggested transitioning to low-emission rice production systems by leveraging these genetic variations.

In this regard, monitoring CH_4 and N_2O emissions from commercial varieties and experimental genotypes resistant to high temperatures is imperative. The goal is to discover genotypes capable of reducing such emissions and adapting to extreme climatic conditions without compromising grain productivity. In order to guide future genetic improvement efforts, understanding the mechanisms driving CH_4 and N_2O emissions reductions is crucial. The hypothesis for this study is that genotypes resistant to high temperatures may generate less CH_4 and N_2O, adapting to the conditions of tropical regions without affecting their performance.

5.5 Materials and methods

Between May and September 2023, an experiment was conducted in a rice field at the "Lagunas" experimental station in Saldaña, Tolima, Colombia. The adopted methodology involved a randomized complete block design with four treatments and replications. Four rice cultivars were utilized, including two commercial varieties (Fedearroz 67 and Fedearroz 2000), chosen for their demonstrated potential in reducing the GWP compared to different commercial varieties in Fedearroz field trials. Additionally, two experimental lines resistant to elevated temperatures (IR 93341 and IR93353) were included. Direct mechanized seeding with a seeding density of 100 kg ha^{-1} was performed in May. Information on nitrogen fertilization throughout the productive cycle and soil parameters is provided in Tables 5-1 and 5-2, respectively. The soil, characterized as sandy loam, exhibited neutral pH (6.7) and low electrical conductivity (0.21 dS m^{-1}), indicating non-salinity, good levels of microelements, and medium levels of available phosphorus (33.23 mg kg^{-1}), showing suitable soil conditions for rice production. Experimental plots underwent flooding and intermittent irrigation. During the growth season, the flooding treatment involved constant water application to maintain flood conditions in plots above saturation. Water was replenished to near saturation and field capacity for the intermittent irrigation treatment. The experimental site underwent mechanical preparation, with a gross plot size of 50 m^2, while the net harvested plot was reduced to 25 m^2.

Four samples of the aerial component, comprising stems, leaves, and panicles, were collected at different growth stages from each treatment. The samples were dehydrated at a constant temperature of 70°C for 24 hours, following the methodology described by Yepes et al., (2011). At the physiological maturity stage, a specific area of 25 m^2 was harvested from each plot to assess the rice grain yield. The harvested grains were dried in an oven at 70 °C for 72 hours, and the reported grain yield figure reflects a moisture content of 14%.

Detailed measurements of the breakdown, final viscosity, and setback parameters were conducted following the meticulously outlined protocol by Ye et al., (2016). The procedure involved the precise dispersion of 3 g of rice flour with a 14% moisture content in 24 ml of distilled water, resulting in a suspension with a 12% concentration. This suspension underwent testing on the DHR3 Discovery rheometer from TA Instruments, USA, operating at 250 RPM, applying a specific thermal profile: initially held at 50°C for 2 minutes, followed by a gradual heating from 50 to 90°C at a rate of 5°C/min for 8 minutes. Subsequently, it was maintained at 90°C for 4 minutes, followed by cooling from 90°C to 50°C at a rate of 5.7°C/min for 7 minutes. Finally, it was held at 50°C for another 2 minutes, and the total analysis time spanned 23 minutes. Data was collected using the TRIOS v. 4.3.1 software from TA Instruments, and the parameters mentioned were accurately calculated. The breakdown, final viscosity, and setback parameters are crucial indicators of the cooking and textural properties of rice products. In the context of rice, breakdown refers to the extent to which rice grains separate or become overly soft during cooking, indicating the rice's ability to maintain its structural integrity. Final viscosity, on the other hand, refers to the consistency of the cooked rice after it has reached its peak of cooking and has cooled down, reflecting its ability to retain water and proper structure. Lastly, setback measures the change in viscosity of cooked rice when it cools down after cooking, indicating the rice's ability to regain its original gelatinized consistency. These parameters provide valuable insights for food processing and product development, helping to ensure the desired texture and quality of rice-based dishes.

From May 31 to September 6, 2023, a comprehensive set of measurements was conducted throughout the rice growing season, encompassing greenhouse gases (CH_4 and N_2O), soil moisture tension using a Time Domain Reflectometry (TDR) to monitor moisture levels for each treatment, as well as pH and electrical conductivity (EC) on 98 different days. About fertilization, more frequent gas samplings were implemented. Specifically, four gas samples were collected from each treatment plot one day before and three days after fertilizer application. Throughout the rice growing season, gas measurements were conducted weekly until harvest. All sampling procedures were conducted in the morning (from 8:00 to 11:00 a.m.). The static closed chamber technique (48) was employed for gas collection. Plastic cubes with a volume of 114 L and a height of 80 cm were used, equipped with custom-made chamber bases of 30 cm height and featuring a channel allowing for a water seal during chamber deployment. These static chambers included vents for pressure equilibrium and a fan for air mixing (Chirinda et al., 2017). During each sampling campaign, gas samples (20 ml) were obtained from the closed static chambers in each treatment plot over four intervals of 20 minutes (0, 20, 40, and 60 minutes). These samples were extracted with a syringe and injected into pre-evacuated vials before analysis. The concentration of CH_4 and N_2O in the vials was determined using gas chromatography (Shimadzu GC-20C14), equipped with a Flame Ionization Detector (FID) and an Electron Capture Detector (ECD). CH_4 and N_2O fluxes were calculated using the gas concentration rate, the ideal gas equation, and the sampling time.

$$F = \frac{\Delta C}{\Delta t}\frac{VM}{AV_m} \quad (1)$$

In calculating CH_4 or N_2O flux (F, measured in mg m^{-2} h^{-1}), the rate of linear change in CH_4 or N_2O concentration ($\Delta C/\Delta t$, measured in ppm h^{-1}) over time is considered. The relative molecular mass (M) is taken as 16 for CH_4 and 44 for N_2O, while the chamber volume (V) and the surface area (A) of the chamber are also factored in. The molar volume of gas (Vm, measured in L mol^{-1}) is determined according to the ideal gas law. Seasonal cumulative fluxes for CH_4 and N_2O emissions (measured in kg ha^{-1}) are computed using linear interpolation between sampling dates. The GWP is then determined regarding carbon dioxide equivalent (kg CO_2 equiv. ha^{-1}) over a 100-year time frame, employing the IPCC guidelines and radiative forcing potentials of 27.2 for CH_4 and 273 for N_2O (IPCC, 2021).

Table 5-1: Agronomic Management of rice cultivation was assessed during the 2023 planting season for two commercial varieties and two genotypes in the Saldaña region, Tolima. Intermittent irrigation and flooding systems were implemented. Fertilizer sources included a combination of urea (U) – 46% N; potassium chloride (KCl) – 60% K_2O; MicroEssentials (ME) – 12% N, 40% P_2O_5, 10% S, 1% Zn; and ammonium sulfate (SAM) – 21% N, 24% S; Korn Kali +B (KB) – 40% K_2O, 6% Mg, 4% S, 0.25% B; Sakon (SK) – 90% Mg; PatenKali (PK) – 30% K_2O, 10% MgO, 17% S.

Sowing date (dd/mm/yy)	8/05/2023
Germination date (dd/mm/yy)	15/05/2023
Application dates (dd/mm/yy), Fertilizer sources, and Fraction of dose (kg ha^{-1})	31/05/2023→250(Microessential+U+ KCl+SAM) 07/06/2023→150 (U+KB,+SAM G) 20/06/2023→ 150 (U+ KB+SK) 05/07/2023→150 (U+KB) 18/07/2023→ 150 (U + PK)
Nitrogen applied (kg N ha^{-1})	188
Harvest date (dd/mm/yy)	IR93341 → 28/08/2023 IR93353 → 1/09/2023 FD 67 - FD2000 → 6/09/2023

Table 5-2: Soil properties (0-10 cm) at the study site.

Soil property	Unit	Value
Sand	%	52.47
Clay	%	19.36
Silt	%	28.17
pH	---	6.7
Organic matter	%	1.47%
Cation exchange capacity	cmol kg^{-1}	6.36
Available phosphorus	mg kg^{-1}	49.39

Soil property	Unit	Value
Sulphur	mg kg^{-1}	6.32
Iron	mg kg^{-1}	147.98
Calcium	cmol kg^{-1}	5.09
Magnesium	cmol kg^{-1}	0.91
Potassium	cmol kg^{-1}	0.27
Sodium	cmol kg^{-1}	<0.14
Copper	mg kg^{-1}	4.32
Zinc	mg kg^{-1}	4.10
Boron	mg kg^{-1}	0.24
Bulk density	g cm^{-3}	1.58
Total porosity	%	41
Volumetric moisture		
Saturation	%	40-48
Field capacity	%	19-29
Permanent wilting point	%	14-21

5.6 Statistical analysis

Statistical analyses were performed utilizing R Studio software, where data was processed using the ADE4 and Agricolae libraries. Then, the Shapiro-Wilk test was used to assess normality. In comparison, to evaluate the normality of datasets, the Kolmogorov-Smirnov test was employed for datasets exceeding 50 observations, both at a significance level of 5%. Parametric data underwent comprehensive one-way and two-way ANOVA, succeeded by Tukey's HSD post-hoc tests for meticulous group comparisons. For non-parametric datasets, such as daily emissions, the Kruskal-Wallis tests were applied, followed by Dunn's test for post-hoc analysis.

The exploration of the connections between daily methane and nitrous oxide emissions and climatic conditions involved multivariate PCA, co-inertia analysis, and permutation Monte Carlo tests. These analyses, which aimed to compare cultivars and treatments and assess the influence of climate on emissions, were executed within the R Studio environment utilizing the ADE4 library (Posit team, 2023; Thioulose et al., 2018).

5.7 Results

5.7.1 Climatic conditions

The growing season of 2023 was characterized as the driest semester, with an accumulated precipitation of 131 mm spread across 15 rainfall events. The average temperature ranged between 28 and 29°C, with minimums at 24°C and maximums at 33°C (Fig. 5-1a). A decrease in the maximum temperature occurred around 21:00 hours, reaching temperatures of 26 to 27°C during the planting semester (Fig 5-1b).

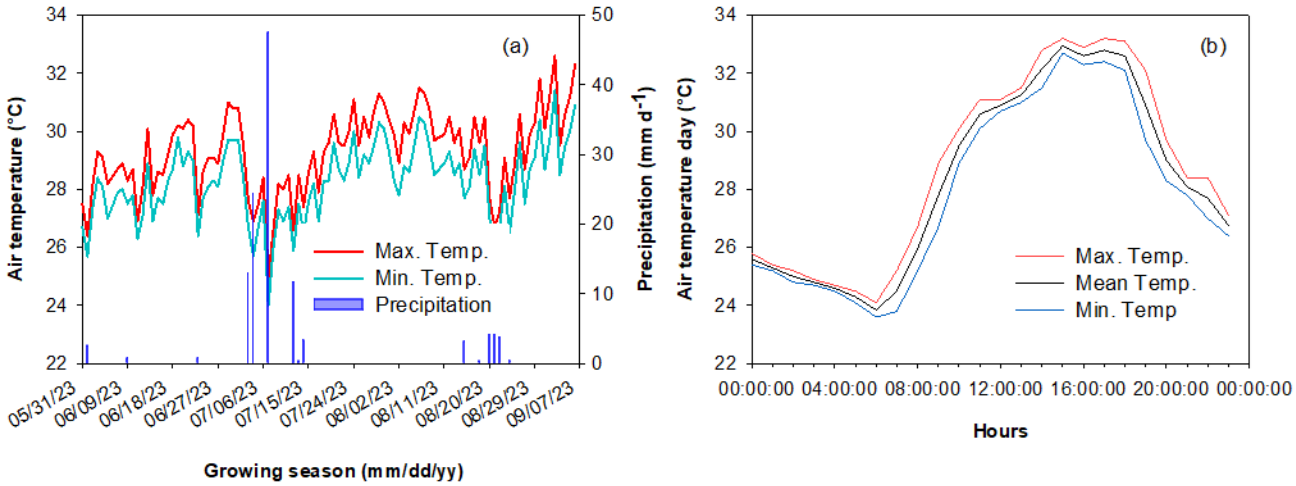


Fig. 5-1: (a) Max. and min. temperatures, and precipitation from June to September 2023 in the Saldaña - Tolima region planting season, (b) Average daily temperature throughout the growing semester.

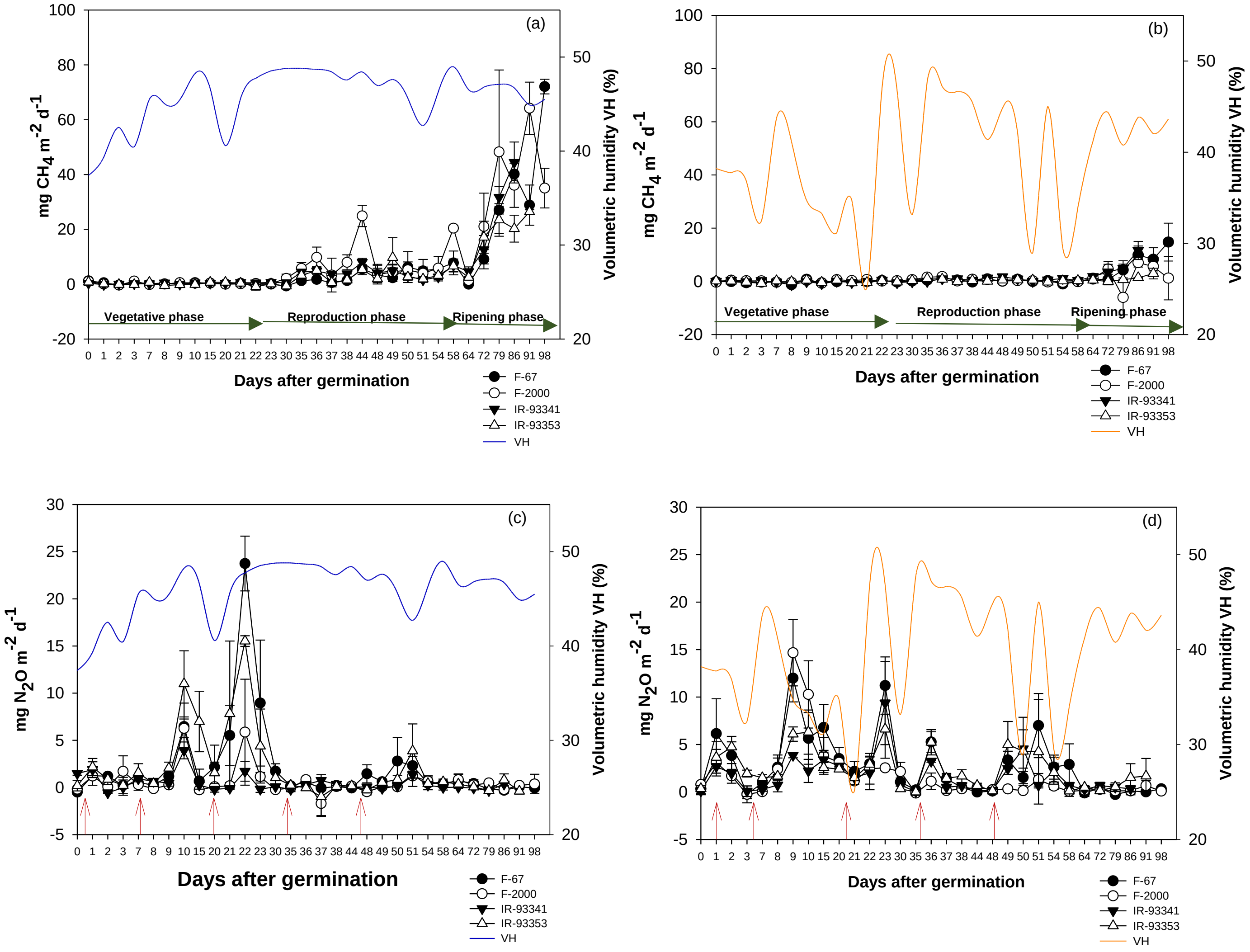
5.7.2 CH_4 and N_2O Daily emissions

The daily emissions of CH_4 and N_2O under flooding and intermittent irrigation are shown in Fig. 5-2. Both evaluated treatments observed a low CH_4 flux during the vegetative phase. In the flooding treatment, CH_4 emissions began to gradually increase 30 days after germination, during the reproductive phase, reaching the highest values during the maturation phase (between days 64 and 98) for the four cultivars, with soil moisture ranging between 40% and 48% (Fig. 5-2a). In the intermittent irrigation treatment throughout the productive cycle, a notable flux was recorded only 72 days after germination, during the maturation phase, with peak emission values of 20 mg m^{-2} d^{-1} and soil moisture between 38% and 43% (Fig. 5-2b). The peaks of CH_4 emissions in both treatments coincided with the highest ambient temperatures throughout the productive cycle. Significant differences were observed between treatments for all evaluated cultivars ($p < 0.05$).

The daily emissions of N_2O are presented in Figures 5-2c and 5-2d. Following the second and third fertilization in both treatments, elevated levels of N_2O were observed, with more pronounced levels in saturated soils of the flooded treatment and between field capacity and saturation in the intermittent irrigation treatment. The maximum values were recorded in the flooded treatment. Subsequently, N_2O emissions rapidly decreased, remaining below 5 mg m^{-2} d^{-1} in the flooded treatment. In the intermittent irrigation, each fertilizer application increased emissions, unlike the flooded treatment, which only responded in 2 out of 5 applications (Figures 5-2c and 5-2d). Significant differences were observed between treatments for 3 out of 4 evaluated cultivars ($p < 0.05$), except for the F-67 cultivar. Overall, there were no significant differences between cultivars in CH_4 emissions ($p > 0.05$). Regarding N_2O emissions in the flooded treatment, a slight statistical difference between cultivars was evident ($p < 0.05$). No significant changes were recorded in soil pH throughout the cycle, remaining neutral, while EC showed significant variations ($p < 0.001$), indicating alterations without reaching saline soils.

5.7.3 Covariations among daily emissions, climate, and chemical conditions

The PCA among the data matrices of CH_4 emissions, N_2O emissions, soil moisture, pH, EC, and climatic conditions revealed a significant effect between intermittent irrigation and flooding treatments (57% of the explained variance; $p < 0.001$), with no significant effect between cultivars for each treatment ($p > 0.05$). Intermittent irrigation's impact on CH_4 and N_2O emissions was determined by the effect between treatments (Annex A). Axis 1 (32.9% of explained variance) highlighted that flooded treatments generate higher CH_4 emissions and that CH_4 emissions directly correlate with soil moisture, pH, and CE. Axis 2 (24.1% of variance) emphasized that the flooded treatment is associated with N_2O emissions without highlighting any correlation of N_2O emissions with the rest of the evaluated variables. The graphical representation greenhouse demonstrated that each treatment is associated with GHG.



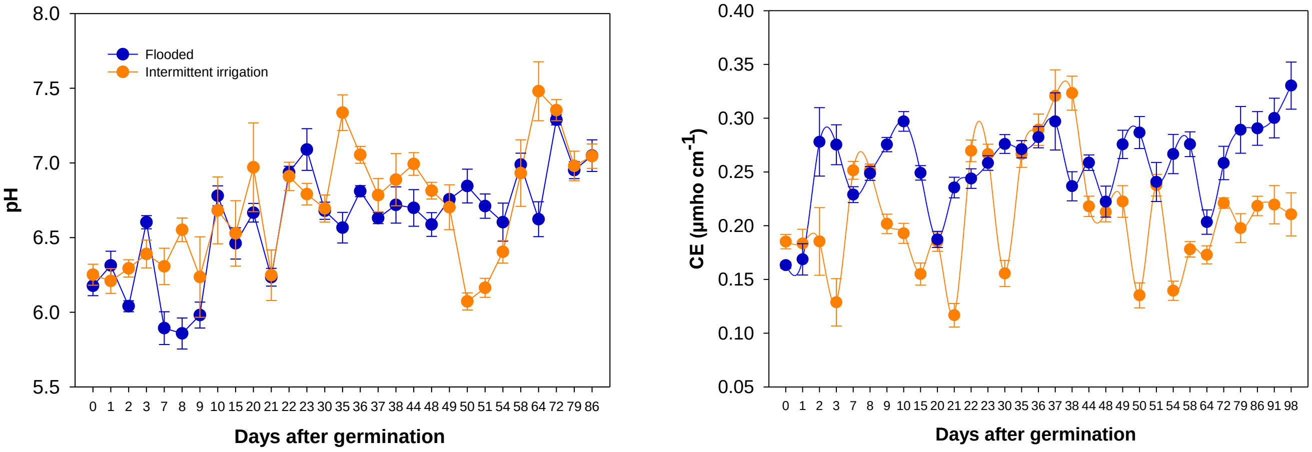


Fig. 5-2: Daily emissions of CH_4 (a and b) and N_2O (c and d), soil moisture (a and c), under flooding treatment, and (b and d) under intermittent irrigation. Additionally, soil pH and electrical conductivity are included. The CH_4 and N_2O fluxes represent averages, reflecting the daily mean of four consecutive measurement data per day for four different cultivars. Red dates on the timeline indicate fertilization events.

5.7.4 Cumulative fluxes and Global warming potential

Among the four evaluated cultivars, the commercial varieties F-67 and F-2000 exhibited the highest cumulative emissions of CH_4 in both treatments, contrasting with the heat-resistant genotypes (Table 5-3). However, when comparing the treatments, intermittent irrigation stood out for accumulating the least amount of CH_4 throughout the productive cycle, demonstrating a significant reduction of 74-75% among commercial varieties and 81-95% among genotypes compared to flooded treatment. A substantial decrease of 85% and 61% in CH_4 emissions was observed for the evaluated genotypes compared to commercial varieties for intermittent irrigation and flooded treatment, respectively.

Concerning the specific role of CH_4 in the GWP, noteworthy percentages contributing to this potential were identified, ranging from 55 to 73% for commercial varieties and 14 to 27% for genotypes in the intermittent irrigation treatment. For the flooded treatment, these percentages ranged from 77% to 94% for commercial varieties and 80 to 95% for genotypes. The statistically significant differences in cumulative CH_4 emissions among varieties and treatments ($p < 0.001$) underscore the specific relevance of intermittent irrigation in mitigating these GHG emissions.

The results of cumulative N_2O emissions did not show significant differences among varieties and treatments ($p > 0.05$). Cumulative emissions ranged from 1.66 to 2.28 kg ha^{-1} for intermittent irrigation and from 0.23 to 3.37 kg ha^{-1} for flooded treatment. Although no significant differences were observed, there was a tendency for slightly higher emissions in intermittent irrigation. The contribution of N_2O to the GWP ranged from 27 to 45% for commercial varieties and 73 to 80% for genotypes in the intermittent irrigation treatment. In contrast, for the flooded treatment, this contribution ranged from 3 to 23% for commercial varieties and 5 to 20% for genotypes. Regarding GWP, no significant differences were observed among cultivars for intermittent irrigation ($p > 0.05$), unlike the flooded treatment that showed higher GWP in the F-67 variety, with a higher contribution of N_2O. However, genotype IR 93341 presented the lowest GWP due to low cumulative N_2O emissions under flooded treatment.

T**able 5-3:** Cumulative CH_4 and N_2O emissions from rice systems of four cultivars subjected to Flooded and intermittent irrigation treatments and their contribution to the Global Warming Potential (Kg CO_2 eq. ha^{-1}). Significance Levels Indicated by Distinct Letters ($P < 0.05$), with *, **, *** Denoting Significance at P = 0.05, P = 0.01, P = 0.001, and $P < 0.001$, Respectively; NS Represents Non-Significance at the P = 0.05 Level.

Treatments	**Intermittent irrigation**			**Flooded**		
GHG / **Cultivars**	**CH_4 (kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP**	**CH_4 (kg ha^{-1})**	**N_2O (kg ha^{-1})**	**GWP**
F-67	2.77 ± 0.87$_{ab}$	2.28 ± 0.01$_{a}$	699$_{a}$	11.02 ± 2.05$_{ab}$	3.37 ± 2. 32$_{a}$	1220$_{a}$
F-2000	4.38 ± 1. 43$_{a}$	1.66 ± 0. 27$_{a}$	571$_{a}$	17.67 ± 5. 55$_{a}$	0.58 ± 0.07$_{a}$	640$_{ab}$
IR-93341	0.74 ± 0.12$_{bc}$	2.00 ± 0. 58$_{a}$	565$_{a}$	3.96 ± 0.96$_{b}$	0.23 ± 0.04$_{a}$	171$_{b}$
IR-93353	0.32 ± 0.03$_{c}$	1.89 ± 0. 61$_{a}$	526$_{a}$	7.32 ± 1.93$_{b}$	1.84 ± 0. 92$_{a}$	702$_{ab}$
Variables	**CH_4**	**N_2O**	**GWP**	**CH_4**	**N_2O**	**GWP**
Cultivars	***	NS	NS	**	NS	**
Variables	**CH_4**		**N_2O**		**GWP**	
Treatments	***		NS		**	
C x T	***		NS		*	

5.7.5 Contrasting properties of different rice cultivars

Table 5-4 presents the results of parameters related to grain quality for different cultivars and evaluated treatments. Regarding the Breakdown and Setback parameters, no significant differences were observed among cultivars when the intermittent irrigation treatment was applied. However, the flooding treatment revealed significant disparities among cultivars, with the IR-93353 genotype showing a lower value for the breakdown parameter and the F-67 variety exhibiting a lower value for the setback parameter. Significant differences were observed among cultivars for both treatments ($p<0.001$) regarding the final viscosity parameter. Commercial varieties displayed higher values for this parameter than genotypes in water management treatments. When evaluating treatments as a factor, no significant differences were found among all grain quality variables ($p>0.05$).

Table 5-4: Breakdown, final viscosity, and setback of all varieties. Mean of independent triplicate experiments ± Error. Significance Levels Indicated by Distinct Letters ($P < 0.05$), with *, **, *** Denoting Significance at P = 0.05, P = 0.01, P = 0.001, and $P < 0.001$, Respectively; NS Represents Non-Significance at the P = 0.05 Level.

Treatments	**Intermittent irrigation**			**Flooded**		
Cultivars	**Breakdown (cPs)**	**Final (cPs)**	**Setback (cPs)**	**Breakdown (cPs)**	**Final (cPs)**	**Setback (cPs)**
F-67	378 ± 24$_{a}$	2969 ± 229$_{a}$	466 ± 42$_{a}$	282 ± 12$_{c}$	3209 ± 95$_{a}$	286 ± 48$_{b}$
F-2000	454 ± 52$_{a}$	3226 ± 50$_{a}$	549 ± 62$_{a}$	457 ± 07$_{a}$	3449 ± 52$_{a}$	597 ± 26$_{a}$
IR-93341	387 ± 25$_{a}$	2748 ± 34$_{ab}$	580 ± 15$_{a}$	355 ± 12$_{b}$	2745 ± 77$_{b}$	551 ± 30$_{a}$
IR-93353	345 ± 13$_{a}$	2335 ± 07$_{b}$	486 ± 12$_{a}$	335 ± 21$_{bc}$	2390 ± 46$_{c}$	534 ± 17$_{a}$
Variables	**Breakdown**	**Final**	**Setback**	**Breakdown**	**Final**	**Setback**
Cultivar	NS	***	NS	***	***	***
Variables	**Breakdown**		**Final**		**Setback**	
Treatments	NS		NS		NS	
C x T	NS		NS		*	

5.7.6 Aboveground biomass and grain yield

Aboveground biomass accumulation remained comparatively constant across all cultivars for both treatments during the tillering, leaf primordia, and stuffing stages (Fig. 5-3). However, genotype IR-93353 exhibited lower aboveground biomass in the flowering stage than other cultivars without showing statistically significant differences between treatments (p>0.05). In the context of intermittent irrigation, rice cultivars, including F-67, F-2000, IR-93341, and IR-93353, have exhibited similar outcomes regarding the number of panicles and Full grain weight. No statistically significant differences were observed among these cultivars for both variables (p>0.05). However, under flooded conditions, significant variations were evident (p<0.01). F-67 stood out with more panicles and superior total grain weight, statistically superior to the other cultivars. In contrast, genotypes IR-93341 and IR-93353 showed inferior performance compared to F-67 and F-2000 in terms of both parameters. These results underscore the influence of irrigation type on the specific characteristics of rice development, providing valuable insights into genotypic adaptation to different cultivation conditions. In contrast, the flooding treatment and the commercial varieties F-67 and F-2000 demonstrated higher grain yields than intermittent irrigation and genotypes IR93341 and 93353 (Table 5-5). Significant differences were observed among cultivars and treatments (p<0.001). Genotype IR 93353 recorded the lowest yield in both treatments, concurrently indicating a decline in aboveground biomass during the flowering stage.

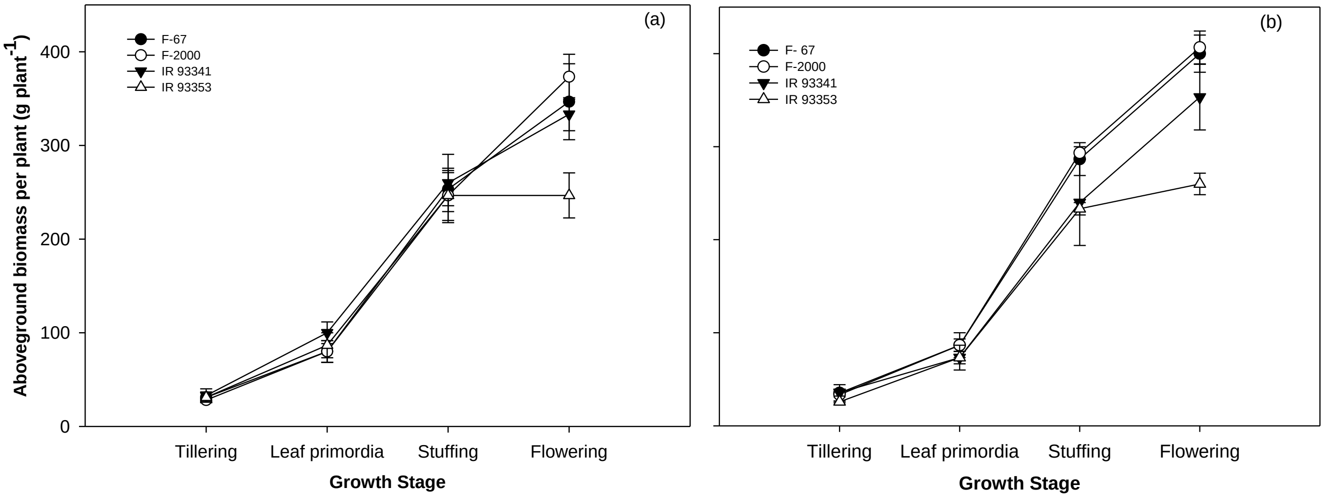


Fig. 5-3: Aboveground biomass accumulation by the four rice cultivars at four growing stages (tillering, Leaf primordia, stuffing, and flowering). a) intermittent irrigations, b) flooding treatment. The error bars represent the standard error of the means.

Table 5-5: Comparative Analysis of Rice Grain Yield Performance and # panicles and full grain weight: Assessing Two Treatment Types and cultivars. Significance Levels Indicated by Distinct Letters ($P < 0.05$), with *, **, *** Denoting Significance at $P = 0.05$, $P = 0.01$, $P = 0.001$, and $P < 0.001$, Respectively; NS Represents Non-Significance at the $P = 0.05$ Level.

Treatments	**Intermittent irrigation**			**Flooded**		
Cultivars	**# panicles m^{-2}**	**Total grain weight (g)**	**Grain yield (Mg ha^{-1})**	**# panicles m^{-2}**	**Total grain weight (g)**	**Grain yield (Mg ha^{-1})**
F-67	485 ± 39$_a$	6339 ± 1382$_a$	5.42 ± 0.7$_{ab}$	553 ± 7$_a$	8597 ± 424$_a$	8.21 ± 0.4 $_a$
F-2000	483 ± 20$_a$	8484 ± 1421$_a$	6.06 ± 0.6 $_a$	460 ± 29$_b$	7834 ± 577$_a$	7.63 ± 0.6 $_a$
IR-93341	381 ± 09$_a$	4728 ± 356$_a$	3.67 ± 0.1$_b$	388 ± 08$_b$	5706 ± 282$_b$	4.13 ± 0.4$_b$
IR-93353	397 ± 17$_a$	5828 ± 503$_a$	3.64 ± 0.4$_b$	399 ± 22$_b$	4921 ± 335$_b$	3.89 ± 0.1$_b$
Cultivars	NS	NS	*	**	***	***
Variable	**# panicles**		**Total grain weight (g)**		**Grain yield**	
Treatments	***		***		**	
C x T	NS		NS		*	

5.8 Discussion

Given the prevalence of CH_4 release originating from rice cultivation in flooded soils into the atmosphere, along with the consideration of N_2O emissions from nitrogen fertilization (Kritee et al., 2018; Tariq et al., 2017), previous research has shown that genetic variations in rice influence both CH_4 (Chirinda et al., 2018; Gogoi et al., 2008; Habib et al., 2023; Simmonds et al., 2015; Soremi et al., 2023) and N_2O emissions (Baruah et al., 2010; Chen et al., 2019; Yulianingsih et al., 2022) in flooded or intermittently irrigated rice systems. The current research supported the hypothesis that the experimental heat-resistant genotypes reduce CH_4 emissions under intermittent or flooded conditions. However, the evaluated cultivars showed no correlation with N_2O emissions, indicating that cumulative N_2O emissions depend more on soil moisture conditions for applying synthetic nitrogen fertilizers. Our results demonstrated that proper water management close to field capacity and saturation can exhibit a similar range of emissions as continuously flooded rice systems, as evidenced by Loaiza et al. (2024) and Ogawa et al. (2022).

Although we have investigated various parameters related to plant development, with a particular focus on cultivars and water management, we have observed a significant correlation between daily CH_4 emissions during the plant's peak development, specifically in the tillering and flowering stages. This pattern is evident in both flooded and intermittent irrigation treatments. This finding supports previous research that identified disparities in phenotypic characteristics, such as aboveground biomass and aerenchyma development, as key factors contributing to variations in CH_4 emissions among cultivars (Aulakh et al., 2001; Bhattacharyya et al., 2019; Huang et al., 1997; Sun et al., 2015). In intermittent irrigation treatment, aeration throughout the productive cycle reduced soil pore water content, facilitating sufficient oxygen entry that favored methanotrophic processes. This led to the organic carbon in the soil oxidizing to CO_2 instead of CH_4, as demonstrated in previous research (Bo et al., 2022; Sun et al., 2016; Yang et al., 2012). In flooded production systems, reduced CH_4 emissions were observed in genotypes, suggesting an expected decrease in CH_4 oxidation in anaerobic soils. However, it is essential to note that the rice aerenchyma system also facilitates the transport of atmospheric oxygen to the rhizosphere, stimulating root respiration and thereby contributing to CH_4 oxidation (Gerard & Chanton, 1993; Kirk et al., 2019; Rajendram et al., 2023).

We initially hypotheses that different cultivars and water management strategies could influence the pattern of N_2O emissions, expecting that this would significantly change cumulative emissions, effectively reducing the total emissions. However, the results only partially support this hypothesis, indicating that proper water management during fertilizer application promotes the solubilization of these compounds. Our findings reveal that N_2O emissions under intermittent irrigation and high-volatilization fertilizer sources fall within the emission range observed in flooded systems, demonstrating their effectiveness in suppressing volatilization. This support is grounded in previous research, such as the studies by Riya et al. (2017) and Islam et al. (2020), which reveal that fluctuations in soil water levels create microaerobic conditions, avoiding abrupt shifts between aerobic and anaerobic conditions, essential for nitrification and denitrification processes. Although this support has been confirmed, it is essential to note that the hypothesis related to the influence of genotypes on the N_2O emission pattern still needs to be fully realized. The results did not support the idea that genotype selection would significantly impact reducing N_2O emissions. In other words, while water management proved effective, genotypic variability did not have the expected effect on mitigating N_2O emissions in agriculture. This finding suggests that, in this specific context, water management may be more decisive than genotype selection in reducing N_2O emissions.

The application of urea under high temperatures in an intermittent irrigation system, with fertilization conducted under soil moisture conditions close to saturation and field capacity, exhibited no significant differences in net N_2O emissions compared to fertilization under flooding conditions. This suggests that ammonium volatilization was comparable in both water management systems. Traditionally, applying urea in rice fields under intermittent irrigation and high temperatures poses challenges due to the high susceptibility of urea-based fertilizers to ammonia volatilization (Roger et al., 2018; Jones et al., 2020). Several studies (Bouwman et al., 2002; Jones et al., 2013; Saggar et al., 2013; Siman et al., 2020) have demonstrated that the application of synthetic fertilizers, such as urea, under high temperatures and dry soil conditions can result in NH_4^+ volatilization of approximately 10 to 60%, consequently increasing N_2O emissions. However, research suggests that maintaining a high-water level in rice systems can prevent ammonium volatilization and thus reduce N_2O emissions. Previous studies (Bhagat et al., 1996; Milford et al., 2001; Willians et al., 1990) have shown that continuously flooded rice systems effectively suppress ammonium volatilization. Continuous water coverage can dilute ammonium concentrations (Hayashi et al., 2006; Jayaweera & Mikkelsen, 1991). Our results indicate that despite applying a highly volatile nitrogen source under high temperatures, it was only necessary to maintain soil moisture between saturation and field capacity to match ammonium volatilization and, thus, N_2O emissions compared to a flooded rice system. Similar findings were reported by Li et al. (2008), Xu et al., (2012) and Zhou et al., (2008), suggesting that water management with flooding-dry cycles is effective in controlling ammonium volatilization and reduction of N_2O emissions.

Water management practices significantly impacted the cumulative emissions of CH_4 and N_2O, and the GWP in rice cultivation systems. In contrast, no effect attributable to cultivars was identified in N_2O emissions. This study revealed that, in flooded systems, GWP was primarily associated with CH_4 emissions, supporting previous research that has established positive connections between GWP in flooded rice systems and CH_4 emissions (Bayer et al., 2015; Camargo et al., 2018; Zschhornack et al., 2018). On the other hand, intermittent irrigation effectively reduced GWP by significantly decreasing CH_4 emissions, keeping the contribution of N_2O at a lower level. This result aligns with research demonstrating the reduction of CH_4 emissions due to soil aeration conditions during the productive cycle (Cowan et al., 2021). Overall, our findings highlight the importance of CH_4 emissions in flooded rice systems and underscore the need to implement gas mitigation measures. In this study, both genotypes resistant to elevated temperatures and water management proved effective strategies for mitigating CH_4 emissions and GWP.

Even though cultivars did not show differences in aboveground biomass in both water management treatments during tillering, leaf primordia, and booting stages, yields were lower for the genotypes, especially for genotype IR 93353, where a significant reduction in biomass was evident during the flowering stage for both treatments. This phase is crucial for determining crop yields, as it is also the sensitive period to damage caused by high diurnal and nocturnal temperatures (Yang et al., 2008). Our results showed that high temperatures during these critical stages of grain formation and filling would lead to a shortening of the grain-filling period, reducing the size of endosperm cells, resulting in lower grain weight and yield (Kobata et al., 2004; Morita et al., 2005), according to our performance results for genotypes, high nocturnal temperatures during the reproductive and maturation phases contributed to yield reduction, attributed to a decrease in grain weight compared to commercial varieties. Numerous studies support our findings, demonstrating that productive systems under nocturnal warming affect grain filling and weight, reducing yields by 2 to 11% for every degree Celsius of increased temperature without significant changes in physiological responses at the leaf level during the day (Huang et al., 2021; McAusland et al., 2023; Peng et al., 2004; Shi et al., 2017; Zhang et al., 2013). Similarly, an increase in daytime temperatures above 3°C can dramatically reduce rice yields due to a decrease in grain weight and quality (Hussain et al., 2019; Krishnan et al., 2011; Wang et al., 2023).

Our findings indicate that, in both treatments, the type of fertilizer and soil moisture conditions during application showed no significant differences in N_2O emissions, nor were they associated with crop yield. However, a marked disparity in yields was observed when comparing intermittent and flood irrigation methods. Specifically, the yield of varieties and genotypes resistant to high temperatures was significantly higher in flood-irrigated plots than those under intermittent irrigation. According to the literature review, the effects of intermittent or water-efficient irrigation systems on grain yields may vary, with some suggesting similar or slightly higher yields than flood systems (Avila et al., 2015; Massey et al., 2014; Nugroho et al., 1994 and 2018; Thakur et al., 2018). However, evidence demonstrates that intermittent irrigation systems may reduce crop yields (Carrijo et al., 2017; Hasan et al., 2015; Tarlera et al., 2016). Nonetheless, beyond the dichotomy between irrigation methods, it is crucial to focus on soil water management during critical stages of the growth cycle, such as flowering and grain filling, which are particularly susceptible to water stress. Our study's arid and hot climatic conditions during the evaluation period emphasize the importance of maintaining an optimal soil moisture level close to saturation to prevent soil dehydration. This underscores the necessity for careful control of soil water content, especially during critical stages of crop development, to maximize yield in adverse climatic conditions.

Intermittent and flooded irrigation treatments also influenced rice quality. The parameters of final viscosity (VF), setback, and breakdown showed distinct characteristics among the cultivars IR-93353, IR-93341, F-67, and F-2000 are highlighted. In the intermittent irrigation treatment, the cultivar IR-93341 is more susceptible to starch breakdown, as evidenced by the high breakdown rate. This phenomenon may have implications for the final texture of cooked rice, affecting its culinary quality by causing a more pronounced starch breakdown during cooking (Chun et al., 2015). On the other hand, the cultivar F-2000 exhibits elevated values of VF and setback, suggesting increased starch retrogradation (Shekhar et al., 2019). In contrast, the high VF value indicates lower amylose content (Sasaki et al., 2000). This process can influence the texture and consistency of cooked rice, providing a firmer and stickier texture. In contrast, under flooded treatment, the cultivar F-2000 stands out again with high values of VF and setback, indicating consistent starch retrogradation (Ardhiyanti & Indrasari, 2021). The cultivar F-67, on the other hand, shows a decrease in Breakdown under this treatment, which could indicate lower susceptibility to starch breakdown under flooded conditions.

The genotypes IR-93353 and IR-93341 exhibit unique VF, setback, and breakdown responses under both treatments. IR-93353 shows lower values in these parameters, suggesting more excellent starch stability against breakdown. According to Kesarwani, et al., (2016), low breakdown values indicate high protein content. These results could have positive implications for the quality of cooked rice, providing a more consistent texture. The findings indicate that genotypes IR-93353 and IR-93341 exhibit characteristics that could suggest improved rice quality in certain aspects compared to the commercial varieties F-67 and F-2000, depending on specific irrigation conditions. High temperatures throughout the production cycle could seriously affect the physicochemical characteristics of rice starch, resulting in poor rice quality (Chun et al., 2015; Mishra et al., 2017;), which supports the results obtained with genotypes resistant to high temperatures that showed better grain quality compared to commercial varieties. The final texture of cooked rice, influenced by starch breakdown susceptibility and retrogradation, emerges as a critical aspect to consider when selecting irrigation strategies to optimize rice quality across different cultivars. These findings offer valuable insights for agronomic decision-making aimed at enhancing rice quality in various cultivation scenarios.

The primary objective of rice farmers is to maximize crop yields while preserving grain quality. Our results show that adopting genotypes resistant to elevated temperatures can significantly reduce CH_4 emissions, but more is needed to achieve the food security goal fully. However, the genotypes show great potential, serving in terms of grain quality as a benchmark for further work in developing genotypes with increased resistance to extreme weather conditions without compromising yield. The integration of these practices holds promise for sustainable and environmentally friendly rice production, contributing to global efforts to address greenhouse gas emissions in agriculture.

5.9 Conclusions

In conclusion, this study, provided insights into GHG emissions dynamics, specifically CH_4 and N_2O, from two commercial rice varieties with mitigation potential and two heat-resistant genotypes under flooding and intermittent irrigation treatments in an especially arid season in Colombia. Daily methane emissions were influenced by drainage events for water control and fertilizer application, ensuring reduced CH_4 emissions in the intermittent irrigation treatment. The evaluated genotypes demonstrated the potential to decrease CH_4 emissions significantly. The daily CH_4 emissions of cultivars under both water management treatments indicated that the critical emissions point occurs during the maturation phase, highlighting strategic opportunities for implementing mitigation strategies in direct-seeded rice production systems.

N_2O emissions in the assessed cultivars were influenced by soil moisture conditions and the optimal timing for fertilizer application, without exhibiting evidence that genotypes impacted the reduction of this gas. Additionally, within intermittent irrigation systems and with the utilization of high volatilization fertilizers, N_2O emissions were observed to be comparable to those in flooded systems, indicating an effective suppression of volatilization. This discovery highlights the significance of not only considering agricultural practices but also environmental conditions and soil management techniques in mitigating greenhouse gas emissions in agriculture. The contribution of N_2O to the GWP varied among cultivars and treatments, emphasizing the complexity of these emissions in rice cultivation. The study highlighted that genotypes have the potential to reduce CH_4 emissions significantly, but there is a risk of below-average yields. In order to promote low-CH_4-emitting rice cultivars further, additional research is needed to generate further evidence supporting the classification of these genotypes as clean development technologies adaptable to atypical dry conditions. While low absolute emissions may result from a low-yielding rice variety (per unit area), farmers may need more land to produce enough rice to alleviate rice scarcity in the region.

Furthermore, the evaluation of grain quality parameters showed the influence of water management treatments on specific traits. Although no significant differences were observed in grain quality variables under intermittent irrigation, disparities among cultivars emerged under flooding treatment, indicating the importance of considering environmental and genetic factors in rice cultivation. This study provides valuable information on the complex interactions between greenhouse gas emissions, water management practices, and rice cultivars, contributing to our understanding of sustainable rice production in the context of changing climatic conditions. The findings underscore the potential of intermittent irrigation as a strategy to mitigate CH_4 emissions while maintaining grain quality in rice cultivation.

Further research is warranted to investigate the genetic and environmental factors influencing emissions and yield trade-offs. It would be crucial to explore the scalability and feasibility of implementing intermittent irrigation on a larger scale and assess its economic implications. Moreover, investigating the long-term impacts of different water management strategies on soil health and overall ecosystem resilience should be considered. This paper aims to stimulate further discussion and research in these directions, fostering a holistic approach to sustainable rice production in the face of climate change challenges.

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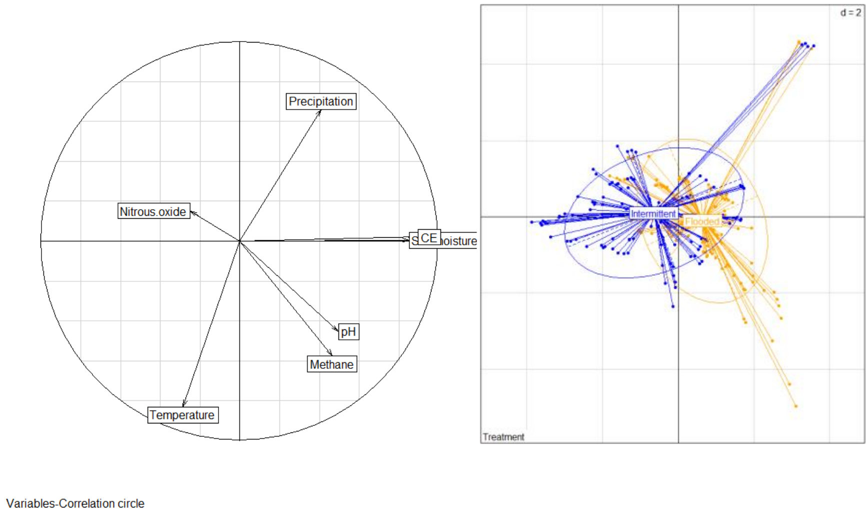
5.12 Annex

Annex A: Results of Principal Component Analysis (PCA) for the relationship between daily emissions of CH_4, N_2O and climatic conditions.



Treatments	Intermittent irrigation Flooded	
Variables	**Comp 1**	**Comp 2**
CH_4	0.4653	- 0.5750
N_2O	- 0.2525	0.1521
Soil moisture	0.8521	0.0047
pH	0.4953	- 0.4537
CE	0.8980	0.0207
Temp.	- 0.2870	- 0.8321
Precipitation	0.4071	0.6615
Total variance	70%	

Fig. 5-1S. Correlation circle of indicators with factors PCA 1 and 2 (left), and projection of individual plots of each treatment on the F1/F2 plane defined by PCA on indicators.

6 Future work

Building upon the findings of our study, several avenues for future research emerge, each presenting new opportunities for investigation and potential doctoral theses. Three critical areas of inquiry are outlined below:

1. Aerenchyma Development and Varietal Adaptation: Further exploration into the role of aerenchyma development in the stems and roots of rice varieties with mitigation potential is essential. Investigating how these varieties adapt to diverse climatic conditions within different rice-growing regions and production systems will deepen our understanding of their resilience and effectiveness in reducing methane and nitrous oxide emissions. This line of research could lead to the development of tailored cultivation practices optimized for specific environmental contexts.

2. Methodology for Estimating Emission Factors: Developing a robust methodology for estimating emission factors at the producer level is imperative. By considering diverse rice production

systems, climatic variations, and soil conditions, such a methodology aims to identify representative regions suitable for quantifying emission factors. This effort will contribute to more accurate emissions calculations, enhancing the precision of national greenhouse gas inventories.

3. Soil Microorganism Dynamics and Emissions: Exploring the dynamics of soil microorganisms and emissions presents a promising area of research. Investigating how biological processes in the soil, influenced by factors such as pest and disease control and planting frequency, affect carbon emission and capture could provide valuable insights. Similarly, examining the impact of pest and disease management on the diversity and abundance of methanotrophic and methanogenic bacteria and Nitrobacter and Nitrosomas bacteria involved in soil nitrification and denitrification processes could yield significant findings. This research may inform strategies to optimize soil health and mitigate greenhouse gas emissions while ensuring food security and economic efficiency.

By addressing these research gaps, future studies can advance our understanding of greenhouse gas emissions in rice cultivation and inform the development of more effective mitigation strategies tailored to specific environmental contexts and production systems.

7 Publications

The development of this research has allowed the following scientific publications as partial progress of the thesis and other experiments.

7.1 Journal

- Publication in the scientific journal ELSEVIER/Agriculture, Ecosystems & Environment (Q1)

Loaiza, S., Verchot, L., Valencia, D., Guzmán, P., Amezquita, N., Garcés, G., Puentes, O., Trujillo, C., Chirinda, N., Pittelkow, C. M. Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production. Agriculture, Ecosystems & Environment, 360, 1-13. https://doi.org/10.1016/j.agee.2023.108787.

https://www.sciencedirect.com/science/article/pii/S0167880923004462

- Publication submitted in the science journal ELSEVIER/Field Crops Research.

Loaiza, S., Verchot, L., Valencia, D., Garcés, G., Puentes, O., Ardila,J.,Trujillo, C., Chirinda, N., Pittelkow, C. M. Identifying rice varieties for mitigation of methane and nitrous oxide emissions in two regions of Colombia. Field Crops Research.

- Publication submitted in the science journal Grassland Research. I utilized the skills acquired as a PhD student to expand my scientific analysis capacity, particularly in experiments related to soil organic carbon.

Loaiza, S., Costa Jr. C., Da silva, M., Chirinda, N., Rao, I., Arango, J., Tapasco, J., Hyman, G. (2024). Soil organic carbon changes in contrasting grazing lands in two regions of Colombia. Grassland research. [Under review].

7.2 Science communications

Publication in a general interest magazine of the rice sector: Rice Magazine

- Actions toward the mitigation of greenhouse gas derived from rice cultivation in Casanare.
- Advances that contribute to reducing the greenhouse gas emissions in rice.

https://fedearroz.com.co/es/publicaciones/revista-arroz/copies-of-the-magazine-rice/

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