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Higher Methane Emission Rates in the Vegetative Rice Growing Stages in the Lower Mekong Delta, Vietnam

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ABSTRACT

The Mekong Delta in Vietnam is a region that produces rice and emits methane, a potent greenhouse gas. Vietnam's rice exports, which rank among the top four globally, have a significant impact on the world's food suppy. The Eddy Covariance system, positioned in the rice field, has been recording methane emission rates and bio-meteorological factors. This study presents the findings of three crop seasons (Summer-Autumn 2020 (S-A20), Winter-Spring 2021 (W-S21), and Spring-Summer 2021 (S-S21)) from the year 2020 to 2021. The highest CH_4 emission value was observed in the S-S21 crop, reaching 4.14 µmol s^{-1} m^{-2}. Elevated CH_4 emission rates were predominantly recorded during the vegetative stage within first 21 days after planting, while lower CH_4 emissions were observed during the reproductive and ripening stages. This pattern clearly indicates higher methane emissions at the vegetative stage of the growing rice, likely due to the abundance of organic matter in the rice fields. The average CH_4 emission rate was 0.1 µmol m^{-2} s^{-1}. Notably, high methane emissions were recorded when the soil surface temperature was below 33 °C. As a results, the S-S21 exhibits the highest methane emission rates compared to other seasons.

Keywords: Rice Field Ecosystem; Methane Emission; Soil Surface Temperature; Eddy Covariance

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1. Introduction

Methane is a significant component of greenhouse gas with the chemical formula CH_4, accounting for approximately 20% of global emissions [1]. According to the US Environmental Protection Agency, the global warming potential (GWP) of CH_4 gas is about 28 times that of carbon dioxide, and the lifetime of CH_4 in the atmosphere is about ten years. The presence of greenhouse gases (GHGs) in the atmosphere affects the Earth's temperature directly and the climate system [1]. Since the pre-industrial period, the mixing ratios of CH_4 have steadily increased up to now. However, at the end of the years 1990 and 2006, there was a stable period of CH_4 emissions [2, 3]. From 1970 to 2019, the global average temperature increased by 1.1 °C, with CH_4 gas contributing 0.3 °C [4, 5].

CH_4 is formed from two primary sources: natural and anthropogenic sources. In nature, CH_4 accounts for approximately 40% of anaerobic decomposition activities in wetlands, swamps, lakes, and soil [6]. On the other hand, anthropogenic CH_4 constitutes about 60% of human activities and originates from areas such as energy production, waste management, agriculture-forestry, rice fields, landfills, and biomass burning and combustion of fossil fuels [7–9]. Globally, CH_4 emissions from agricultural activities contribute around 50% to the total CH_4 emissions [10, 11]. Notably, rice fields and wetlands are the most important sources of CH_4 emissions, responsible for about 40% [12]. With its extensive wet rice agriculture, Vietnam has two large wet rice-growing deltas, the Red River Delta and the Mekong Delta, providing optimal conditions for methane production in wetlands. These rice fields are a prominent source of CH_4 emissions, contributing approximately 10–30 percent of methane through the anaerobic decomposition of organic matter [6]. Wetlands are known to be conducive environments for anaerobic processes and produce CH_4 gas [13]. Once CH_4 is formed, it is released into the atmosphere through three primary sources: emission through internodes and leaf blades, diffusion due to concentration gradients, and gas bubble emissions pathways [14]. It's important to note that upland paddy grows in dry fields, without flooding and does not release greenhouse gases into the atmosphere.

CH_4 emissions in rice fields vary over time and across geographical locations. These emissions in rice fields are influenced by factors such as soil temperature, rice growth stages, water levels, soil moisture, pH, and soil properties [15, 16]. The CH_4 production is produced in an anoxic soil environment with abundant organic matter such as rice straw and fertiliser. However, methanogenesis depends on different factors in soils. Soil temperature directly impacts the CH_4 emission rate and is linked to other factors, such as humidity, pH, and the growth stages of rice plants, which contribute to CH_4 production. The release of CH_4 into the atmosphere depends on different factors, with land surface temperature significantly affecting this process. CH_4 formation peaks at 35 °C in waterlogged alluvial soils, while temperatures below 20 °C lead to minimal CH_4 formation [17]. Soil surface temperature influences biological processes in the soil, thereby affecting CH_4 production [18]. As soil temperature increases, the abundance and activity of microorganisms in the soil increase, accelerating the production and emission of methane into the atmosphere [19]. The previous studies collected discrete hourly sampling across various crop seasons, except nighttime, to monitor soil temperature conditions [20, 21]. However, the limited duration of sampling time makes it challenging to observe methane fluctuations. Soil temperature is known to be a critical environmental factor that enhances methane production or inhibits this process. Therefore, our study aims to examine the variations in consistency in relation to soil temperature and to identify the threshold for CH_4 emission at specific temperatures.

2. Materials and Methods

2.1. Study Area

The research area is located in Lang Sen, known as a Wetland Conserved Area in Tan Hung district, Long An Province, Vietnam. The geographical coordinates of the area are 10°45′–10°48′ North and 105°41′–105°45′ East, with a natural area of more than five thousand hectares. The monitoring measurements location is marked with a black star in **Figure 1**. Lang Sen consists predominantly of low land area, covering 93.2% of the total area, and with an elevation of less than 1 m, accounting for approximately four thousand hectares. This makes it a representative example of a wetland and an inland wetland within the broader lowland area of the downstream Mekong River [22, 23]. Long An experiences a tropical monsoon climate characterized by long radiation times, abundant heat, and humidity. According to the Natural

Resources and Environment of Long An Province (2020), the annual air temperature is about 27 °C to 28 °C. Typically, the highest temperature occurs in April or May, while the lowest is experienced in December or January. Monthly air temperature fluctuations range from 2–4 °C (www.longan.gov.vn). Air humidity depends on rainfall and seasonal variations. The average humidity at monitoring stations in Long An ranges from 72% to 93%. Annual rainfall varies from 966 mm to 1325 mm, unevenly distributed, decreasing gradually from the area bordering Ho Chi Minh to the Western and South Western regions. The area comprises 1412 hectares of alum and alluvial soil, with alum underneath occupying most of the area. About 333.29 hectares are covered by grey soil developed on ancient alluvial foundations [24]. According to Soil Taxonomy (USDA), the majority of the soil in the Lang Sen area is classified as seasonally flooded alum soil. Part of the land area also comprises sand dunes formed by Pleistocene sediments [24]. The total field area is 13,500 m^2 and serves the cultivation of three crops per year. Here, wetting and drying techniques have been widely implemented in the Lower Mekong River to reduce CH_4 emissions and increase crop yield. Rice seeds (*Oryza sativa*) of the cultivar OM4900 are grown for 90–105 days, depending on the environmental condition and flooding time.

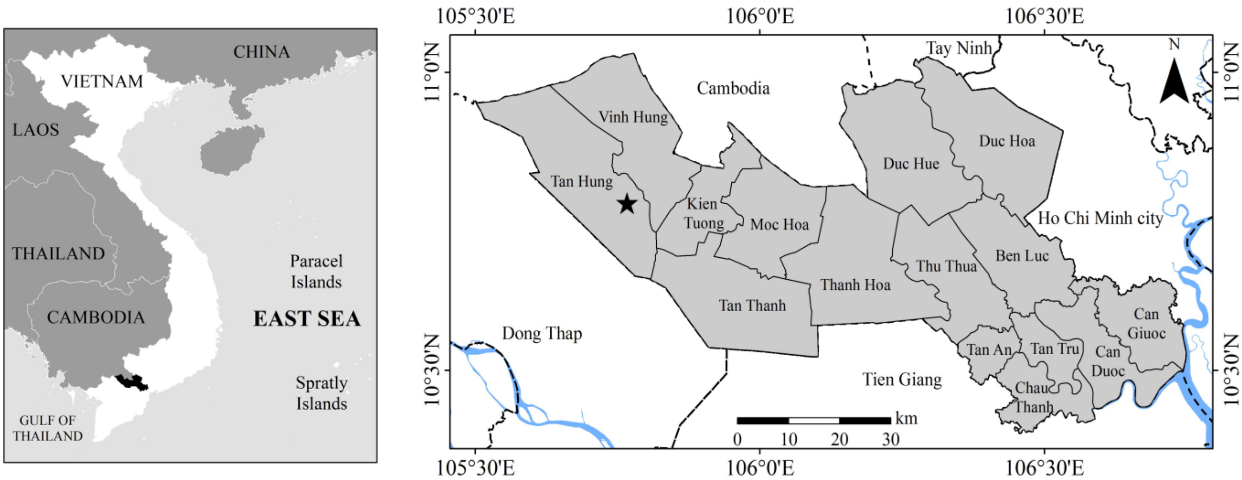


Figure 1. Location of Vietnam (left panel), Long An Province (right panel), and location of monitoring station (star on the right panel).

2.2. Data Source

The CH_4 fluxes were recorded in the rice field and the atmosphere throughout the study automatically and continuously. These data are continuously recorded using the Eddy Covariance (EC) system and bio-meteorology system with high frequency in order to measure continuous flux over larger agricultural areas. It can provide the short-term variation of CH_4 flux with high precision in a short time response. This is an improved method with many advantages in measurements with high precision compared to the closed chamber method. The raw data were obtained from the Research Center for Greenhouse Gases and Climate Change, which belongs to the University of Science (US, VNU-HCM) and the Czech Globe. The monitoring station is located in the rice fields inside the Lang Sen wetland reserve (**Figure 2**). On the tower, the sensorsfor monitoring greenhouse gases and biometeorology factors are attached. CH_4 fluxes are measured using an LI-7700 sensor (LI-COR, USA), integrated with an eddy covariance system, and positioned at a 2-meter height above the ground at a 45-degree angle to the vertical to minimize interference from water. The range of CH_4 detection is from 0 to 25 ppm at minus 25 °C and from 0 to 40 ppm at 25 °C. Surface soil temperature (Ts) was measured using a PT100 sensor (Sensit, Czech Republic), which was buried at the ground level (0 cm depth). Air temperature (Ta) and air humidity (RH) are measured by HMP155 (Vaisala, Finland), which is located at a height of 1.2 meters from the ground and mounted on the tower. The measurement range of temperature is from −40 °C to 60 °C with an accuracy of less than ±0.4 °C (in voltage output condition). These instruments maintain high accuracy over various weather conditions on land. For air relative humidity, measurement ranges from 0 to 100%, with an accuracy of ±1% RH. Raw EC data was processed using Eddy Pro 7.0 software (LI-COR, Inc., USA) and exported at 30-minute intervals on average after noise filtering. Then, the quality assessment of the data series is a process of checking and evaluating the quality of collected data over time. This process aims to ensure the data is reliable, accurate, and consistent before serving for research and analysis. We used the Pettitt (1979) test to assess the homogeneity of collected CH_4 emission rates, temperature, and soil moisture at the monitoring station. For analysis, the missing data were not mentioned, the descriptive statistical analysis is used in this study.

We focus here on the relation between CH_4 emission rates and soil surface temperature. Other bio-meteorology, including air temperature, net radiation, air humidity, and soil moisture, were also used in the study. Rice's growing stages are divided into different stages, according to Nguyen[25] in this study. The S-A20 crop starts in late June and ends in late September, the W-S21 season starts in early November and ends in mid-February, and the S-S21 season starts around early March and ends in late May 2021 (**Figure 2**). Up to now, Vietnam has four operating greenhouse gas emission measurement stations. However, three of them are located in forests, and only this station is established in rice fields within the reserved wetland area. Data on CH_4 emissions at this station have not yet been published. Therefore, the data published in the study is meaningful in determining the amount of CH_4 emissions from rice fields and is also an important step in greenhouse gas inventory for the agricultural sector.

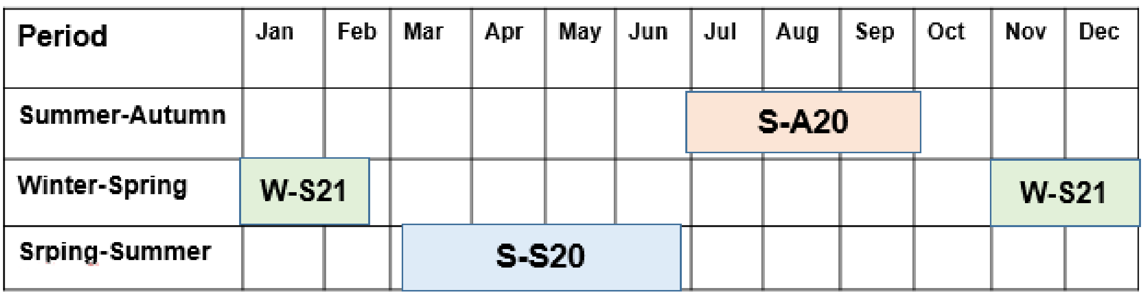


Figure 2. Crop calendar of three crops planted in the study area.

3. Results and Discussion

3.1. Higher CH_4 Emission and Relation with Soil Surface Temperature in Vegetative Growth

The life cycle of rice contains vegetative (germination, seedling growth, and tillering), reproductive (booting, heading, flowering, and grain-filling), and ripening (milk, mature) stages. The soil temperature has distinct effects on the growth stages of rice plants[26, 27]. They have proposed that high temperatures impact the growth stage of rice and the amount of organic matter, which serves as a source of methane production and may impact CH_4 emissions in the rice field. This study examines CH_4 emissions during the vegetative stage across three crops over a year (from July 2020 to June 2021). The early growth stages of rice are divided into germination, seedling growth, and tillering periods.

3.1.1. Methane Emission in Summer-Autumn (S-A20) (from Jul 2020 to Sep 2020)

In the initial crop, the average air temperature was 27.5 °C, ranging from 23.0 °C to 35.7 °C, and the average relative humidity was 88%. **Figure 3** illustrates CH_4 flux and surface soil temperature (Ts) in the first crop divided into three stages: vegetative stage (Stage 1, **Figure 3a**), reproductive stage (Stage 2, **Figure 3b**), and ripening stage (Stage 3, **Figure 3c**). The crop takes place during the rainy season. According to the results, methane emissions were high in the first stage, particularly up to the 20th day after planting (DAP). The peak CH_4 emission reached 1.7 µmol s^{-1} m^{-2} at the 7th DAP and 17th DAP. CH_4 emission was low during the second and third stages, with most values being less than 0.5 µmol s^{-1} m^{-2}. The average CH_4 emission rate for the first crop is 0.1 µmol s^{-1} m^{-2} (**Figure 3a**).

The correlation between methane emissions and temperature changes in the rice field is not strongly correlated [28, 29]. However, previous studies have shown a positive correlation between CH_4 emission rates and soil temperature [19, 30]. These studies suggested that temperature plays a significant role in the biological processes within the soil, which in turn regulates methane production [14]. Our study also found that the CH_4 emission rates are high when the soil surface temperature exhibits significant fluctuations in the first 20 days. The result demonstrates a strong positive correlation between methane flux and soil temperature ($CH_{4\_flux} = 0.2 \times Ts - 4.4$, n = 80, $R^2 = 0.9$). It shows that methane emissions tend to increase with higher soil surface temperature. On these two days, elevated methane emissions were observed during the first stage of rice growth.

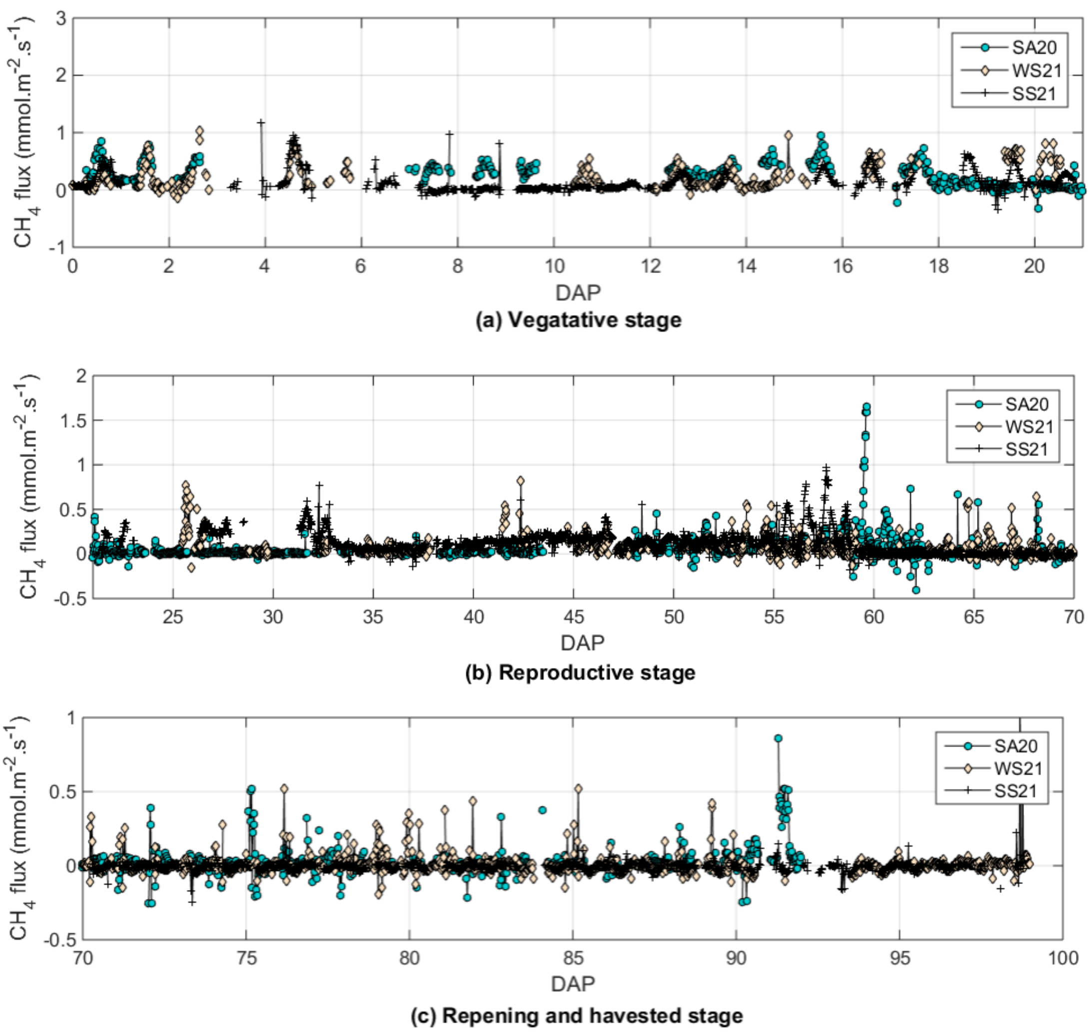


Figure 3. Variation of hourly methane emission rates over three periods: (**a**) vegetative stage; (**b**) reproductive stage; (**c**) ripening and harvested stage.

3.1.2. Methane Emission in the Winter-Spring (W-S20) (from Nov 2020 to Feb 2021)

In the second crop, the average air temperature in W-S20 was lower than in S-A20, with a value of 25.9 °C. This crop occurs during the dry season, following the flood season in October. The previous crop was harvested before the October flood. During flooding, fluvial sediment is carried and used to fertilize rice fields [31]. Natural floods contribute to rice field fertilization, with about 4% of the sediment reaching the Delta [32]. Methane production post-flooding is mainly influenced by the ratio of potential organic compounds to ferric iron reduction [33, 34]. Nutrient-rich sediment originating from floods serves as a natural fertiliser for farmers at no cost. Similar to the first crop, stage 1 of the second crop is characterized by high CH_4 emissions. It has been observed that CH_4 production begins immediately upon the initial inundation. In the subsequent stages of the second crop, most CH_4 emission values were recorded as less than 1.0 µmol s^{-1} m^{-2}. The average CH_4 emission rate in the second crop is 0.07 µmol s^{-1} m^{-2} (**Figure 3a**).

3.1.3. Methane Emission in the Spring-Summer (S-S21) (from Feb 2021 to May 2021)

During the third crop, the average air temperature was 27.4 °C and experienced a higher temperature, higher than the previous crop. This leads to increased irrigation for the rice field. CH_4 emission rates during stage 1 of the third crop were higher than in other stages, averaging CH_4 emission of 0.1 µmol s^{-1} m^{-2} (**Figure 3a**). This season typically experiences hotter and drier conditions, impacting the seedling and tillering stages. Rice plants are placed under temperature stress in the vegetative and reproductive stages. High temperatures during the vegetative growth phase have been observed to affect germination rate, root growth, and tillering, potentially reducing panicle number by about 28–35%[35]. As a result, the harvest yield from these crops is lower than that of other crops in the year, which has also been confirmed by the owner field.

The comparison of the methane emissions from three different rice crops indicates that CH_4 emissions are higher in the summer (S-S21) crop compared to other crops (S-A20, W-S21). These findings are similar to the result of a previous study[36], which also reported approximately 40% higher methane emissions during summer compared to spring. The average CH_4 flux during S-S21 was similar to that of S-A20 but almost doubled during W-S20. Previous studies have demonstrated that lower CH_4 emissions occur during the early vegetative stage in Northwest Vietnam due to lower soil temperature, which slows down the methanogenic activity responsible for CH_4 production during this period[30]. Additionally, the availability of organic matter, which serves as a source for methanogens, is affected by the treatment of crop residues from the previous crop. While leftover crop residues from the last crop are either dried or consumed by local grazing cattle, farmers bury the burned rice straw and the leftovers from the previous crop during farming cultivation. In our study, the high CH_4 emission during the rice-growing stage is attributed to the significant soil organic matter content, primarily from the buried residue of rice straw and rice root after harvest. Another study revealed that CH_4 flux peaked 7–14 days after transplanting[37, 38]. However, our study indicates a broader time range of high methane emissions during the vegetative stage, from 7 to 21 days after planting. No correlation was found between CH_4 emission and Ts in both W-S21 and S-S21 during the vegetative stage. However, a positive correlation between CH_4 and Ts exists in the S-A20 season. This indicates that surface soil temperature is not the sole controlling factor for methane emission in the rice field.

3.2. Mediate Methane Emission in the Reproductive Stage

During the reproductive stage, which includes booting, heading, flowering, and maturation or grain filling, there was minimal variation in S-A20, especially between 58–62 DAP. CH_4 emission averaged 0.13 µmol s^{-1} m^{-2} on average over about 50 days, with the peak CH_4 flux occurring toward the end of the rice heading stage, reaching 1.6 µmol s^{-1} m^{-2}. In the W-S21, methane flux was lower at 0.07 µmol s^{-1} m^{-2}, but there were fluctuations with values exceeding 0.5 µmol s^{-1} m^{-2} during the booting and heading stage (**Figure 3b**). This period experiences higher temperatures during the day and summer, leading to a more significant variation of methane flux in the S-S21. Oda and Chiem (2018) also proposed that the increase in methane emission during the heading stage is caused by the methanogenesis process in the organic rice at the rice field[39]. However, it is challenging to definitively ascertain the source of the methane at this stage.

Exposure of pre-flowering spikelets to temperatures higher than 33 °C for about an hour can cause sterility, which has a more significant impact than exposure to a wider range of temperatures after flowering[40, 41]. The S-S21 crop spends over the higher temperatures, the hotter summertime, with the booting and heading stages occurring at 31.8 °C. The highest air temperature is 31.8 °C during the booting and heading stages. The effect of soil temperature on grain yield but did not show a clear difference in yield up to 32 °C[42]. Even though the air temperature is not as high as in the previous studies, rice yield was lower than that of other crops over the years. This observation has been confirmed by the owner of the rice field where the monitoring station was located. Therefore, early flowering at moderate air temperature can help produce spike heads, successfully pollinate them, and maintain productivity before experiencing periods of high air temperature.

3.3. Low CH_4 Emission in the Ripening Stage and Harvested Stage

The ripening stage includes the milk stage and mature; the harvested stage occurs when rice seeds turn brown rice seeds completely. Previous studies have demonstrated that the reproductive stage significantly affects rice seed production [43, 44]. During this period, there is minimal activity in the rice field. Senthilraja et al. [45] reported an upward trend from the heading to the harvest stage. In contrast, CH_4 emission is low in the ripening stage in this study. The average CH_4 emission rates are 0.03, 0.007 and –0.01 μmol s^{-1} m^{-2}, respectively, in the S-A20, W-S21, and S-S21 (**Figure 3c**, **Table 1**). Generally, CH_4 emissions are low in the harvested stage over the three periods. It is challenging to accurately measure CH_4 emission rates during the burning of rice straw due to the need to switch off the sensor to prevent ash from attaching to it. Further detailed research is needed in this area.

Table 1. Comparison of average methane emission (mean ± SD) between rice growth stage between three crop S-A20, W-S21, and S-S21.

	Flux of Methane Emission in Each Season		
	S-A20	**W-S21**	**S-S21**
Weather condition	Late dry season	Wet season	Dry season
Air temperature	27.5 ± 2.5	25.9 ± 3.4	27.3 ± 2.9
Relative air humidity (%)	91.1 ± 8.9	85.7 ± 10.7	88.1 ± 10.4
Soil surface temperature (°C)	28.5 ± 2.0	26.1 ± 2.5	28.3 ± 2.6
Soil moisture (m^3 m^{-3})	0.60 ± 0.01	0.58 ± 0.02	0.59 ± 0.01
Vegetative	0.40 ± 0.32	0.29 ± 0.33	0.18 ± 0.34
Reproductive	0.05 ± 0.13	0.07 ± 0.12	0.12 ± 0.13
Ripening	0.03 ± 0.10	0.01 ± 0.06	–0.01 ± 0.03
Average of CH_4 emission	0.10 ± 0.2	0.07 ± 0.17	0.10 ± 0.19

3.4. Comparing Methane Emissions in Different Seasons over a Year

Rice-growing areas in the Mekong Delta typically experience three crop seasons. During the first crop season, they endure the late dry season, while the third crop coincides with the driest period of the year. CH_4 emissions were found to be higher during the vegetative stages than the reproductive and ripening stages (**Table 1**). The results in **Figure 4** indicate significant fluctuation in CH_4 emissions during the vegetative period compared to other rice growth stages. Additionally, our findings reveal that CH_4 emissions were approximately 30% higher in the dry season compared to the wet season.

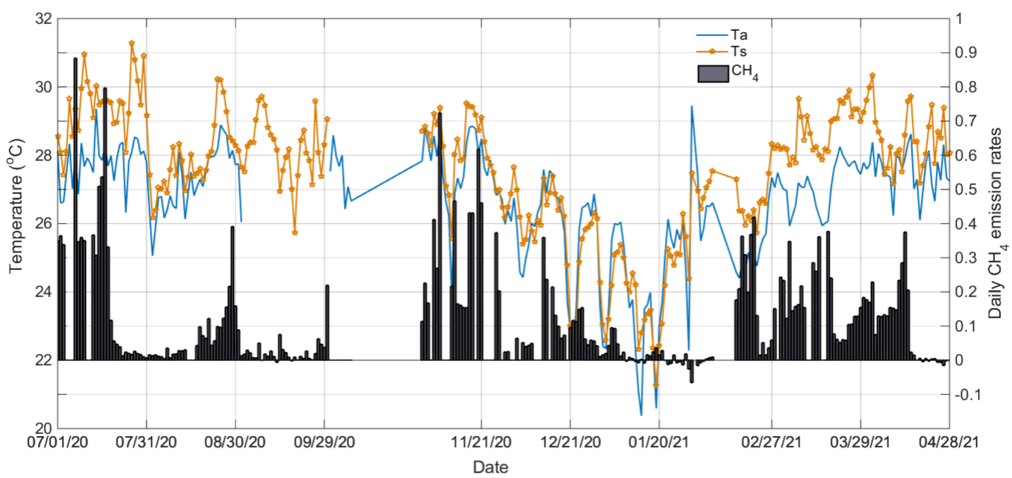


Figure 4. Daily mean air temperature (Ta), soil surface temperature (Ts), and methane emission rates (CH_4).

3.5. Effect of Soil Surface Temperature on Methane Emission

Methane emission rates are positively related to soil temperature until 34.5 °C[45]. This indicates that the methanogens responsible for methanogenesis in the soil of the fields exhibit optimal metabolic activity of microorganisms at temperatures below 34.5 °C[46], with temperatures above 35 °C delaying the methanogenic activity. Meanwhile, another study stated that the optimal temperature for CH_4 formation is typically below 30 °C[44] and has minimal influence on microbial CH_4 oxidation[47, 48]. Previous studies have confirmed that soil temperature is the primary factor controlling seasonal methane emissions from wetlands[49–51].

Our study observed that the maxima methane emission rates occurred at 30.2 °C in S-A20, 32.5 °C in W-S21, and 29.7 °C in S-S21. Interestingly, the highest CH_4 emission rates did not align with the maximum at the soil surface temperature. However, we found a positive relation between Ts and CH_4 emission rates as Ts increased, and after reaching the specific threshold soil surface temperature (32.5 °C), CH_4 production did not increase more. The threshold of soil surface temperature in this study is 32.5 °C, which is lower than that reported by Parashar et al.[45] but higher than that of Svensson[44] (**Table 2**). A temperature higher than 32.5 °C may cause the potential for organic carbon, which is the main source of methanogenesis in anoxic conditions at the site. In this study, we found no clear relationship between soil temperature and methane emissions (**Figure 5**). In fact, soil temperature is affected by soil moisture, which directly affects methane emission rates compared to air temperature. Unfortunately, the addition of fertilisers and water management was not mentioned in the study. We also highlighted the influence of soil surface temperatures and other environmental factors, such as anoxic or oxic conditions, ambient temperature, and soil moisture, on the CH_4 emission rate.

Table 2. Comparing values of the threshold for soil surface temperature (°C).

	Soil Surface Temperature (°C)			
	S-A20	**W-S21**	**S-S21**	**Average**
This study	30.2	32.5	29.7	30.8
Svensson (1984)[44]		Less than 30		
Parashar et al. (1993)[46]		34.5		

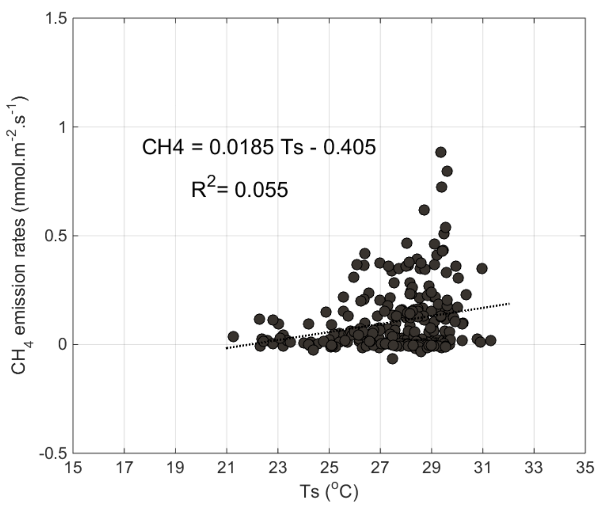


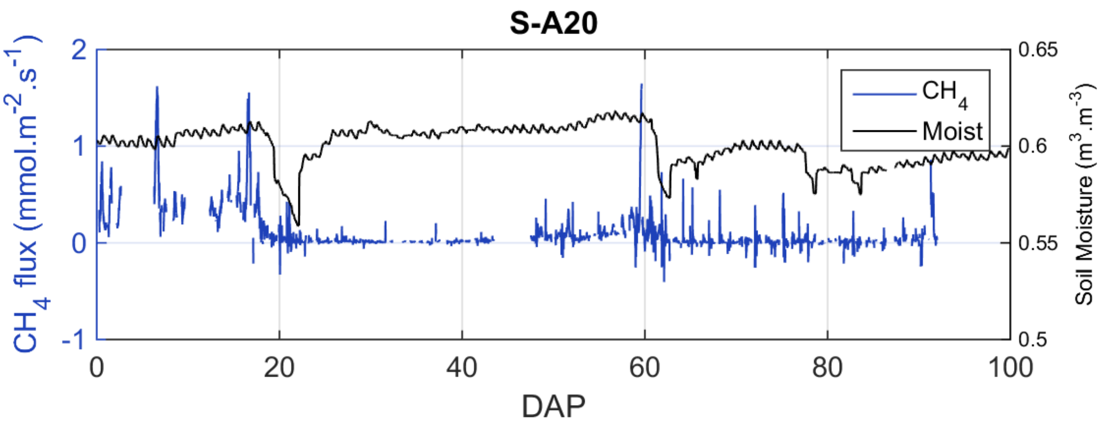
Figure 5. Relation between mean daily CH_4 emission rates and soil surface temperature (Ts).

3.6. Influence of the Environmental Factors on Methane Fluxes

This research aims to initially analyse the continuous rates of methane emission data from three rice crops in a year, which is common in the Mekong Delta regions. The mean radiation was 152 W. m^{-2}, with a maximum radiation of 975 W m^{-2}. The mean of air humidity was 88% over three crops. Elevated methane emission also occurred in high radiation but was only present in the first stage of rice growth. Rice-growing techniques have been applied in rice-growing areas to significantly limit greenhouse gas emissions in the atmosphere of each crop, mainly through the use of alternative wetting and drying techniques to limit the CH_4 emission effectively. Although the water level in the field was not evaluated in this study, it is evident that high

CH_4 flux occurs at the vegetative stage. The rice field has been considered a carbon source during the germination and seedling stages in anoxic conditions. It was observed that the net ecosystem exchange (NEE) changed during the daytime over 15 days to about -1.82 µmol m^{-2} s^{-1} [52], indicating a contribution to the CH_4 formation. This study indicates high methane emissions at the beginning of the season during sowing, with the source of organic materials for the methanogenesis process being residual rice stems and roots left over from the previous crop. The decomposition of leftover rice plant material in the soil provides additional nutrients for the soil, which may make it noncohesive. While burning stubble is a traditional method, it contributes to greenhouse gas emissions. Utilising the remaining part of the rice plant after harvest as agricultural products offer more sustainable solutions. The temperature difference between soil and air temperature ($\Delta T = Ts - Ta$) does not significantly impact CH_4 emission rates. In S-A20, the ΔT values fall within smaller ranges ($-2 \leq \Delta T \leq 2$). In contrast, in the S-S21 crop, ΔT values fall in smaller ranges ($-2 \leq \Delta T \leq 2$), while in the S-S21 crop, ΔT values range fall from ($0 \leq \Delta T \leq 4$). Even though the range of ΔT is the same, the CH_4 emission rates exhibit a slight difference.

Soil moisture is considered as an indicator to control CH_4 production in soil. Elevated methane production is produced in high moisture, high water content in soil, and in anaerobic conditions during rice farming[53]. In this case, farms apply alternative wetting and drying methods, which create anaerobic conditions for methanogenic bacteria and aerobic conditions for methanogenic bacteria (**Figure 6**). The irrigation technique helps limit methane production and accumulation in the fields in a short time. In fact, the results reveal the peak of methane emission occurred when soil moisture decreased after a slight increase in moisture. It could be explained that when soil moisture was high, it would be anoxic environment for producing methane. Until soil moisture suddenly decreases, it may be a condition for methane emission or release into the atmosphere.



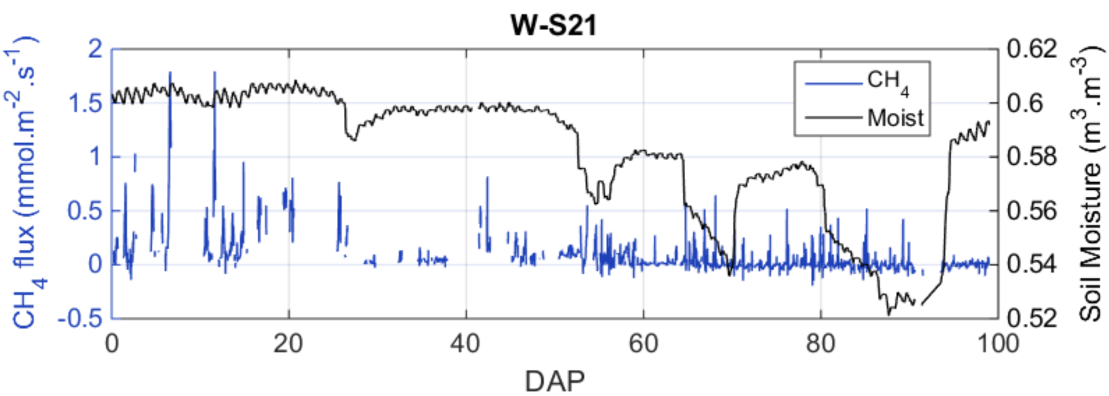


Figure 6. *Cont.*

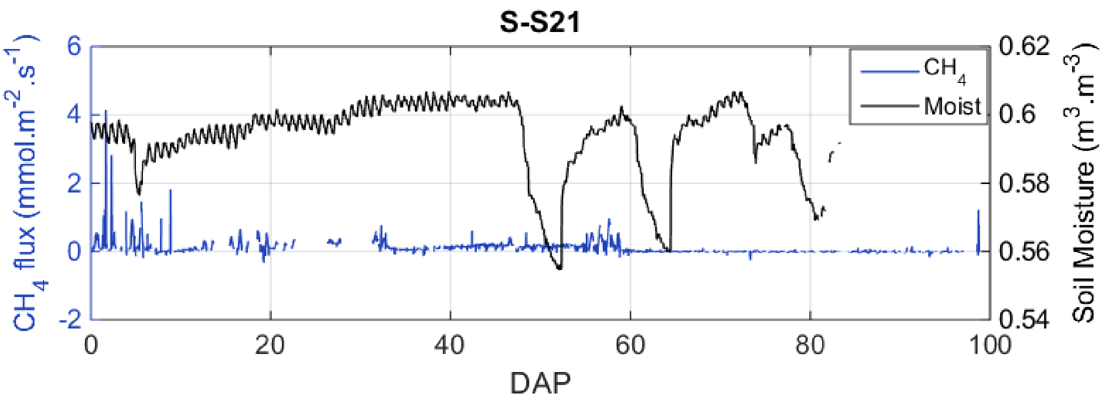


Figure 6. Variation of hourly methane emission rates and soil moisture over three periods: S-A20, W-S21, and S-S21.

There is no clear relation between CH_4 emission rates and environmental factors (such as soil temperature, air temperature, and soil moisture) for three crops. It implies that an environmental factor controls the CH_4 emission rate but also relates to the others.

4. Conclusions

Using the eddy covariance technique, our research represents the first CH_4 flux measurement from a rice field in the Lower Mekong Delta. The rice field in this region serves as a carbon source and CH_4 source. Our method allowed us to examine the variation of CH_4 over three different crop stages. We observed high CH_4 emissions during the crop stages (vegetative, reproductive, ripening, and harvest), particularly during the vegetative stage. CH_4 emissions were elevated in the dry season compared to the wet season by about 30%. Our findings indicate that the optimal temperature for high methane production is about 32.5 °C, with higher soil temperatures leading to reduced methane production.

The findings of this study provide a crucial scientific basis for assessing and better understanding the methane flux in the rice field in the Mekong Delta. The study helps to understand the background of the CH_4 emission from agricultural sectors in reducing greenhouse.

Author Contributions

Conceptualization: B.T.N.O., V.H.H., and E.A.; methodology: B.T.N.O., and E.A.; analysis: B.T.N.O., V.H.H. and E.A.; writing—original draft preparation: B.T.N.O.; writing—review and editing: B.T.N.O.; visualization: B.T.N.O. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study have been generated but are not currently available in a public repository. The data can be made available by the corresponding author upon reasonable request.

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Conflicts of Interest

There are no conflicts of interest among the authors.

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