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Artigo

SEASONAL METHANE EMISSIONS IN PADDY RICE WITH TWO CULTIVARS IN THE SOUTHEAST OF BRASIL

EMISSÕES SAZONAIS DE METANO EM ARROZ IRRIGADO POR INUNDAÇÃO COM DUAS CULTIVARES NO SUDESTE DO BRASIL

EMISIONES ESTACIONALES DE METANO EN EL ARROZ DE RIEGO CON DOS CULTIVARES EN EL SURESTE DE BRASIL

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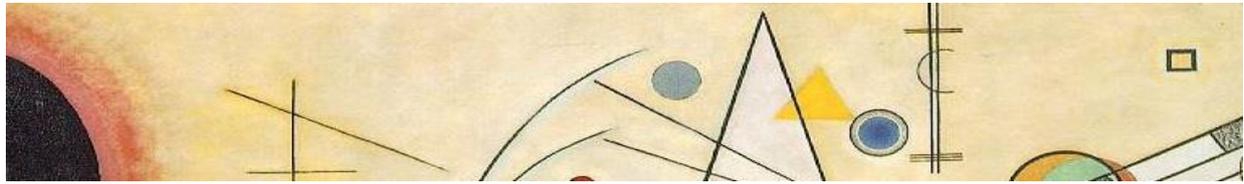
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ABSTRACT: Flooded rice cultivation represents one of the main global anthropogenic sources of methane (CH₄), a major greenhouse gas that strongly affects atmospheric photochemistry. CH₄ production and emissions are influenced by several factors, such as climate, organic residues in water and soil, root exudates, water management, soil physicochemical and biological characteristics, and the cultivar. There are few studies in Brazil focused on the influence of cultivars on CH₄ emissions. This experiment aimed to evaluate seasonal methane emissions using two varieties, IAC 105 and Epagri 106, in a pre-germinated cultivation system with a continuous water regime in the municipality of Pindamonhangaba, São Paulo. Methane emissions were quantified using the static chamber method and chromatographic analysis. Methane emissions increased with increasing tillering, with the main peak occurring at flowering. Despite the different life cycles of the varieties, no significant difference was found between seasonal methane emissions (117.91 kg CH₄ ha⁻¹ for IAC 105 and 108.92 kg CH₄ ha⁻¹ for Epagri 106). These emissions were not related to plant height, number of tillers, and grain yield. An emission factor of 0.98 kg CH₄ ha⁻¹ day⁻¹ was estimated for IAC 105 and 0.95 kg CH₄ ha⁻¹ day⁻¹ for Epagri 106. The yield-scaled *p*GWP (*Yp*GWP) was estimated at 1.02 kg CO₂eq kg⁻¹ grain for both cultivars.

KEYWORDS: methane, flooded rice, pre-germinated system, IAC 105, Epagri 106.

RESUMO: O cultivo de arroz irrigado por inundação representa uma das principais fontes antrópicas globais de metano (CH₄), um importante gás de efeito estufa que afeta fortemente a fotoquímica da atmosfera. A produção e a emissão de CH₄ são influenciadas por diversos fatores, como o clima, resíduos orgânicos na água e no solo, exsudatos das raízes, manejo de água, características físico-químicas e biológicas do solo e a cultivar. Há poucos estudos no país focados na influência de cultivares nas emissões de CH₄. Este experimento objetivou a avaliação das emissões sazonais de metano utilizando-se duas cultivares de arroz, IAC 105 e Epagri 106, em sistema de cultivo pré-germinado, com regime contínuo de água, no município de

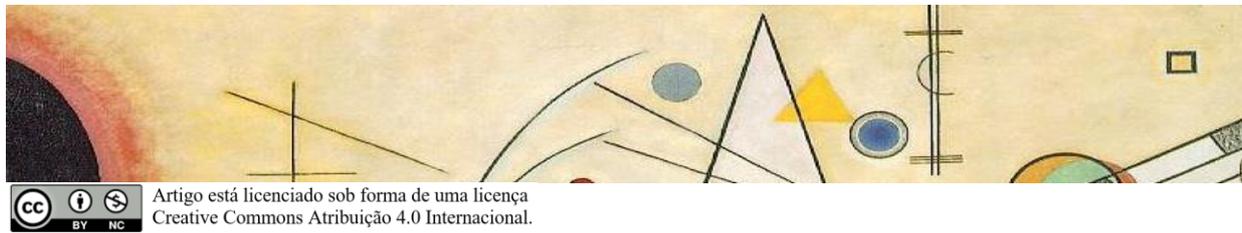


Pindamonhangaba, SP. A quantificação das emissões de metano foi realizada utilizando o método de câmara estática e análise cromatográfica. As emissões de metano aumentaram com o aumento do perfilhamento das plantas, com pico principal ocorrendo na floração. Apesar dos diferentes ciclos de vida das cultivares, não foi encontrada diferença significativa entre as emissões sazonais de metano ($117,91 \text{ kg CH}_4 \text{ ha}^{-1}$ para a IAC 105 e $108,92 \text{ kg CH}_4 \text{ ha}^{-1}$ para a Epagri 106). Estas também não se relacionaram com a altura de planta, número de perfilhos, e com a produção de grãos. Foi estimado um fator de emissão de $0,98 \text{ kg CH}_4 \text{ ha}^{-1} \text{ dia}^{-1}$ para a cultivar IAC 105 e de $0,95 \text{ kg CH}_4 \text{ ha}^{-1} \text{ dia}^{-1}$ para a Epagri 106. O potencial de aquecimento global parcial ($p\text{GWP}$) escalonado pelo rendimento ($Yp\text{GWP}$) foi estimado em $1,02 \text{ kg CO}_2\text{eq kg}^{-1}$ de grãos para ambas as cultivares.

PALAVRAS-CHAVE: metano, arroz irrigado por inundação, sistema pregerminado, IAC 105, Epagri 106.

RESUMEN: El cultivo de arroz de Riego representa una de las principales fuentes antropogénicas globales de metano (CH_4), un importante gas de efecto invernadero que afecta fuertemente la fotoquímica atmosférica. La producción y emisiones de CH_4 están influenciadas por varios factores, como el clima, los residuos orgánicos en el agua y el suelo, los exudados radiculares, el manejo del agua, las características fisicoquímicas y biológicas del suelo y el cultivar. Pocos estudios en Brasil se han centrado en la influencia de los cultivares en las emisiones de CH_4 . Este experimento tuvo como objetivo evaluar las emisiones estacionales de metano utilizando dos cultivares, IAC-105 y Epagri-106, en un sistema de cultivo pregerminado con un régimen hídrico continuo en el municipio de Pindamonhangaba, São Paulo. Las emisiones de metano se cuantificaron utilizando el método de cámara estática y análisis cromatográfico. Las emisiones de metano aumentaron con el aumento del macollamiento, con el pico principal ocurriendo en la floración. A pesar de los diferentes ciclos de vida de las cultivares, no se encontraron diferencias significativas entre las emisiones estacionales de metano ($117,91 \text{ kg CH}_4 \text{ ha}^{-1}$ para IAC 105 y $108,92 \text{ kg CH}_4 \text{ ha}^{-1}$ para Epagri 106). Estas emisiones tampoco se relacionaron con la altura de la planta, el número de macollos ni el rendimiento de grano. Se estimó un factor de emisión de $0,98 \text{ kg CH}_4 \text{ ha}^{-1} \text{ día}^{-1}$ para IAC 105 y de $0,95 \text{ kg CH}_4 \text{ ha}^{-1} \text{ día}^{-1}$ para Epagri 106. El potencial de calentamiento global parcial ($p\text{GWP}$) escalado por rendimiento ($Yp\text{GWP}$) se estimó en $1,02 \text{ kg CO}_2\text{eq kg}^{-1}$ de grano para ambas cultivares.

PALABRAS CLAVE: metano, arroz de riego, sistema pregerminado, IAC 105, Epagri 106.

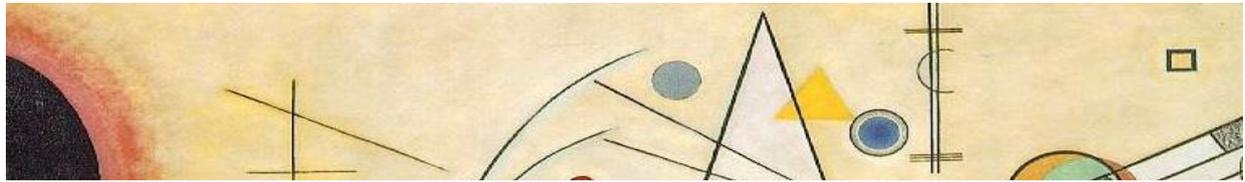


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1. Introduction

Methane (CH_4), one of the main greenhouse gases (GHG), has a global warming potential approximately 28 times greater than carbon dioxide (CO_2) over a 100-year horizon. Among anthropogenic sources, flood-irrigated rice fields are estimated to be responsible for approximately 8% of global methane emissions, estimated at 380 Tg CH_4 in 2017 (Saunois *et al.*, 2020). Flooded rice cultivation promotes the formation of an anaerobic environment in the soil, resulting in the production of CH_4 as an end product of the decomposition of organic compounds by methanogenic bacteria (Lai, 2009). In these environments, methane is released through three pathways: 1) CH_4 boiling from the soil, 2) diffusion at the soil-water interface, and 3) the aerenchyma (vascular tissue) of rice plants (Le Mer; Roger 2001), which constitutes the main emission pathway. Water management plays an important role in CH_4 emissions from rice fields (Moterle *et al.*, 2013; Darikandeh *et al.*, 2025), as well as the quality and quantity of soil organic matter (Humphreys *et al.*, 2018), cropping systems (Amadori *et al.*, 2022) and type of cultivars (Zheng *et al.* 2014). Other factors that influence CH_4 emissions include climatic conditions, root exudate production, soil physicochemical and biological properties, and plant physiology (Sass; Fisher Jr. 1998).

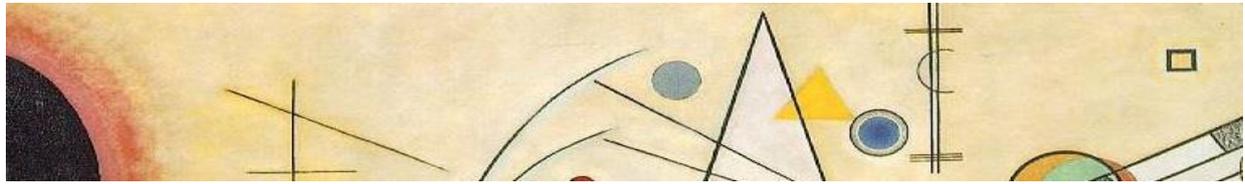
Rice varieties with lower aboveground and belowground biomass were associated with lower CH_4 emission potential and higher grain yield (Gorh & Baruah 2019). Similarly, other authors found a strong correlation between CH_4 emissions and aboveground biomass, root length, root volume, and root surface area (Soremi *et al.* 2023). Traits such as plant height, number of tillers, and leaf area index were also associated with CH_4 emissions in rice



fields (Ding *et al.* 1999, Gogoi *et al.* 2005). Qin *et al.* (2015) also found a significant correlation between methane fluxes and the number of tillers and stalk biomass, and a negative correlation with plant height and number of panicles, indicating that the number of canals (aerenchyma), and not plant size or biomass determines methane transport. Other authors found no positive correlation between methane emissions and plant weight (Watanabe *et al.*, 1995). In addition, Gutierrez *et al.* (2013) reported no correlation between any plant growth parameters (e.g., straw production, total aboveground biomass, plant height, number of tillers, number of grains per panicle) and methane emissions. These various studies demonstrate that further investigations are needed to elucidate the relationships between CH₄ flux and plant characteristics under local conditions.

In Brazil, more than 80% of rice production comes from paddy areas, whose basic cultivation system is flood irrigation (Mascarenhas *et al.*, 2020). Flooded rice cultivation systems used in the country include conventional systems, no-till farming, minimum tillage, seedling transplanting, and pre-germinated systems (Adequação..., 2014). The latter type of management is characterized by the use of pre-germinated seeds in previously flooded soil.

Paddy rice fields in Brazil have been evaluated mainly for the influence of soil and water management (Moterle *et al.* 2013, Bayer *et al.* 2014, Zschornack *et al.* 2016) on methane emissions, and few studies have focused on assessing CH₄ emissions based on the use of different rice varieties (Silva *et al.* 2014, Nunes *et al.* 2022). A better understanding of the potential effects of different varieties can help farmers and policymakers select the best rice varieties for environmental and economic benefits. Therefore, the objective of this study was to quantify seasonal CH₄ emissions from flooded rice soils cultivated with two distinct cultivars, IAC 105 and Epagri 106, and to compare the resulting CH₄ emission factors, in order to identify their potential contributions to gas emissions.



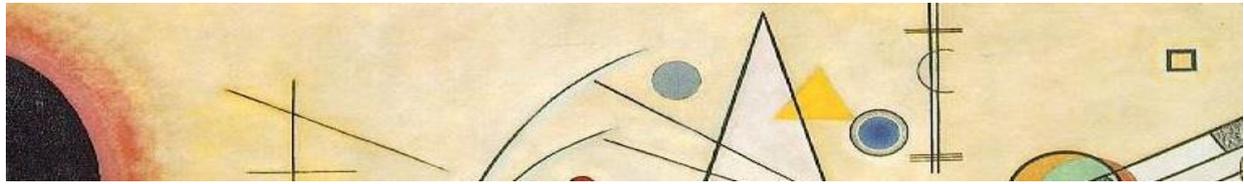
2. Material and Methods

2.1 Study Area and Crop and Soil Management

The study was carried out in 2015 at the experimental site of the Paraíba Valley Regional Development Center of the São Paulo Agribusiness Technology Agency (APTA) in the municipality of Pindamonhangaba, SP, São Paulo State, Brazil (22°55' S, 45°30' W). This municipality is located in the Paraíba Valley region, where rice production in the state is concentrated (Lima; Villela, 2016). The climate is Cwa, according to the Köppen classification, with an average maximum temperature above 22°C and an average minimum temperature below 18°C. The study area has been used for flooded rice cultivation for decades. The soil is classified as Haplic Gleysol (Embrapa, 2013), with $39.4 \pm 2.5\%$ sand, $24.9 \pm 2.4\%$ silt, and $35.6 \pm 0.3\%$ clay, and a soil bulk density of $1.3 \pm 0.3 \text{ g cm}^{-3}$.

The experimental design consisted in randomized blocks with two cultivars (IAC 105; Epagri 106) with three replicates. The study area was less than one hectare, with the cultivars planted in plots of approximately 125 m², in broadcast pre-germinated cultivation with continuous water management. Seed density was 140 kilograms per hectare for both cultivars. The IAC 105 cultivar, developed by the Agronomic Institute of Campinas, has an intermediate life cycle, with an average time of maturity of 135 days and an average height of 92 centimeters (IAC 2005). Epagri 106 cultivar, developed by the Agricultural Research and Rural Extension Company of Santa Catarina, has a short cycle, with an average time of maturity of 114 days and an average height of 97 centimeters (Vieira *et al.*, 2007).

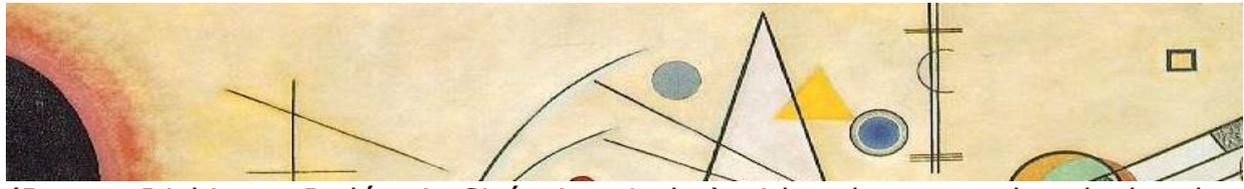
The soil was flooded on January 30th, 2015, with mud formation on February 6th. Sowing was carried out on February 13th, and germination occurred four days later (February 17th). Initially, a 6-cm water depth was established and subsequently it was maintained at an average of 14 cm until



drainage. On March 4th, the plots were sprayed with Furadan. Fertilization was applied on March 4th (250 kg of NPK ha⁻¹ in the 12-06-12 formulation), at 33 days after flooding (DAF) and on March 25th (250 kg of NPK ha⁻¹ in the 20-05-20 formulation), at 54 DAF. Urea, potassium chloride, and single superphosphate were used as sources of N, K, and P, respectively. Anthesis of Epagri 106 and IAC 105 occurred on May 3th (93 DAF) and May 14th (104 DAF), respectively. Maturation of Epagri 106 and IAC 105 was observed on June 3th (124 DAF) and June 13th (134 DAF), respectively. Soil drainage occurred on June 4th (125 DAF) for both cultivars. Harvesting of Epagri 106 and IAC 105 occurred on June 11th (132 DAF) and June 22th (143 DAF), respectively.

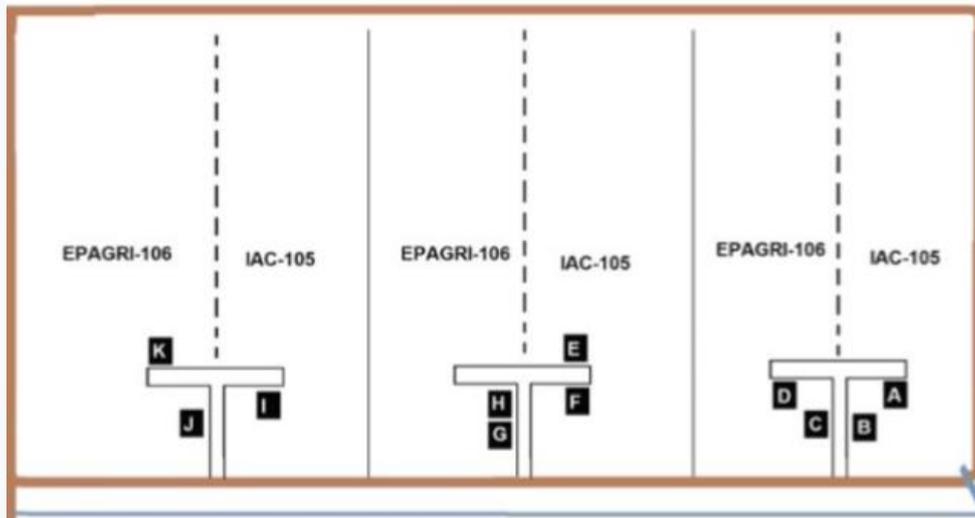
2.2 Quantification Method

The gas collection method was the static chamber (IAEA *et al.*, 1992, Sass *et al.*, 2002, Lima *et al.*, 2023). One day before sampling, eleven gas collection chambers were randomly positioned in the plots. Walkways were used to allow access to the flooded field. The chambers were identified with letters from A to K in a clockwise direction, as shown in Figure 1. Sampling campaigns were conducted at least once a week using 60 cm x 60 cm aluminum chambers. In total, samples were collected on 21 dates throughout the growing season and five dates after harvest. The chamber consisted of three components: 1) a 20 cm base, fixed to the soil throughout the experiment, with spherical openings for water circulation that was sealed at the time of collection; 2) 25 cm extenders, which were placed on the base as the plant grew; and 3) a removable top, which was positioned at the time of collection. The seal between these parts was made with water. The top had internal fans for air homogenization; a hole for a digital thermometer to record the internal temperature at the time of gas collection (°C); an opening for a rubber septum with a hose connection to a 60 mL syringe



(Becton Dickinson Indústria Cirúrgicas Ltda.) with a three-way luer lock valve for gas sampling; and an opening for a rubber septum to equalize the internal air after the top is positioned on the base or extender (Batista *et al.*, 2015).

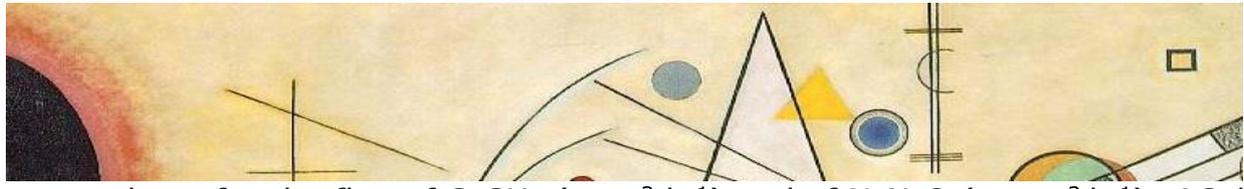
Figure 1. Diagram (not to scale) of the positioning of the gas collection chambers, the layout of the walkways and the distribution of the cultivars. The letters indicate the positions of the chambers



Source: (Adapted from Batista *et al.*, 2015).

Gas sampling was performed at intervals of 5, 10, 15, 20, and 25 minutes, with the internal fan turned on 30 seconds before each sampling time. The gas was extracted by pumping the syringe for the gas collection. The gas samples were then transferred to 12 mL vacuum glass vials (Labco Exetainer) using 0.45 x 13 mm hypodermic needles (Becton Dickinson Indústria Cirúrgicas Ltda.). The samples were taken to the laboratory for analysis on a gas chromatograph (Shimadzu, model GC 2014 Greenhouse Gas Analyzer). The carrier gas was nitrogen, and the makeup gas was P4 (argonium + methane). CH₄ fluxes were calculated from the linear increase in gas concentration inside the chamber during gas sampling, using Equation 1:

$$f = \frac{\Delta C}{\Delta t} \frac{PV}{RT} \frac{M}{A} \quad (\text{Eq. 1})$$



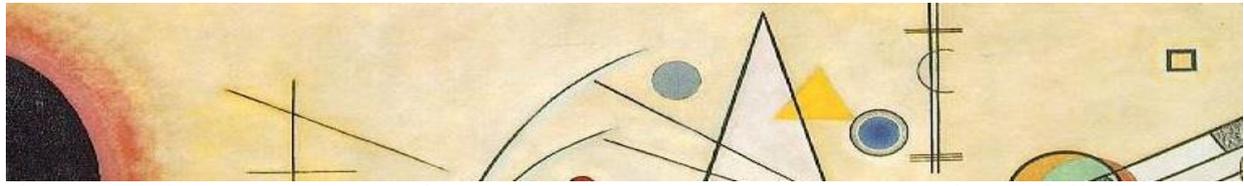
where f = the flux of C-CH₄ (g m⁻² h⁻¹) and of N-N₂O (μg m⁻² h⁻¹), $\Delta C / \Delta t$ = the change in gas concentration over the sampling time (Δt) (mol h⁻¹); P = the mean atmospheric pressure in the chamber (assumed as 1 atm), V = the chamber volume (L), R = the universal gas constant (0.08205 L atm mol⁻¹ °K⁻¹), T = the temperature inside the chamber during sampling in degrees Kelvin (°K), M = the gas molecular mass (g mol⁻¹), A = the chamber basal area (m²). The gas emission rate was converted to μmol C-CH₄ m⁻² h⁻¹. The emission flux generated at each measurement was integrated to produce an estimate of the seasonal methane and nitrous oxide flux (kg ha⁻¹), representing the accumulated gas emission in the chambers. The CH₄ emission factor, in kg per hectare, was estimated by dividing the total emission by the total number of days in the growing season. The partial global warming potential ($pGWP$), expressed in kg CO₂eq ha⁻¹, was calculated by multiplying the accumulated CH₄ emission and its GWP ($pGWP_{CH_4} = CH_4 * 28$), according to Myhre *et al.* (2013). The yield-scaled global warming potential ($YpGWP$) was then calculated as the ratio of the $pGWP$ and the yield of rice grains (Bayer *et al.*, 2014). On five occasions, aboveground biomass (dry weight) sampling was also performed.

2.3 Statistical Analysis

Descriptive statistics were used to summarize the data variation observed during the study. Analysis of variance (ANOVA) and Pearson's correlation test were used to evaluate the relationship between plant variables and methane fluxes.

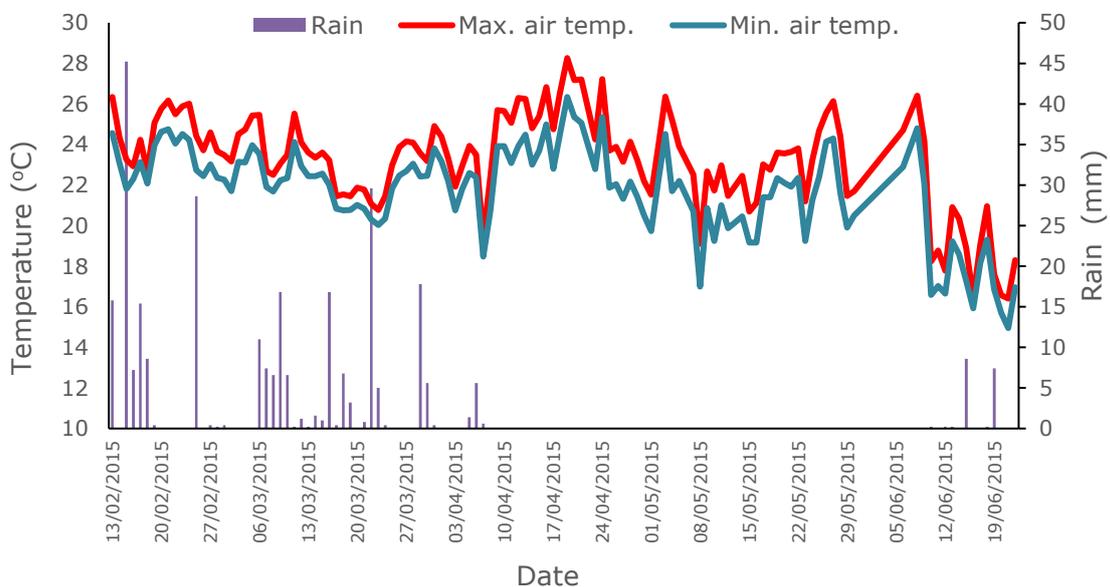
3. Results and Discussion

The average temperature throughout the growing season was estimated at 23.14 °C, and a total of 500 mm of rainfall was recorded during



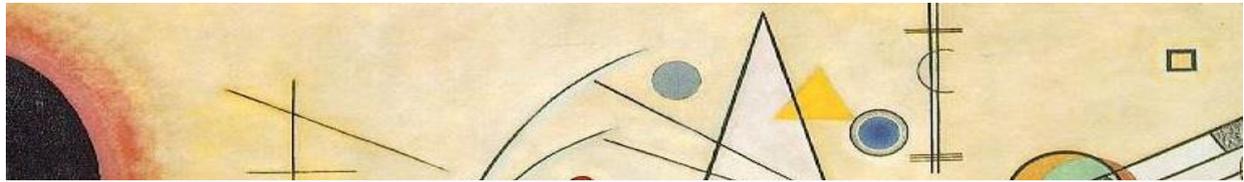
the period. Maximum and minimum air temperatures and rainfall data are presented in Figure 2. The average soil temperature at 5 cm depth was estimated at 23.7 °C, ranging from 17.1 and 33.2 °C. Grain production for both cultivars was low relative to their potential, estimated at 3.200 kg ha⁻¹ and 3.000 kg ha⁻¹, respectively, for IAC 105 and Epagri-106. This yield was likely affected by the late planting of these cultivars and climate conditions.

Figure 2. Climate data during the 2015 agricultural year (Source: INMET, Taubaté Meteorological Station). Max.air temp.: Maximum air temperature; Min. air temp.: Minimum air temperature.



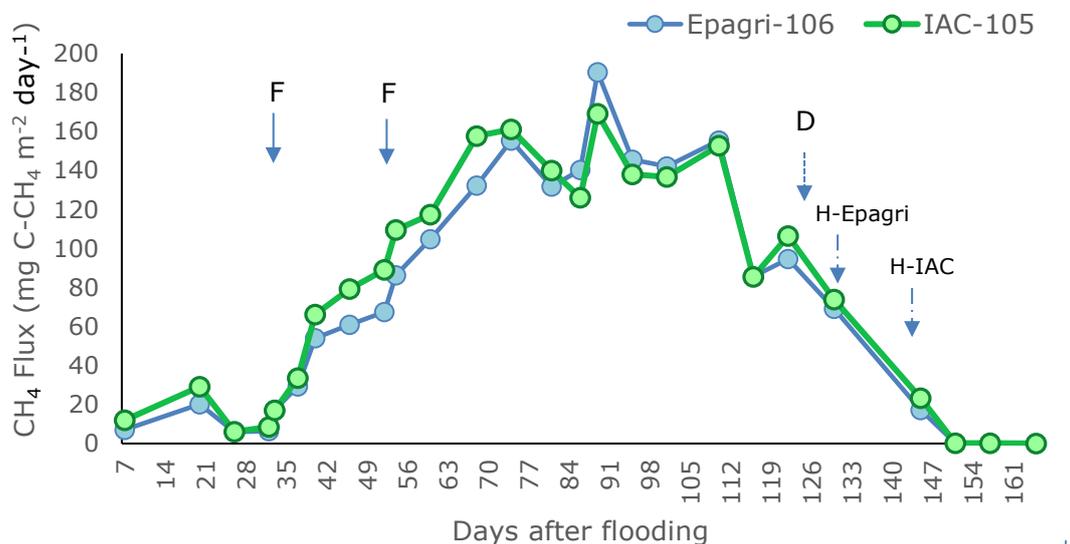
Source: the authors.

The evolution of emissions calculated on the sampling dates from flooding until post-harvest, is presented in Figure 3. The illustration shows that there was no influence of the cultivars on the pattern of seasonal variation in CH₄ emission rates, as also observed by Watanabe *et al.* (1995). Since the germination, the fluxes of both cultivars increased during tillering, favored by nitrogen fertilizer applications. During this phase, a higher density of aerenchima occurs, which favors the CH₄ transport capacity (Kim *et al.* 2018). The increase in CH₄ fluxes observed at this stage is well documented (Ahmad *et al.* 2009). For both cultivars, the highest fluxes were observed



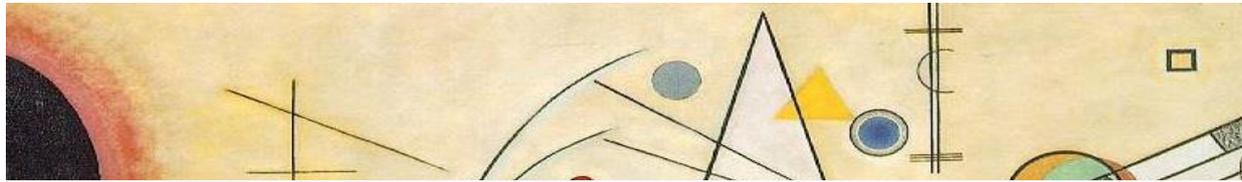
mainly after panicle differentiation, at 52 and 57 DAF in the plots with Epagri 106 and IAC 105, respectively. Other authors observed the same pattern (Singh *et al.*, 1998, Wang *et al.*, 2017, Saha *et al.*, 2017). The main peaks were observed during flowering, between 96 and 117 DAF. During the reproductive phase, photosynthesis is the most important source of CH₄ production, probably due to increased exudation of photosynthates by roots as well as their decomposition (Watanabe *et al.*, 1997).

Figure 3. Methane emissions (mg CH₄ m⁻² day⁻¹), by days after flooding. F: Fertilization, D: Drainage, C-Epagri: Epagri 106 Harvest, H-IAC: IAC 105 Harvest.



Source: the authors.

For the IAC 105 cultivar, on average, 28% of CH₄ emissions occurred in the vegetative phase, 42% in the reproductive phase, and 30% in the maturation phase. For the Epagri 106 cultivar, 23% of emissions occurred in the vegetative phase, 33% in the reproductive phase, and 44% in the maturation phase. The ability of rice plants to transport CH₄ from the soil to the atmosphere through aerenchyma channels varies at different plant stages, maximizing at flowering and maturation stages. However, according to Aulakh *et al.* (2001), to explain the potential for CH₄ emissions, it is

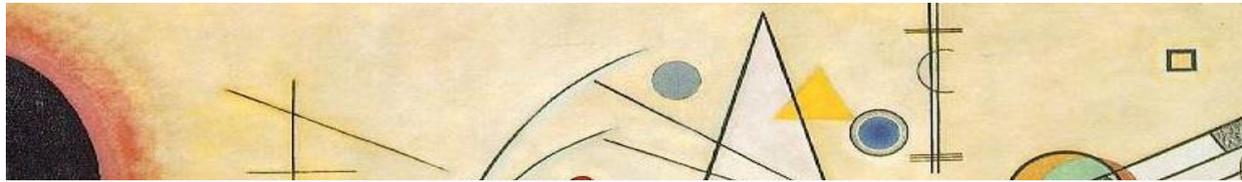


necessary to consider the carbon exudation rates of rice plants, so that the lower the carbon exudation capacity of the cultivar, the lower its methane production and emission.

The average seasonal CH₄ emissions were estimated at 117.91 ± 26.79 kg CH₄ m⁻² ha⁻¹ (CV: 22.72%) for IAC 105 and 108.92 ± 25.55 kg CH₄ m⁻² ha⁻¹ (CV: 23.46%) for Epagri 106, not being significantly different from each other. These values are lower than those found in the national literature (Costa *et al.*, 2008, Lima *et al.*, 2014, Lima *et al.*, 2019a,b) and are lower than the global average value of 180 kg CH₄ ha⁻¹ indicated by Akiyama *et al.* (2005) for paddy rice fields under continuous water management. One explanation for this result may be the late planting of the cultivars, and the soil and climate conditions observed in this growth season, such as the absence of rain during part of the period studied (from April 8 to June 9, 2015), although the continuous water regime was maintained in the area.

The CH₄ emission factor was calculated at 0.98 kg CH₄ ha⁻¹ for the IAC 105 and 0.96 kg CH₄ ha⁻¹ for Epagri. These values are lower than the average indicated by the IPCC (2019) for Brazil, of 1.62 kg CH₄ ha⁻¹ day⁻¹, and in relation to the global range of 1.10 to 2.40 kg CH₄ ha⁻¹ day⁻¹. Lima *et al.* (2019b) estimated 2.27 kg CH₄ ha⁻¹ for the same study area, using the IAC 105 cultivar in the 2010/2011 agricultural year, in a pre-germinated cultivation system, and with a productivity of 7.3 t ha⁻¹ (sowing carried out on January 11, 2011). These results reinforce the importance of monitoring seasonal CH₄ emissions in different years, under distinct soil and climatic conditions, to reach a better average estimate for this type of rice crop systems.

In the current study the rice production was low for both cultivars. Thus, the yield-scaled *p*GWP (*Yp*GWP) for the studied growth season was estimated at 1.02 kg CO₂eq kg⁻¹ grain⁻¹ for both the Epagri 106 and the IAC 105, showing similar impact of the cultivars on the greenhouse gas



emissions. This value of $YpGWP$ was into the ranges found in the literature (Lima *et al.*, 2019a).

In a study carried out in the state of Rio Grande do Sul, using 19 irrigated rice cultivars with different morphophysiological characteristics, Silva *et al.* (2014), found that CH_4 emissions were positively correlated with rice plant height. In our experiment, plant height, panicle number, and grain yield were similar among cultivars (Table 1), with no correlation between these characteristics and CH_4 emissions for both cultivars. Gutierrez *et al.* (2013) suggest that CH_4 emissions might depend more on the substrate-producing capacity and gas transport capacities of each cultivar than on external plant variables. Figure 4 shows the increase of CH_4 fluxes with the progressive increase of plant dry weight. However, the final biomass estimated for each chamber showed no correlation with the seasonal CH_4 emissions for both cultivars (Table 1). In our experiment, the selected cultivars presented very similar characteristics, not allowing us to demonstrate the expected effects on CH_4 emissions, when compared to studies involving different cultivars (Ding *et al.*, 1999, Silva *et al.*, 2014, Asch *et al.*, 2023). The selection of varieties with different methane transport abilities and exudation rates constitutes an important perspective for conducting new research on this topic. The data generated in this study will contribute to future databases and modeling on greenhouse gas fluxes in tropical areas.

Table 1. Average values of plant height, number of tillers, dry weight of the aerial part of plants, and yield ($t. ha^{-1}$), and correlation (r) between each parameter with CH_4 flux.

	IAC 105	CH_4	Epagri-106	CH_4
Average plant height (cm)	97a	0.03	98a	-0.29
Average number of tillers	303a	0.03	266a	-0.07
Average dry weight of plants (g)	415a	0.27	478a	0.07
Average yield ($t. ha^{-1}$)	3,25a	0.78	3,00a	-0.69

Means followed by the same letters within rows do not differ significantly from each other, $p < 0.01$.

Source: the authors.

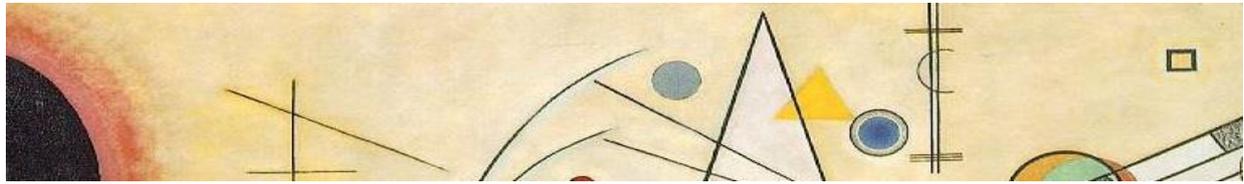
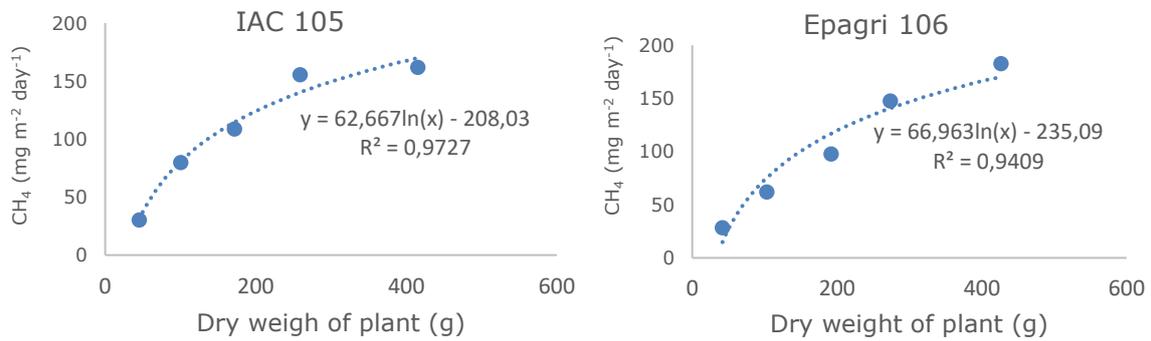


Figure 4. Dry weight and methane emission throughout the growing season.



Source: the authors.

4. Conclusions

Rice cultivars characteristics did not influence the seasonal variation in CH₄ emission rates, with no correlation found with the parameters plant height, tiller number, or grain yield of these cultivars.

CH₄ emission factors as well as their yield scaled partial global warming potential were similar for the IAC 105 and Epagri 106 cultivars, despite their different life cycles, showing a similar impact on environment.



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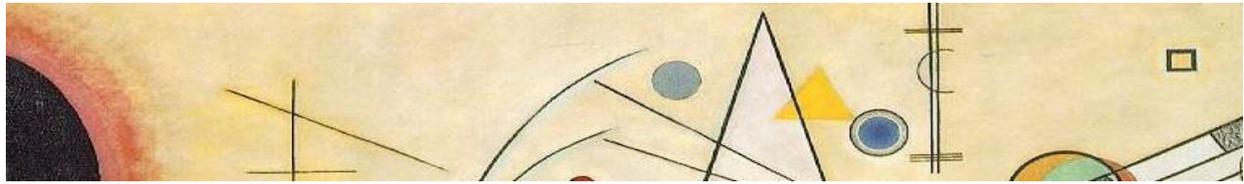
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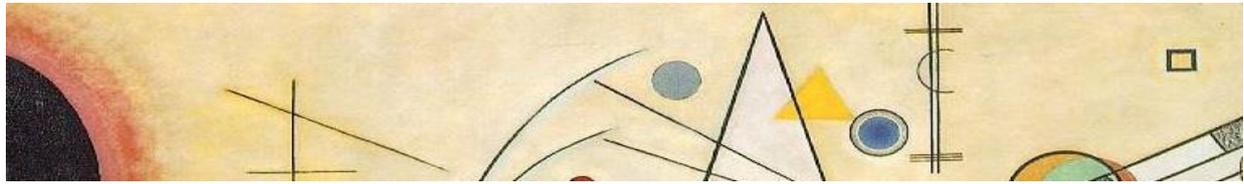
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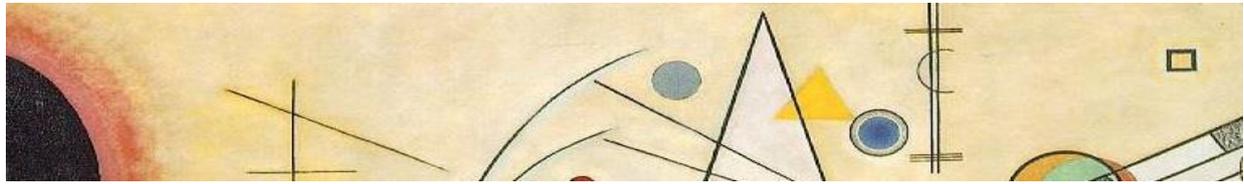
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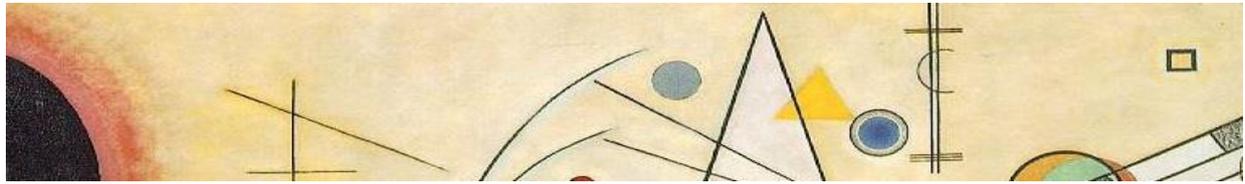
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