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Fluxes of Methane Gases (CH_4) in Sediments of Mangrove and Seagrass Ecosystems in Tanjung Tiram, Ambon Bay, Indonesia

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ABSTRACT

This study aimed to analyze the flux of CH_4 gas in the sediments of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay. The research was conducted in May – June 2024. The mangrove and seagrass ecosystems at this location get inputs from the organic matter originating from litter production and domestic waste from people living around the ecosystem area. In each ecosystem, three observation points were determined based on the sediment type: sand, muddy sand, and sandy mud, each coded M1, M2, and M3 for mangrove and L1, L2, and L3 for seagrass ecosystems. Gas sampling was carried out by placing cylinder covers on each sediment type. Furthermore, 10ml of gas was taken seven times with an interval of 30s, namely 0, 30, 60, 90, 120, 150, and 180s. The gas was put into a vial, and then the gas concentration was analyzed using chromatography (GC-MS), flux, and global warming potential. The single factor ANOVA and t-test (α = 0.05) were carried out to determine the difference in each sediment's average gas concentration. The results showed that the average comparison of CH_4 gas concentrations in mangrove and seagrass ecosystems (M:L) showed no significant difference with P = 0.0637 ($P>$ 0.05). The average CH_4 flux in mangrove sediments was 0.1476mg/ m^2/ hour, more significant than that in seagrass sediments, which was 0.1424mg/ m^2/ hour. M1 and L1 recorded the most significant CH_4 fluxes in each ecosystem sediment, which were 0.1794 and 0.1509mg/ m^2/ hour. Meanwhile, the most minor flux was found in M2, which was 0.1005mg/ m^2/ hour, and L3, which was 0.1320mg/ m^2/ hour. The GWP of mangrove sediments was 3.6907mg CO_2e /m^2/ hour, more significant than the seagrass GWP of 3.5590mg CO_2e/ m^2/ hour. The flux of CH_4 gas was significantly affected by the sediment type, especially in sandy sediments. It is related to the level of porosity of sediment, which acts as a circulating space for methane gas produced from the degradation process of organic matter contained in each type of sediment. The flux and GWP values of methane gas released from sediments of mangrove and seagrass ecosystems should not be ignored in climate change mitigation, especially in areas with very low-density levels and high organic waste inputs.

INTRODUCTION

An increase in greenhouse gas emissions can trigger climate change that has a real impact on various sectors of human life, such as marine, health, ecological damage, and a decline in ecosystem services that affect the food security of a region **(Badjeck *et al.*,**

2010; Brander, 2010; Wang *et al.*, 2016; Shawket *et al.*, 2019). **IPCC (2001)** states that CO_2, CH_4, and N_2O are the main contributors to climate change. These gases are produced through anthropogenic activities such as forest burning, industry, motor vehicles, domestic waste, and water pollution. Apart from this activity, greenhouse gases, especially CH_4, are also formed naturally through the decomposition of organic matter by methanogenic bacteria **(Rahman *et al.*, 2020a; 2020c)**. The resulting CH_4 gas emissions in mangrove ecosystem range from 0.0447 – 0.2154mg/ m^2/ hour **(Rahman *et al.*, 2024a)**.

In coastal areas, organic matter accumulation occurs when the waters have calm conditions and a long flushing time **(Noor *et al.*, 2020)**. Such conditions are generally found in closed or semi-closed bay waters. **Sembel (2012)** reported that organic matter in the estuary waters of Lampung Bay exceeded the assimilation capacity of the waters. Since bay waters have a long residence time, they cannot accommodate the input of pollutant loads produced by anthropogenic activities **(Idris *et al.*, 2018)**.

One type of semi-closed waters in the Ambon Islands is the Inner Ambon Bay (TAD) waters. These waters are surrounded by mangrove ecosystems scattered along the coast and are dominated by *Rhizophora* and *Sonneratia* species **(Suyadi, 2012)**. In addition, these waters have a seagrass ecosystem that acts as a buffer for organic matter inputs from the mainland **(Krisye *et al.*, 2023)**. Forty-two rivers flow into the TAD area, and 25 of them flow throughout the year **(Asyiawati, 2010)**, so that the input of organic matter from land enters the TAD, and most of it will be deposited in the sediments of mangrove and seagrass ecosystems **(Gemilang *et al.*, 2017)**. **Salamena *et al*. (2023)** elucidated that the flushing time of organic matter entering the Outter Ambon Bay area is 1.5 weeks, while TAD is about two weeks in the rainy season **(Salamena *et al.*, 2022)**. The prolonged accumulation of organic matter in the TAD area will affect the richness of organic matter in the sediments of mangrove and seagrass ecosystems. The accumulation of organic matter in the sediments of the ecosystem will trigger a methanogenic reaction that produces CH_4 gas causing global warming **(Chauhan *et al.*, 2015)**. The amount of CH_4 gas emissions produced from the decomposition of organic matter in mangrove areas will be influenced by sediment types such as sludge, sandy mud, muddy sand, or sand **(Lilitnuhu *et al.*, 2024)**. It is related to the porosity and permeability of sediments in accommodating organic matter and releasing gases into the atmosphere **(Nurwidyanto *et al.*, 2006)**.

Studies on the CH_4 gas flux of mangrove sediments are often carried out partially, and the results have not been compared with the flux of seagrass ecosystems, especially in the same area as the gulf. Therefore, this study aimed to analyze the flux of CH_4 gas in the sediments of mangrove and seagrass ecosystems in the bay waters. The research results are expected to be scientific information adequate for managing coastal ecosystem areas that are integrated and based on greenhouse gas mitigation.

MATERIALS AND METHODS

1. Description of the study area

The study was conducted on sediments in Inner Ambon Bay's mangrove and seagrass ecosystem (Fig. 1). The research was conducted in May – June 2024. The mangrove and seagrass ecosystems in this location get inputs from organic matter from litter production and domestic waste from people living around the ecosystem area. In each ecosystem, three observation points were determined based on the type of sediment coded M1, M2, and M3 for mangrove ecosystems and L1, L2, and L3 for seagrass ecosystems. The sediment type in the mangrove ecosystem are based on the studies of **Lilitnuhu *et al.* (2024)** and **Rahman *et al.* (2024a)**. On the other hand, the characteristics of sediments in seagrass ecosystems are referred to the study of **Krisye *et al.* (2023)**. The description of the sediment types in each ecosystem can be presented in Table (1).

Table 1. Sediment type at the gas sampling point

Ecosystem	Code	Sediment type	Source
Mangrove	M1	Sandy	**Lilitnuhu *et al*. (2024);**
	M2	Sandy mud	**Rahman *et al*. (2024a)**
	M3	Muddy sand	
Seagrass	L1	Sandy	**Krisye *et al*. (2023)**
	L2	Sandy mud	
	L3	Muddy sand	

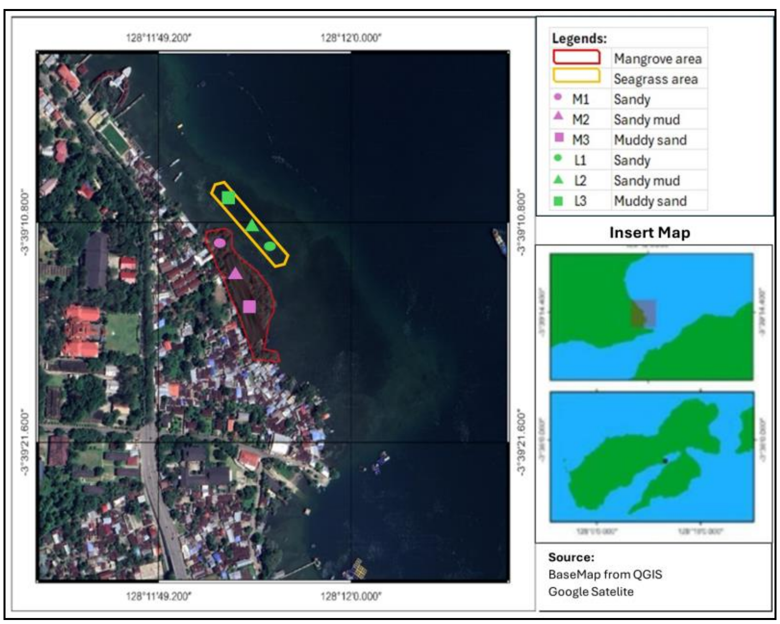

Fig. 1. Map of study sites

2. Gases sampling

Gas sampling was carried out by placing the cylinder cover concerning the **Nazareth and Gonsalves (2022)** methods on each sediment type, namely M1-M3 and L1-L3 (Fig. 2). Of each kind of sediment, 10ml of gas was taken seven times with an interval of 30s, namely 0, 30, 60, 90, 120, 150, and 180s. The gas was put into vial bottles and sent to the laboratory for gas concentration analysis using the chromatography method (GC-MS).

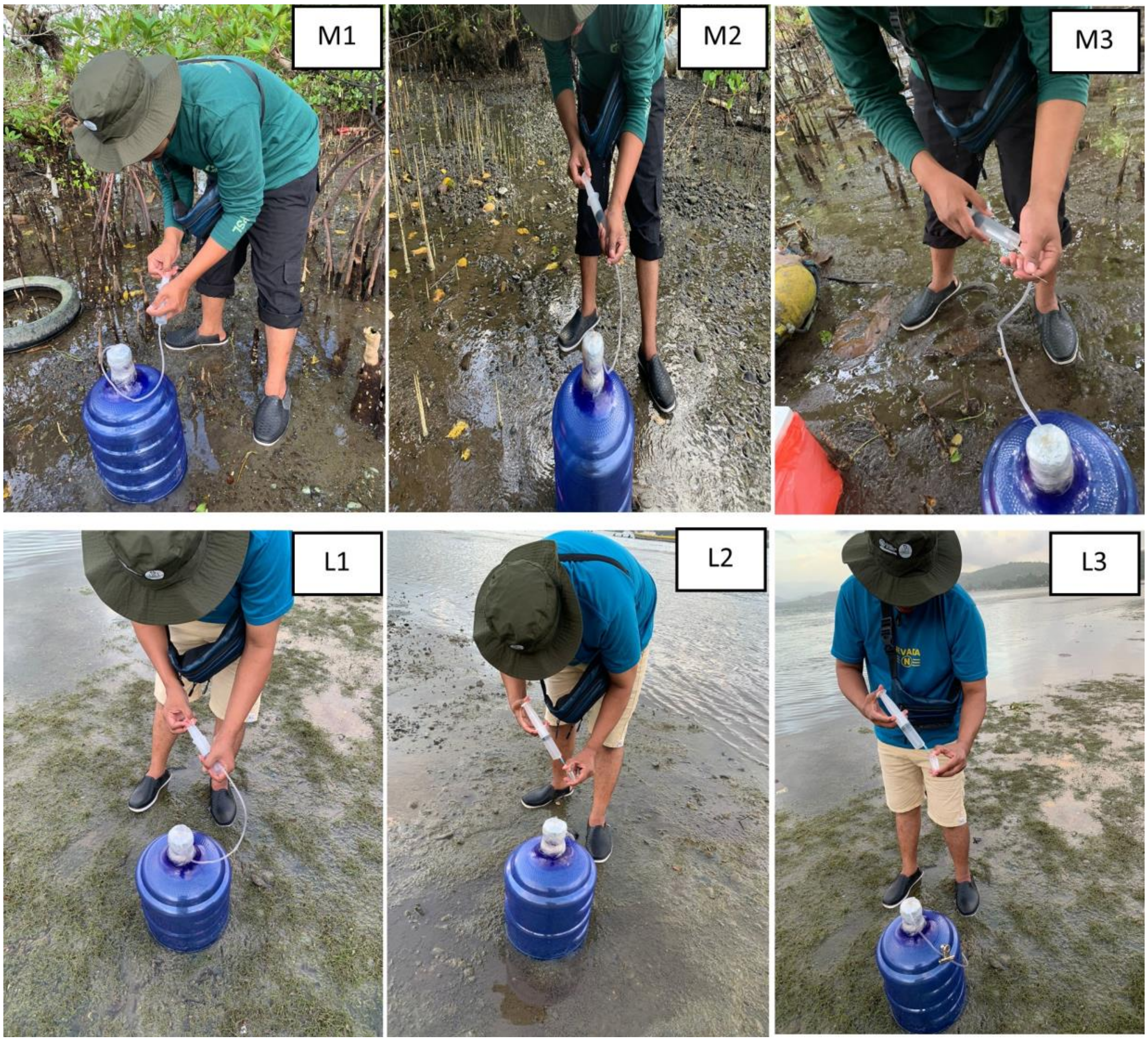

Fig. 2. Gas sampling in each sediment: M1-M3 is a mangrove sediment area; L1-L3 is a seagrass sediment area

3. Data analysis

3.1. Concentration of methane gases

The concentration of CH_4 gas was analyzed using the gas chromatography method. 3ml of gas was passed through a flame ionization detector (FID) for 2 minutes with three repetitions (Fig. 3).

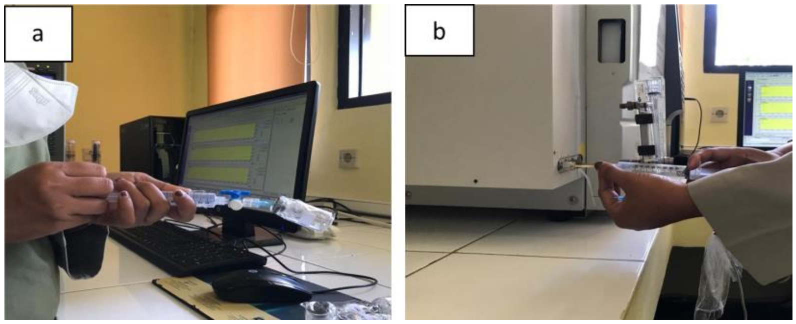

Fig. 3. Analysis of CH_4 gas concentration by gas chromatography (GC-MS) method: a) taking 2- 3ml of gas from the sample bottle; b) carbon gas analysis using GC-MS

3.2. Fluxes of methane gases

The flux of CH_4 gases was analyzed using the equation from **Rahman *et al.* (2020b)** and **Rahman *et al.* (2023)**. The value was obtained based on the methane gas concentration value from the results of the GC-MS analysis.

$$F = \left| \frac{S * V * t * mW}{(RT * A)} \right| \quad (1)$$

Notes: F: CH_4 gas flux (μg/m^2/hour or mg/m^2/hour), *S*: slope regression of carbon gas concentration measured every 30 seconds (ppm/second), V: volume of chambers (L), A: area covered by the chamber (m^2), R: the value of universal gas constant (0.082 L.atm/K/mol), T: temperature in chamber or air temperature (K), t: time transformation setting = (1 hour/gas sampling time interval), and mW = relative molecular mass of CH_4 = 16g/ mol.

3.3. Global warming potential

The global warming potential (GWP) of greenhouse gases is the equivalent value to radiation from the concentration of CO_2 gas in the atmosphere. The calculated GWP is the equivalent of greenhouse gas radiation for 100 years **(IPCC, 2001)**. The analysis of the GWP value of methane gas was carried out based on the equation of **IPCC (2001)**, which is as follows:

$$F_e = Fm \times GWP \quad (2)$$

Where, F_e is the CO_2e flux value (mg/m^2/hour) as an approach to the global warming potential value, *Fm* is the CH4 gas flux (mg/m^2/hour), *GWP* is the global warming potential value of carbon gas, which is the conversion of the emission value per mole of CH_4 gas equivalent to 25 times CO_2e emissions in 100 years **(IPCC, 2001)**.

4. Statistical analysis

The analysis was conducted through the Anova Single Factor test at a confidence level of 95% or $\alpha = 0.05$, followed by a t-test. The variance of the two samples is stated to be significantly different if the *P* obtained is less than 0.05 ($P < 0.05$), and it is stated that there is no real difference if the P is greater than 0.05 ($P > 0.05$). If the variance values of the two samples are the same, then the t-test is carried out with equation three (equation 3), while if the variance values of the two samples are not the same, then the t-test is carried out with equation four (equation 4). Each t-test was carried out at a confidence level of 95% or $\alpha = 0.05$. If $P < 0.05$, then the average concentration of CH_4 from the two sediment types is different. On the other hand, if $P > 0.05$, then the average concentration of CH_4 from the two sediment types is declared to be the same.

$$S_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \qquad t = \frac{\bar{x}_1 - \bar{x}_2}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{3}$$

$$t = \frac{\bar{x}_1 - \bar{x}_2}{S_p\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}\ ;\ df = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{1}{n_1 - 1}\left(\frac{S_1^2}{n_1}\right)^2 + \frac{1}{n_2 - 1}\left(\frac{S_2^2}{n_2}\right)^2} \tag{4}$$

Notes: $\bar{x}_1$ = average of 1 sample; $\bar{x}_{2=}$ average sample 2; n_1 = number of samples 1; n_2 = number of samples 2; S_1 = standard deviation of sample 1; S_2 = standard deviation of sample 2; *sp* = sum standard deviation; *df* = degree of freedom.

RESULTS

1. Methane gas concentration

The largest concentration of CH_4 gas in mangrove sediments was found in M1 and M3, which were 2.0786 ± 0.1503 and 2.0629 ± 0.2421ppm, respectively, while the lowest was found in M2, which was 1.7329± 0.4727ppm. For seagrass sediments, the largest concentration of CH_4 gas was found in L3, which was 2.1786± 0.1648 ppm. This value was slightly more significant than the gas concentration at L1 and L2, which were 2.0557± 0.1147 and 2.0286± 0.1894ppm, respectively (Fig. 4).

Based on the gas concentration value in each sediment, the average concentration of CH_4 gas in seagrass sediments is more significant than in mangrove sediments. The comparison of the concentration was 2.0876± 0.1563ppm for seagrass sediment and 1.9581± 0.2884ppm for mangrove sediment.

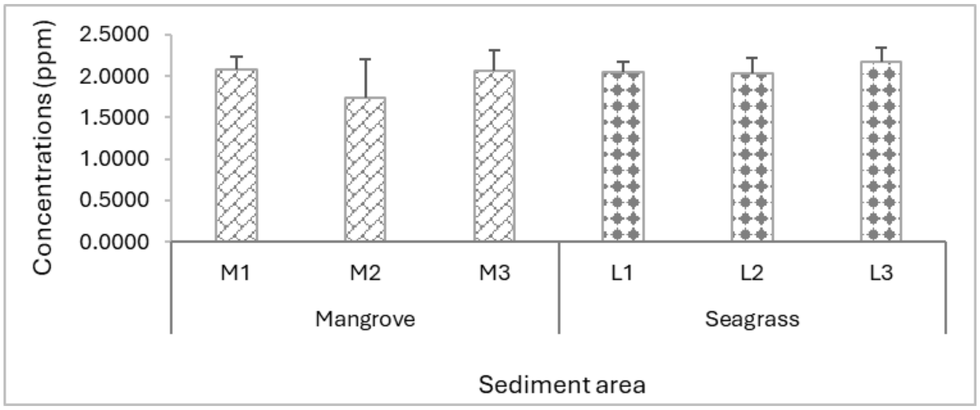

Fig. 4. The average concentration of CH_4 gas in sediments of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay

The average concentration of CH_4 gas in mangrove ecosystem sediments differed markedly, especially in M2. The t-test showed that the average concentration of CH_4 gas in the sediments M1: M2 and M2: M3 was significantly different with P of 0.0450 and 0.0431 ($P < 0.05$, respectively). Meanwhile, the mean concentration at M1:M3 is equal to $P = 0.4432$ ($P > 0.05$) (Table 2). In seagrass ecosystems, the average concentrations in L1, L2, and L3 were the same based on the results of the t-test with $P = 0.3756$ ($P > 0.05$) for L1: L2, $P = 0.0657$ ($P > 0.05$) for L1: L3, and $P = 0.0699$ ($P > 0.05$) for L2: L3 (Table 2). The average comparison of CH_4 gas concentrations in mangrove and seagrass ecosystems (M: L) showed no significant difference with $P = 0.0637$ ($P > 0.05$).

Table 2. The significance test results (t-test) of the average difference in CH_4 gas concentration in the sediment of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay

Sediment type	T*stat*	T-*critical*	*P-value*
M1 : M2	1.8439	1.7823	0.0450*
M1 : M3	0.1459	1.7823	0.4432**
M2 : M3	-1.6438	1.7823	0.0431*
L1 : L2	0.3242	1.7823	0.3756**
L1 : L3	-1.6189	1.7823	0.0657**
L2 :L3	-1.5808	1.7823	0.0699**
M: L	-1.5565	1.6838	0.0637**

Notes: *Significantly different and ** Not significantly different at the confidence level 95% or $\alpha = 0.05$;

2. Fluxes of methane gases

The average CH_4 flux in the mangrove sediments was 0.1476mg/ m^2/ hour, more significant than that in seagrass sediments, which was 0.1424mg/ m^2/ hour. M1 and L1 recorded the most significant CH_4 fluxes in each ecosystem sediment, which were 0.1794 and 0.1509mg/ m^2/ hour. Meanwhile, the most negligible flux was found in M2, which was 0.1005mg/ m^2/ hour, and L3, which was 0.1320mg/ m^2/ hour (Fig. 5).

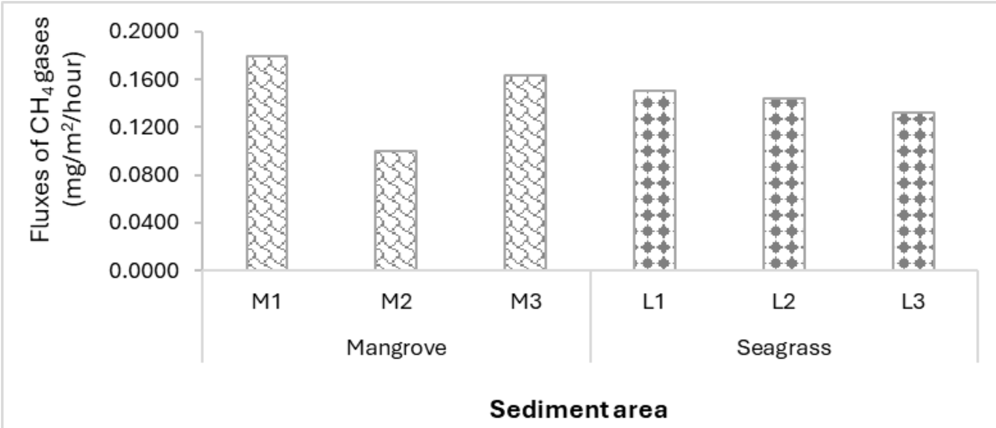

Fig. 5. The average CH_4 gas flux in sediments of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay

3. Global warming potential (GWP)

Based on the CH_4 gas flux value released from each ecosystem sediment, the GWP value of mangrove sediment was 3.6907mg CO_2e/ m^2/ hour and was greater than the seagrass GWP of 3.5590mg CO_2e/ m^2/ hour. The largest GWP in mangrove sediments was contributed by sediment in M1 and M3 with values of 4.4846mg CO_2e/ m^2/ hour and 4.0762mg CO_2e/ m^2/ hour, respectively. Meanwhile, the largest GWP in seagrass ecosystem sediments was contributed by L1 and L2 sediments with values of 3.7736 and 3.6026mg CO_2e/ m^2/ hour.

Table 3. Global warming potential (GWP) of CH_4 gas flux in sediments of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay

Ecosystem	Sediment	CH_4 fluxes (mg/m^2/hour)	GWP (mg CO_2e/m^2/hour)	average GWP (mg CO_2e/m^2/hour)
Mangrove	M1	0.1794	4.4846	3.6907
	M2	0.1005	2.5113	
	M3	0.1630	4.0762	
Seagrass	L1	0.1509	3.7736	3.5590
	L2	0.1441	3.6026	
	L3	0.1320	3.3008	

DISCUSSION

1. Concentration of methane gases

Statistically, the concentration of methane gas in mangrove and seagrass ecosystem sediments is the same both between mangrove sediments (M1 – M3), seagrass sediments (L1 – L3), and between mangrove sediments and seagrass as a whole (M-L). The CH_4 gas concentration value equation indicates that the input of organic matter, both in the form of litter and domestic waste, is evenly distributed due to seawater tides **(Rahman *et al.*, 2018)**. The even distribution of organic matter between the two ecosystems is due to their close proximity, being less than 10 meters apart. In addition, the relatively calm water conditions, since it is part of the semi-closed bay waters, allow organic matter to be retained and deposited for long in both ecosystems **(Gemilang *et al.*, 2017)**. It is in line with the findings of **Salamena *et al.* (2022, 2023)** who found a waste of resident time in Ambon Bay, which ranges from 14 to 21 days.

The CH_4 concentration value in sediment from bay water ecosystems is relatively more significant than that of sediment from open water ecosystems. It is confirmed by the CH_4 concentration value from this finding, which is 1.9581± 0.2884ppm for mangrove sediments and 2.0876± 0.1563ppm for seagrass sediments. Both concentrations are larger than the findings of **Krisye *et al*. (2022)** in open-water residential areas, with concentration values ranging from 1.76- 1.85ppm (sparse residential areas) and 1.85-1.97ppm (dense residential areas). This difference is because, in open waters, the input of organic matter from domestic waste experiences flushing by the tides of seawater, which results in less organic matter as a source of CH_4 gas formation. In addition, the difference in settlement density indicates an uneven distribution of organic matter, thus the concentration of CH_4 gas in the two is significantly different ($P< 0.05$).

2. Fluxes of methane gases

The methane gas flux indicates the magnitude of the greenhouse gas value released into the atmosphere per unit area and a given time. Based on these data, the CH_4 gas flux value is always positive, which shows a negative contribution to the increase in greenhouse gas emissions **(Rahman *et al.*, 2023)**. In the sediments of mangrove and seagrass ecosystems, the flux of greenhouse gases is influenced by various factors such as temperature, salinity, pH, dissolved oxygen, and total organic carbon **(Datta *et al.*, 2013; Lofton *et al.*, 2014)**. These factors significantly affect the methanotrophy and methanogenic processes in forming methane gases **(Nazareth & Gonsalves, 2022)**.

In this study, the distribution of organic matter was relatively the same in each ecosystem sediment. It is indicated by the same concentration of CH_4 between sediments of mangrove ecosystems and seagrass and the comparison between the two ($P > 0.05$). Thus, the difference in the flux value of CH_4 gas can be assumed to occur due to the difference in sediment types, namely sand, muddy sand, and sandy mud. **Nurwidyanto *et al.* (2006)** stated that sandy sediment types have higher porosity than the muddy sediments. The porosity of sediment that allows the release of gases into the atmosphere becomes faster **(Pepper & Brusseau, 2019)**. The findings in this study are supported by various research reports, including those of **Dhandi (2023)** and **Ubra (2023)**, who found a greater flux of CO_2 and CH_4 gases in sandy sediments (98.5% sand: 1.15% mud) compared to fluxes in sandy mud sediments (91.9% mud: 8.1% sand) and muddy sand (65.4% sand: 34.6% mud).

Specifically in seagrass ecosystems, CH_4 gas flux is also affected by the type of seagrass species. In this study, the type of seagrass in L1, L2, and L3 was *Halodule pinifolia*. The similarity of these species types is also a factor causing the small range of CH_4 gas flux in each sediment (0.1320– 0.1509mg/ m^2/ hour). Our findings regarding fluxes in each area of seagrass species showed greater values than those reported by **Yau *et al.* (2023)** in the seagrass meadows of the Mediterranean Sea, namely 0.4± 0.1 (CH_4 sediment-water fluxes) and 0.12± 0.1µmol/ m^2/ day (sea-air CH_4 fluxes).

3. Global warming potential (GWP)

The global warming potential (GWP) shows the value of CH_4 gas emissions to the increase in greenhouse gases equivalent to carbon dioxide (CO_2e) emissions. Based on the CH4 gas flux value in each ecosystem sediment, it was obtained that the average GWP in mangrove ecosystem sediments was 3.6907mg CO_2e/ m^2/ hour, while the GWP in seagrass ecosystem sediments was 3.5590mg CO_2e/ m^2/ hour. The GWP value equals 323kg CO_2e/ ha/ year in mangrove ecosystems and 311.7710kg CO2e/ ha/ year in seagrass ecosystems.

The GWP in mangrove ecosystem sediments is much lower than the carbon storage and sequestration potential. The potential carbon storage of mangroves ranges from 965 MgC/ ha **(Alongi, 2014)** to 1082.55 MgC/ ha **(Murdiyarso *et al.*, 2015)**, which are generally stored in above-ground, below-ground, and soil carbon **(Rahman *et al.*, 2024b)**. However, in the coastal area of Tanjung Tiram - Ambon Bay, the density of the existing mangroves is very low, < 500 trees/ha, and is dominated by *Sonneratia alba* and *Rhizophora stylosa*. **Rahman *et al.* (2024c)** reported that a mangrove ecosystem with a < 393 trees/ha density only absorbs 268.48 MgCO_2e/ha carbon. This value is the accumulation of carbon from mangrove stands that are >100 years old. This means the average carbon storage from the mangrove is only around 2.68 MgCO_2e/ha/year.

In seagrass ecosystems, the GWP of CH_4 gas is relatively lower compared to the carbon absorption ability of each seagrass species. **Tupan *et al*. (2021)** reported that the carbon uptake rate (CO_2e) based on leaf length growth was 1.63g/ m^2/ day in *E. acoroides* and 0.485g/ m^2/ day in *T. hemprichii*. This value equals 5.9495 MgCO_2e/ha/year in *E. acoroides* and 3.0843 MgCO_2e/ha/year in *T. hemprichii*.

The GWP of CH_4 gas in both ecosystems should not be ignored. This is because the greenhouse gas flux in the two sediments comes not only from CH_4 but also from CO_2 and N_2O gases, the GWP values of which are also significant. The GWP of mangrove ecosystems in estuary waters is 252.41mg CO_2e/ m^2/ hour or 22.0875mg CO_2e/ ha/ year **(Rahman *et al.*, 2020b)**, which is almost ten times greater than the potential CO_2 absorption from the mangroves with very low density, as reported in the study of **Rahman *et al.* (2024c)**. Meanwhile, the GWP of seagrass ecosystems from CO_2 emissions, according to **Siahaya *et al*. (2023)**, reached 55.91mg CO_2e/ m^2/ hour or 4.8977mg CO_2e/ ha/ year.

CONCLUSION

The flux and GWP of methane gas in mangrove ecosystem sediments are higher than in those recorded in seagrass ecosystem sediments. The flux of CH_4 gas is significantly affected by the sediment type, especially in sandy sediments. It is related to the level of porosity of sediment, which acts as a circulating space for methane gas produced from the degradation process of organic matter contained in each type of sediment. The flux and GWP values of methane gas released from the sediments of mangrove and seagrass ecosystems should not be ignored in climate change mitigation, especially in areas with very low-density levels and high organic waste inputs.

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