Original Research Article

Methane (CH_4) Fluxes in Mangrove Sediments of Negeri Passo, Inner Ambon Bay: Implications for Climate Change

Abstract

Mangrove ecosystems play a significant role in carbon sequestration. However, the accumulation of organic matter in mangrove sediments undergoes decomposition, which triggers the release of CH_4 gas flux. This study aims to analyze the CH_4 gas flux in the mangrove sediments of Negeri Passo, Inner Ambon Bay. Gas sampling was conducted using a cylindrical chamber at three observation stations. Gas was collected using a syringe five times at 30-second intervals. The gas concentration was analyzed using gas chromatography, while the CH_4 flux was calculated using a flux equation that considers the regression slope, chamber volume and area, temperature, gas molecular weight, ideal gas constant (R), and time constant based on the gas sampling interval. The results showed that the average CH_4 concentration was 22.46 ppm. The highest concentration was found at Station 2, with 33.33 ppm, and the lowest at Station 3, with 14.40 ppm. The average CH_4 flux was 3.2194 mg/m²/h. The highest CH_4 flux was observed at Station 3, with 4.8727 mg/m²/h, while the lowest was at Station 1, with 1.3421 mg/m²/h. Based on these findings, it can be concluded that the mangrove ecosystem in Negeri Passo has a relatively higher CH_4 flux compared to other locations within the Inner Ambon Bay area. Additionally, the significant carbon sequestration potential, as indicated by the Tier 1 model approach, suggests that this mangrove ecosystem plays a crucial role in climate change mitigation.These findings highlight the dual role of the mangrove ecosystem in Negeri Passo, acting as both a carbon sink and a source of CH_4 emissions, emphasizing the need for further research to balance its sequestration potential with methane release dynamics.

Keyword:CH_4 fluxes, climate change, mangrove sediment, global warming potential.

Introduction

Mangrove ecosystems are characterized by high biodiversity of both flora and fauna (Rahman *et al*., 2024a). These ecosystems have gained significant attention due to their role in carbon sequestration (Rahman *et al*., 2024), making them a potential nature-based solution for addressing and mitigating global warming (Huxham*et al*., 2023). Various studies indicate that mangrove ecosystems make a significant contribution to carbon sequestration. Consequently, the potential carbon stock approach has become a new paradigm in sustainable mangrove ecosystem management (Sidik*et al*., 2023). However, in addition to storing carbon, mangroves can also be a source of greenhouse gas emissions, including methane (CH_4) (Rahman *et al*., 2018), primarily through microbial respiration and the decomposition of organic matter via acidogenic or methanogenic processes in mangrove sediments (Rahman *et al*., 2020a).

CH_4 gas flux from mangrove sediments is a crucial indicator that reflects the balance between the absorption and release of greenhouse gases within these ecosystems. CH_4 flux fluctuations can be influenced by various environmental factors, such as temperature, humidity, and the composition of organic matter (Chauhan *et al*., 2015). Therefore, understanding CH_4 flux from mangrove sediments is essential for the effective management and conservation of mangrove ecosystems, particularly in the context of climate change mitigation.

Negeri Passo, located in Ambon City, Indonesiahas extensive mangrove areas and is a key site for coastal ecosystem research (Pietersz*et al*., 2024). However, research on CH_4 gas flux from mangrove sediments in this area remains limited. A brief literature review should be included before stating the research objective to highlight key findings from previous studies on CH_4 gas flux in mangrove sediments and emphasize existing knowledge gaps, particularly in Negeri Passo. While global and regional studies (Chauhan *et al.*, 2015) have examined the environmental factors influencing CH_4 emissions in mangroves, research specific to Negeri Passo remains scarce. To address this gap, this study provides site-specific data on CH_4 flux, contributing to a better understanding of methane emissions in tropical mangrove ecosystems and supporting climate change mitigation strategies.

This study aligns with **SDG 13: Climate Action** by providing insights into CH_4 gas flux from mangrove sediments, which is essential for developing strategies to mitigate greenhouse gas emissions and enhance climate resilience. Additionally, it supports **SDG 14: Life Below Water**, as understanding methane dynamics contributes to the conservation and sustainable management of mangrove ecosystems, which play a crucial role in coastal protection and biodiversity preservation.

The findings of this study are expected to contribute to a deeper understanding of carbon dynamics within mangrove ecosystems and provide recommendations for more effective mangrove conservation and management efforts in Negeri Passo, Inner Ambon Bay (TAD). Thus, this research not only holds scientific value but also has practical implications for climate change mitigation and environmental preservation.

Methodology

Description of Study Sites

The study was conducted in July 2022 in the mangrove ecosystem area of Negeri Passobecause this month coincides with the east monsoon characterized by moderate rainfall. These conditions are considered ideal for observing the dynamics of the mangrove ecosystem and the potential accumulation of organic matter in the environment. The mangroves of Negeri Passo cover an area of 21.66 hectares, with a very dense canopy cover reaching 62.70% (Pietersz*et al.*, 2024). Residential areas are located on the western and eastern sides of this ecosystem (Figure 1), where the potential for organic matter accumulation from domestic waste is increasing (Kesaulya *et al.*, 2023).

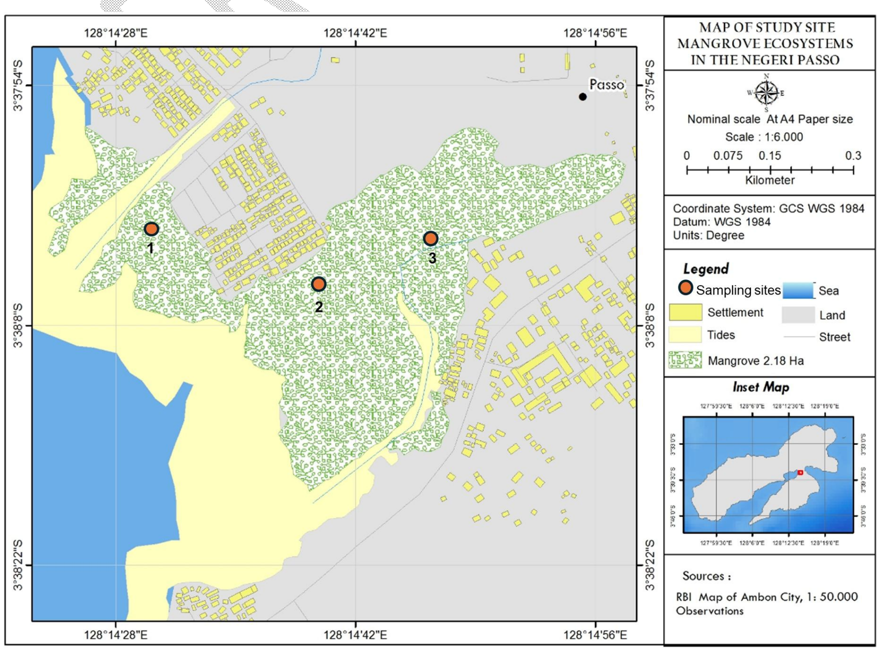

Figure 1. Map of the Study Location: Mangrove Ecosystem of Negeri Passo

Gas Sampling

Gas sampling was conducted at three stations or sediment points in the mangrove area, primarily near residential areas. The selection of the three stations was based on specific environmental and ecological criteria to ensure representative sampling of CH_4 flux variations within the mangrove ecosystem. Key considerations included differences in sediment composition, vegetation density, hydrodynamic conditions, and potential anthropogenic influences. These factors were considered to capture spatial variability in methane emissions rather than relying on random selection.While these sampling points are not fully representative of the entire ecosystem, they are reasonably acceptable for a preliminary study to assess the potential gas flux from mangrove sediments.

At each sampling point (sediment), a single cylindrical chamber (V = 17 L, A = 0.0616 m²) was placed (Figure 2) with two repetitions. During each repetition, gas was sampled five times using a syringe at 30-second intervals: 0s, 30s, 60s, 90s, and 120s, following the method of Nazareth and Gonsalves (2022). The collected gas was then transferred into 10 ml airtight vials and sent to the Greenhouse Gas Laboratory at the Agricultural Instrument Standardization Center (BSIP) in Pati Regency, Central Java.

Figure 2. Gas Sampling Using a Cylindrical Chamber

Analysis of CH_4 Gas Concentration

The concentration of CH_4 gas was analyzed using the Gas Chromatography-Mass Spectrometry (GC-MS) method. In this method, a sample of 2-3 mL of gas was drawn from the vial using a syringe and introduced into the Thermal Conductivity Detector (TCD). The resulting gas concentration analysis is presented in parts per million (ppm).

Analysis of CH_4 Gas Fluxes

The flux of CH_4 gas was analyzed based on the greenhouse gas flux equation developed by Rahman *et al*. (2020b; 2023). Mathematically, the greenhouse gas flux equation can be expressed as follows:

$$F = \left| \frac{S * V * t * mW}{(RT * A)} \right|$$

Explanation:
F = CH_4 gas flux (mg/m²/h)
S = Regression slope of CH_4 concentration measured at each 30-second interval (ppm/s)
V = Volume of the cylindrical chamber (L)
A = Surface area of the chamber (m²)
t = Time transformation factor (1 hour divided by the sampling interval = 3600s/30s or 120)
R = Ideal gas constant (0.082 L.atm/K.mol)
T = Temperature inside the chamber or air temperature (K)
mW = Molar mass of CH_4 (16 g/mol)

Global Warming Potential

Global Warming Potential (GWP) is a metric used to compare the extent to which a specific greenhouse gas can absorb and emit heat in the atmosphere relative to carbon dioxide (CO_2), which is used as a reference with a GWP value of 1. GWP calculates the warming effect of greenhouse gases over a specified period, typically 20, 100, or 500 years (IPCC, 2001). According to the IPCC (2001), the GWP of CH_4 gas flux over a 100-year period is equivalent to 28 times that of CO_2. Mathematically, the GWP of CH_4 can be formulated as follows:

$$F_e = Fm \times GWP$$

Where F_e represents the CO_2-equivalent flux value (mg/m²/h) as an approximation of the Global Warming Potential (GWP), *Fm* represents the carbon gas flux (mg/m²/h), and GWP represents the Global Warming Potential value of carbon gas, which is the conversion of the emission value per mole of CH_4 gas equivalent to 28 times the CO_2-e emissions over a 100-year period.

Result and Discussion

Concentration of CH_4 Gases

The average CH_4 concentrations at St. 1, St. 2, and St. 3 were 19.65 ppm, 33.33 ppm, and 14.40 ppm, respectively (Figure 3). These CH_4 concentration values at the three stations were significantly higher compared to the findings of Rahman *et al*. (2024) in the mangrove sediments of Poka Village, which ranged from 1.80 to 3.60 ppm. They were also higher than the findings of Tubalawony *et al*. (2024), who reported CH_4 concentrations in TanjungTiram ranging between 1.7329 and 2.0786 ppm. Statistically, the average CH_4 concentration in the mangrove sediments of Passo Village differed significantly at a 95% confidence level, with a P-value of 0.0360 ($P < 0.05$). This significant difference may be attributed to the sediment characteristics at each observation station. This assertion is supported by the findings of Rahman *et al*. (2024c) and Tubalawony *et al*. (2024), who found significant differences in CH_4 gas concentrations in sandy mud, muddy sand, and sand sediments within the mangrove ecosystems of Poka Village and TanjungTiram, with *P-values* ranging from 0.0281 to 0.0450 ($P< 0.05$).

The high CH_4 concentrations at all observation stations indicate the accumulation of organic material in the mangrove sediment areas. Furthermore, this accumulation is not counterbalanced by active flushing processes. This is because the Passo Village mangrove ecosystem is in a semi-enclosed bay area, specifically the Inner Ambon Bay (TAD). Semi-enclosed waters have a significantly longer organic material flushing time compared to open waters. In this context, Salamena*et al*. (2022) reported that the flushing time for organic material entering TAD waters can reach 14 days, particularly during the rainy season. Meanwhile, in the relatively open waters of Outer Ambon Bay (TAL), the flushing time for organic material is shorter, approximately 1.5 weeks or 9-10 days (Salamena*et al*., 2023).

In addition to the semi-enclosed water conditions, the accumulation of organic material in the mangrove sediments is also influenced by the very high density of mangroves in Passo Village. According to Pietersz*et al*. (2024), the mangrove ecosystem in this location ranges from dense to very dense. The combination of low flushing time and high organic input leads to a reduction in oxygen availability. Consequently, anaerobic methanogenic reactions occur, which trigger an increase in CH_4 concentration (Rahman *et al*., 2024c).

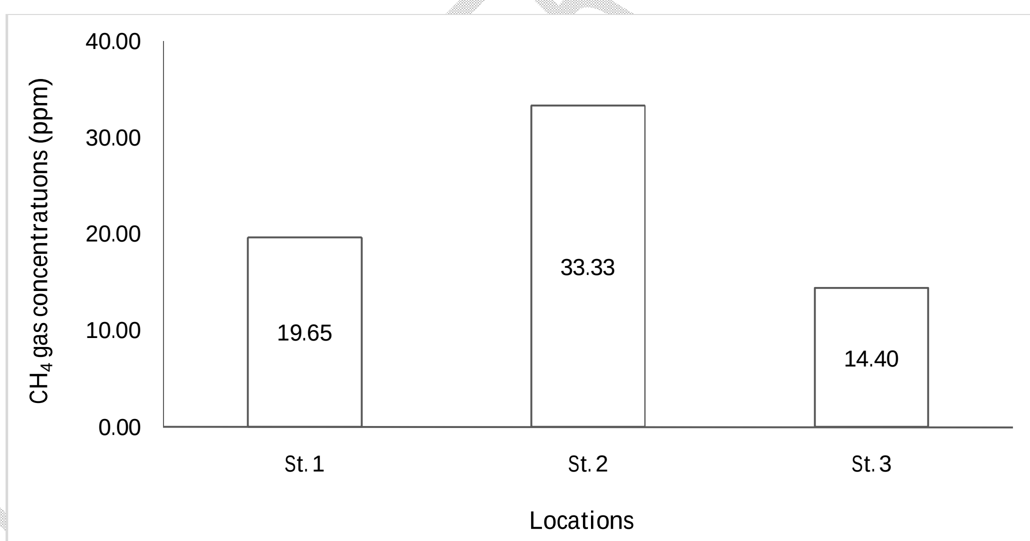

Figure 3. CH_4 Gas Concentration in Mangrove Sediments of Passo Village, Inner Ambon Bay. (Mean concentrations differ significantly at $\alpha = 0.05$; $P = 0.3604$).

Fluxes of CH_4Gases

The average CH_4 flux was 3.29 mg/m²/h. The highest CH_4 gas flux was found at St. 3, measuring 4.87 mg/m²/h, while the lowest flux was recorded at St. 1, at 1.34 mg/m²/h (Figure 4). These findings are significantly higher than those reported by Rahman *et al*. (2024c) in the coastal area of Poka Village, which ranged from 0.0047 to 0.2154 mg/m²/h. Similarly, when compared to the findings of Tubalawony *et al*. (2024), which ranged between 0.1005 and 0.1794 mg/m^2/h, the CH□ flux in this study is markedly higher. The differences in CH□ gas flux at each station may be attributed to sediment characteristics. Sandy sediments tend to have higher porosity, allowing for more rapid release of CH□ from the sediment to the atmosphere. This is supported by the report from Dhandi*et al*. (2024), which found significant differences in gas flux between muddy and sandy sediments in the mangrove ecosystem of Negeri Lama.

However, further studies are needed to determine the factors influencing the differences in CH□ concentrations or fluxes at each observation station. Although many studies have shown that water parameters such as temperature, salinity, and dissolved oxygen (DO) significantly affect the formation and release of greenhouse gases, the narrow range of these parameters makes it difficult to analyze their influence in determining the differences in concentration or flux values between observation points (Rahman *et al*., 2020a). Therefore, in this study, it is emphasized that further investigation is needed to understand the sediment characteristics at St. 1, St. 2, and St. 3.

Internal and external factors generally influence CH_4 emissions in mangrove ecosystems. Internal factors include temperature and salinity, which affect the rate of acidogenic reactions and methanogenesis in the litter decomposition process and the formation of CH_4 gas (Zhang *et al*., 2020). External factors include the input of organic and fresh waste, which increases the amount of organic matter that must be decomposed, thereby increasing the production of CH_4 gas (Kreuzwieser *et al*. 2003; Barnes *et al*. 2006; Kristensen *et al*. 2003; Kristensen *et al*. 2008; Kim 2015).Increases in nutrients and organic matter in mangrove ecosystems can be influenced by anthropogenic activities (Zheng *et al*. 2018). The organic matter accumulated in mangrove sediments can increase the amount of total organic, which is the main factor in the formation of methane gas in mangrove ecosystems (Lekphet *et al*. 2005; Prayitno 2016; Lin *et al*. 2020).

CH_4 gas emissions in mangrove ecosystems are also influenced by season, both spatially and temporally (Allen *et al*. 2010; Chauhan *et al*. 2015; Nobrega *et al*. 2016; Nazareth *et al*. 2022). The length of sunlight in summer causes fluctuations in the temperature or salinity of the water, which triggers the rate of microorganism activity in the CH_4 gas formation reaction (Allen *et al*. 2007).

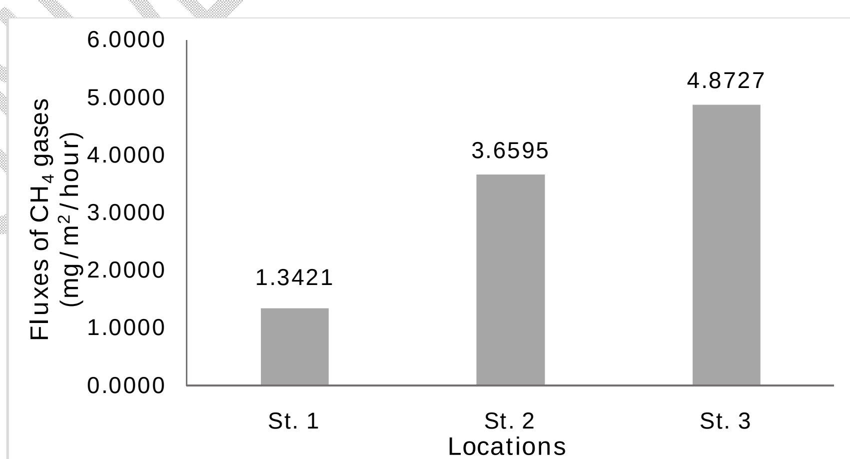

Figure 4. CH_4 Gas Flux in Mangrove Sediments of Negeri Passo, TAD

Global Warming Potential

Methane (CH_4) is one of the most significant greenhouse gases after carbon dioxide. Methane's Global Warming Potential (GWP) is higher than that of CO_2, meaning that in equivalent amounts, methane has a greater ability to trap heat in the atmosphere (IPCC, 2001).

The total GWP in the mangrove sediments of Negeri Passo reached 92.16 $mgCO_2$-e/m^2/hour. The highest GWP was contributed by Station 3, at 136.4347 $mgCO_2$-e/m^2/hour, while the lowest was observed at Station 1, at 37.5780 $mgCO_2$-e/m^2/hour (Table 1). These values correspond to the flux values at each station. The average CH_4 GWP in this study is significantly higher than the values reported by Kesaulya*et al*. (2023), Rahman *et al*. (2024c), and Tubalawony *et al*. (2024), with respective values of 7.0015 mg CO_2-e/m^2/hour, 10.8304 mg CO_2-e/m^2/hour, and 3.6907 mg CO_2-e/m^2/hour (Figure 5).

The differences in GWP, which reflect variations in CH_4 flux, are indicative of differences in the input of accumulated organic material and are not consistent with oxygen content. This assertion certainly requires further study, but findings reported by Chauhan *et al*. (2015) and Nazareth and Gonsalves (2022) have confirmed this. Their studies demonstrate how environmental variables, particularly dissolved oxygen (DO), significantly influence the formation of CH_4 gas in mangrove sediments.

Table 1. GWP of CH_4Gas Flux in the Mangrove Sediment of Negeri Passo, TAD

No		CH_4 Gas Flux (mg/m^2/jam)	GWP ($mgCO_2$-e/m^2/jam)
1	St. 1	1.3421	37.5780
2	St. 2	3.6595	102.4672
3	St. 3	4.8727	136.4347
4	Average	3.2914	92.1600

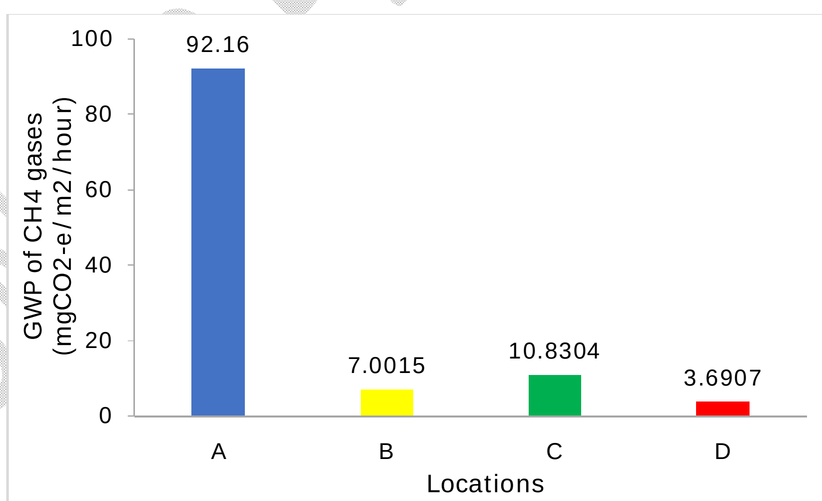

Figure 5. Variation in CH_4 Gas GWP Values in Mangrove Sediments Across Different Locations. Legend: A) This study, B) Mangrove Sediment of Waiheru Village (Kesaulya*et al*., 2023), C) Mangrove Sediment of Poka Village (Rahman *et al*., 2024c), and D) Mangrove Sediment of TanjungTiram Coast (Tubalawony*et al*., 2024).

General Discussion

The dense condition of the mangrove ecosystem in Negeri Passo does not allow for carbon stock potential observations using a Tier 3 model or direct measurements. Therefore, in this situation, carbon estimation can be performed using a Tier 1 model, which involves estimation based on the extent of the mangrove area and the average global carbon stock (IPCC, 2001). According to Alongi (2014), the average global carbon stock is 956 tons C/ha. Based on this, the potential carbon stock of the Negeri Passo mangrove ecosystem is 20,706.96 tons C. If the average age of the mangroves is 20 years, the average CO_2 uptake, based on its molecular mass equivalence, is 175.27 tons CO_2-e/ha/year.

On the other hand, the average CH_4 GWP of 92.16 mg CO_2-e/m²/hour is equivalent to a carbon emission of 8.0732 tons CO_2-e/ha/year. Referring to these values, the Negeri Passo mangrove ecosystem still plays a significant role in reducing carbon emissions, including mitigating climate change. The carbon uptake surplus is relatively large, at 167.1934 tons CO_2-e/ha/year. While this approach is not entirely accurate, in the context of carbon dynamics estimation, the Tier 1 approach is highly scientific and acceptable. However, for a more accurate estimation, carbon dynamics assessments can be conducted comprehensively using a combination of Tier 1 models and complete greenhouse gas emissions assessments, including CO_2, CH_4, and N_2O.

Conclusion

The mangrove ecosystem in Negeri Passo exhibits higher concentrations and fluxes of CH4 gas compared to the average concentrations reported in various studies from other locations. Additionally, the significant carbon sequestration potential, as estimated using the Tier 1 model approach, indicates that the mangrove ecosystem at this site plays a crucial role in climate change mitigation.

Ethical Approval

This study did not involve human or animal subjects, and therefore, ethical approval was not required (not applicable).

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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