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Global warming potential of nitrous oxide fluxes from sediments of mangrove ecosystem in Waiheru coastal area, Ambon Bay

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Mangrove ecosystems can be a source or a sink of N_2O and other greenhouse gases. The Inner Ambon Bay area, including the Waiheru coast, gets organic matter inputs deposited in sediments, which has the potential to trigger an increase in greenhouse gas flux. This research was conducted to evaluate the flux and global warming potential of N_2O in sediments of the mangrove ecosystem in the area of Waiheru coastal, Ambon Bay. The sediment-trapped gas was collected from the chambers of three different types of sediments *viz.* sandy, muddy sand, and sandy mud sediments. The gas was extracted from chambers using a syringe and injected into the 10 ml glass bottle. N_2O concentrations in the samples were analyzed using gas chromatography. Average N_2O concentrations were compared between samples from different sediments using one-way ANOVA. The result showed that the mean concentration of N_2O was significantly different between the sediment types ($P < 0.05$). The highest N_2O flux in mangrove sediments was found in the sandy substrate ($0.0278 \text{ mg.m}^{-2}.\text{h}^{-1}$) and the lowest in the muddy sand substrate ($0.0135 \text{ mg.m}^{-2}.\text{h}^{-1}$). The average Global Warming Potential (GWP) in mangrove sediments of Waiheru coastal area was $6.29 \text{ CO}_2\text{-eq mg.m}^{-2}.\text{h}^{-1}$, which was contributed by sandy substrate ($8.30 \text{ CO}_2\text{-eq mg.m}^{-2}.\text{h}^{-1}$), sandy mud substrate ($6.57 \text{ CO}_2\text{-eq mg.m}^{-2}.\text{h}^{-1}$) and muddy sand substrate ($4.01 \text{ CO}_2\text{-eq mg.m}^{-2}.\text{h}^{-1}$). The reported values of GWP were relatively low based on the standard value of IPCC, which is $298 \text{ CO}_2\text{-eq mg.m}^{-2}.\text{h}^{-1}$ indicating that the nitrification and denitrification processes producing N_2O gas flux are still in normal condition, which would not cause air pollution.

[Keywords: Ambon Bay, Global warming, Nitrous oxide, Sand, Sandy-mud substrate]

Introduction

Global warming phenomena caused by increasing greenhouse gas emissions are an important issue worldwide. Extensive research has been done to estimate the impact of global warming and highlights an increase in sea surface temperature, sea level rise, rainfall, ocean acidification, oxygen concentration, and wind velocity^{1,2}. Agriculture, human health, and fisheries are at risk of being impacted by the global warming phenomena^{3,4}. Predicted changes, if realized, will cause a decrease in the quality of coastal, marine and freshwater ecosystem^{5,6}, leading to decreasing fisheries production and the loss of income of the local communities^{7,8}.

In addition to carbon dioxide (CO_2) and methane (CH_4), nitrous oxide (N_2O) also plays a significant role in driving climate change. N_2O has a climate impact potential over 298 times greater than CO_2 ^(ref 9). Microorganisms in the soil produce N_2O through nitrification and denitrification processes under both aerobic and anaerobic conditions¹⁰. The amount of N_2O formed rises notably with the increased

concentration of organic material entering aquatic environments¹¹.

Formation of N_2O generally occurs in wetland ecosystems, especially mangrove ecosystems. The mangrove litter accumulating in mangrove sediment through decomposition can produce and emit N_2O and potentially influence climate. Research shows that N_2O emission in mangrove sediment varies between 0.03 to $1.58 \text{ mg.m}^{-2}.\text{h}^{-1}$ ^(refs. 12-16).

The information on the Global Warming Potential (GWP) of N_2O flux in Indonesia still needs to be improved, especially in the mangrove ecosystems around Maluku province. It is important to be studied to support the management of mangrove ecosystems based on net zero emissions, especially in the forestry sector. Mangrove ecosystems are present along the coastal areas of Inner Ambon Bay, including locations such as Negeri Lama, Passo, Poka, Nania, and Waiheru. Six species of mangrove trees *viz.* *Avicennia marina*, *Bruguiera cylindrica*, *Ceriops tagal*, *Rhizophora apiculata*, *Sonneratia alba*, and *Osbornia octodonta* are found in Waiheru coastal waters^{17,18}.

Mangroves produce detritus and organic matter, decomposed in mangrove sediment. The decomposition can produce N_2O flux having a global warming potential equivalent to 298 CO_2 -eq. This research focused on evaluating the GWP of N_2O flux in the mangrove ecosystem of Waiheru coastal area, Inner Ambon Bay.

Materials and Methods

Description of research sites

This study was conducted in July 2022 in the ecosystem of mangrove along the coast of Waiheru, located in Inner Ambon Bay (Fig. 1). Ambon Bay is divided into outer and inner Ambon Bay. The substrate of this mangrove ecosystem is dominated by mud, and this can be observed virtually in the study site. The hydrology condition of the study area is influenced by the tidal cycle, affecting the salinity¹⁹ around the mangrove ecosystem in Waiheru. The sampling was conducted between 10.00 – 11.00 AM

with low tide conditions (-0.1 m) so that seawater would not flood mangrove sediments. The air temperature is expected to range from 28 – 30 °C with a relative humidity of 75 %.

Methodology

Sampling procedure

Bio-physicochemical parameters

This study was carried out at the ecosystem of mangrove in the area of Waiheru village coast (Fig. 1). Temperature and salinity were measured using a thermometer and hand refractometer. These parameters were measured three times at each sampling point. *In situ* measurements of Dissolved Oxygen (DO) and pH of the surface waters were done using pH meter (Lutron pH-222) and DO meter (Lutron DO-5510), respectively. Mangrove species were identified by observing mangrove morphology, such as roots, stems, leaves, flowers, and fruits^{20,21}.

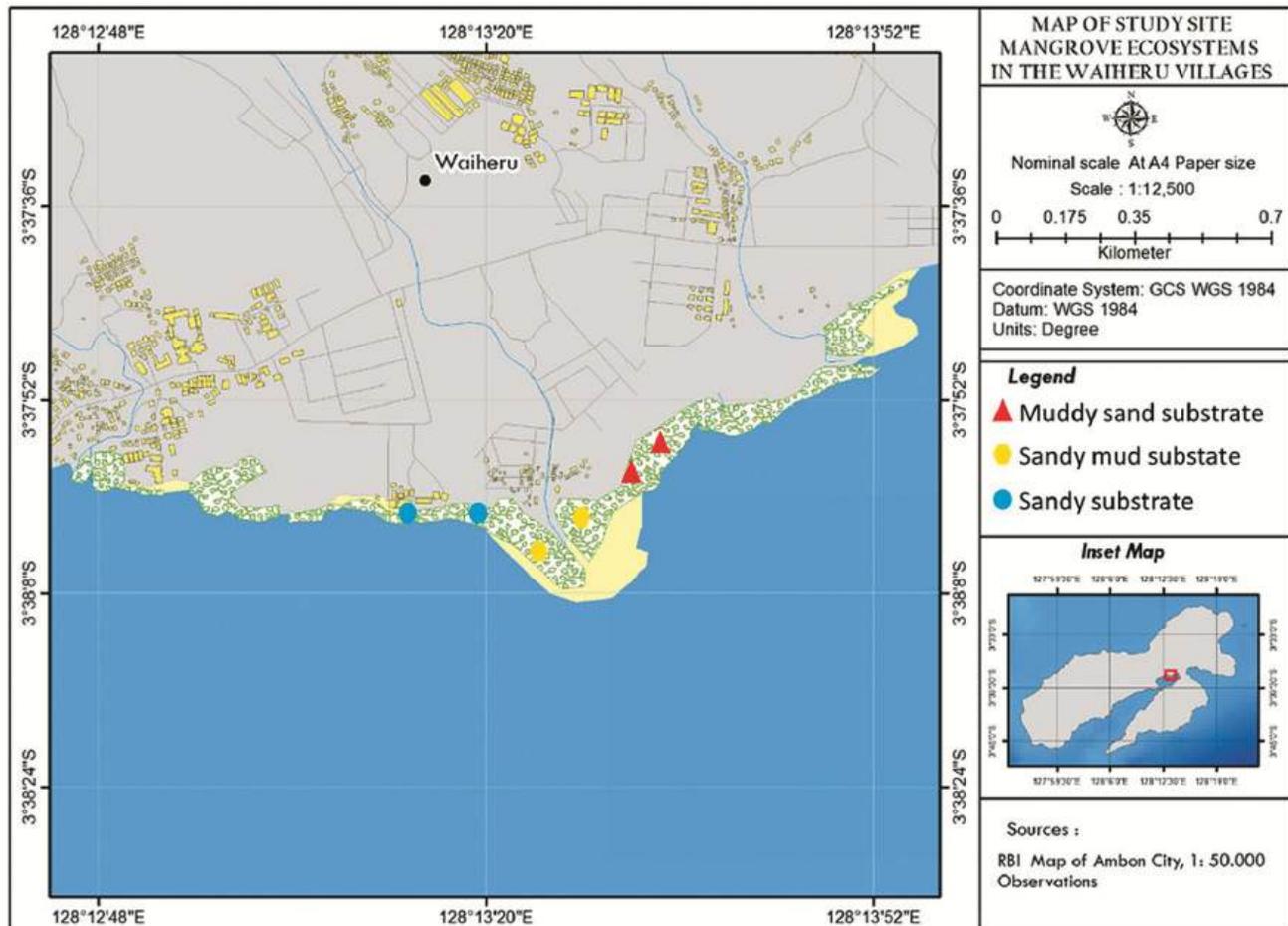


Fig. 1 — Map of the study site

Gas collection

N₂O gas was collected by positioning a chamber under the mangrove canopy on various substrate types, including sandy, sandy mud, and muddy sand substrate. The chamber is made of gallons of aqua made from BPA and PET, the bottom of which is cut so that the remaining chamber volume is 17 L. Such chambers cannot be assumed to affect the incubated greenhouse gases, including N₂O. The use of the chamber has been carried out previously in studies related to CH₄ gas flux in sediment in the Goa mangrove ecosystem²². The placed chamber is plugged into sediment 5 cm deep to avoid potential gas circulation from inside or outside the chamber. Gas was collected from the chamber using a syringe and put into the Airtight Vial Bottle (10 mL) (Fig. 2)²³. The time interval of gas collection in each sediment type was 30 seconds (0s, 30s, 60s, 90s, and 120s). The same method was repeated twice in each type of substrate. The next incubation process is done by opening the chamber and putting it back on the other sediment. All samples were kept in the box and were transported to the laboratory for further analysis.

Analysis of samples

Nitrous oxide concentration

The analysis of N₂O gas concentration was carried out using the gas chromatography method (GC-MS) conducted at the Laboratory of the Agricultural Environment Research Institute of Pati Regency – Central Java. The first stage is to take as much as 2 – 3 ml of gas from each sample bottle using a spoit (Fig. 3a), then the gas that has been taken is flowed through a Thermal Conductivity Detector (TCD) for 5 min with 3 repetitions (Fig. 3b).

Fluxes of nitrous oxide

N₂O fluxes were calculated using formula²³:

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

Where: F = flux of N₂O ($\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ or $\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), S represents the regression slope of nitrous oxide gas concentration measured every 30 seconds (ppm/s), V denotes the chamber volume (L), A indicates the total area covered by the chambers (m^2), R is the ideal gas constant ($0.082 \text{ L}\cdot\text{atm}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$), T refers to the temperature of the chamber or air (K). The constant t is the time transformation factor (1 hour divided by the sampling time interval). Lastly, mW stands for the relative atomic mass of N₂O, which is $44 \text{ g}\cdot\text{mol}^{-1}$.



Fig. 2 — Gas trapped using a chamber

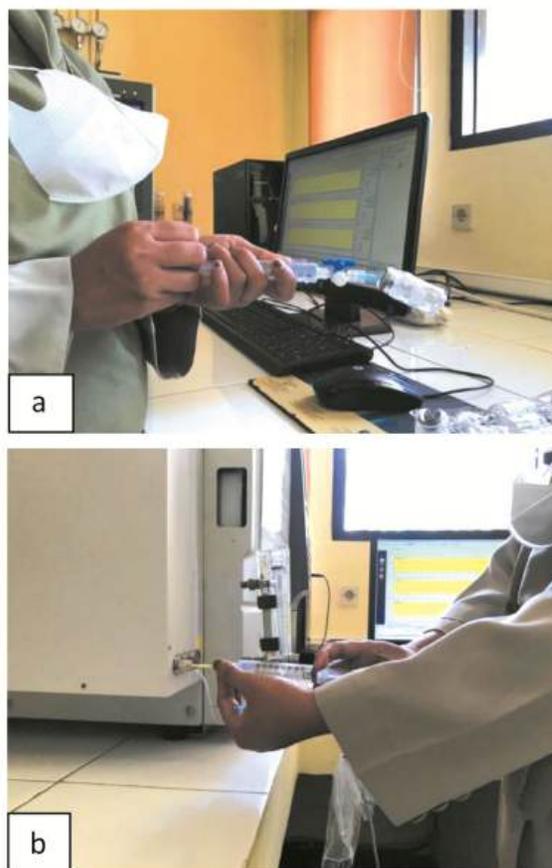


Fig. 3 — Measurement of N₂O concentration using GC-MS: a) 2 – 3 ml N₂O was taken from the bottle using injection; and b) the measurement of N₂O using GC-MS

Global warming potential of nitrous oxide

Global Warming Potential (GWP) of greenhouse gasses is equivalent to radiation of CO₂ concentration at atmosphere⁹. GWP represents the radiative effect of greenhouse gases over a 100-year period. The GWP value of N₂O was calculated using a specific formula⁹:

$$F_e = F_m \times GWP$$

Where: F_e = value of flux CO₂-equivalent (mg.m⁻².h⁻¹), which is equal to a value of global warming potential, F_m = flux of N₂O (mg.m⁻².h⁻¹), GWP = value of global warming potential of carbon which was converted from emission value per mol of N₂O, equivalent to 298 times CO₂-eq emission at 100 years.

Statistical analysis

All univariate data were analyzed using the Shapiro–Wilk normality test. Additionally, one-way ANOVA was conducted using XLStat to examine the differences in mean N₂O concentrations (ppm) across various types of mangrove sediments.

Results and Discussion

Nitrous oxide concentration

The average concentration of N₂O in each type of sediment is obtained from the average of the total concentrations of N₂O gas T_{0s} to T_{120s} and its repetition. The average values of N₂O concentration were 0.584, 0.579, and 0.555 ppm at the muddy sand substrate, sandy mud substrate, and sandy substrate (Fig. 4), respectively. These values were relatively the same as the values of N₂O in mangrove sediment from Benoa Bay, which was 0.50 – 0.60 ppm²⁴.

The concentration of N₂O gas in sandy sediment types ranged from 0.5404 – 0.5818 ppm and was the lowest in all observation time ranges, namely t_{0s} – t_{120s} (Fig. 5). The results of ANOVA single factor analysis showed that the mean concentration of N₂O in three types of mangrove sediments was different significantly with F -value = 5.134, which is higher than F critical (3.354). This means that concentrations of N₂O produced by nitrification and denitrification in mangrove sediment depend on sediment type. The average concentration of N₂O from muddy sand and sandy mud sediments was not significantly different (F -value < F critical = 0.0025 < 4.414). The average concentration of N₂O gas from muddy sand and sandy sediment significantly differed, with a P -value of 0.007 (F -value > F critical = 9.219 > 4.414).

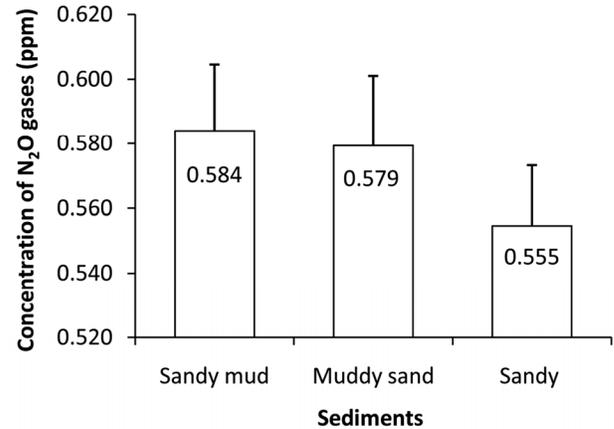


Fig. 4 — N₂O concentrations from different types of mangrove sediments at the coastal zone of Waiheru, Inner Ambon Bay

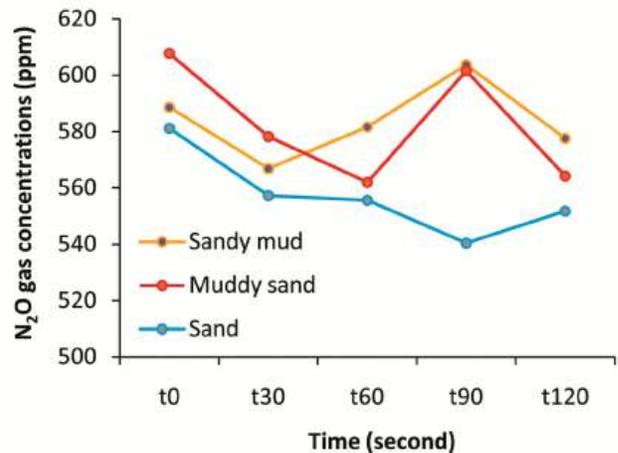


Fig. 5 — The average concentrations of N₂O gas at t_{0s} to t_{120s} in each type of Waiheru coastal mangrove sediments

Moreover, average concentrations of N₂O from sandy mud and sandy substrate showed a significantly different P -value of 0.0159 (F -value > F critical = 7.0799 > 4.414) (Table 1).

The results also showed that N₂O concentration in muddy sand and sandy mud sediment was relatively higher than N₂O concentration in sandy sediment. It shows that the nitrification process during the formation of N₂O in muddy sediment occurred relatively faster than that of sandy sediments²⁵⁻²⁷.

Fluxes of nitrous oxide

N₂O fluxes from each type of sediment were relatively different. Fluxes from muddy sand sediment were about 0.013 mg.m⁻².h⁻¹, sandy mud sediment was 0.022 mg.m⁻².h⁻¹, and sandy sediment was 0.028 mg.m⁻².h⁻¹ (Fig. 6). N₂O emissions fluctuated at

Table 1 — Variant analysis of N₂O concentration at mangrove sediment of coastal water of Waiheru village, Inner Ambon Bay

Gas	Sediment	F-value	F-critical	P-values
N ₂ O (n = 10 – 30)	Sandy mud : Muddy Sand : Sandy	5.1344 ^a	3.3541	> 0.05
	Sandy mud : Muddy Sand	0.0025 ^b	4.4139	< 0.05
	Sandy mud : Sandy	9.2187 ^a	4.4139	> 0.05
	Muddy Sand : Sandy	7.0799 ^a	4.4139	> 0.05

Note: ^a is significantly different, and ^b is not significantly different at 0.05 significance level

Table 2 — Comparison of N₂O gas flux in mangrove sediments

Locations	N ₂ O fluxes (mg.m ⁻² .h ⁻¹)	Sources
Waiheru coastal	0.063	This study
Tallo River – Makassar	0.286	Rahman <i>et al.</i> ²⁵
West Muna Regency	3.36	Rahman <i>et al.</i> ²³
Mangrove India	0.188	Chauhan <i>et al.</i> ³¹
Mangrove South China	0.527	Chen <i>et al.</i> ³²
Mangrove sediment in Colombia	1.168	Konnerup <i>et al.</i> ¹⁵

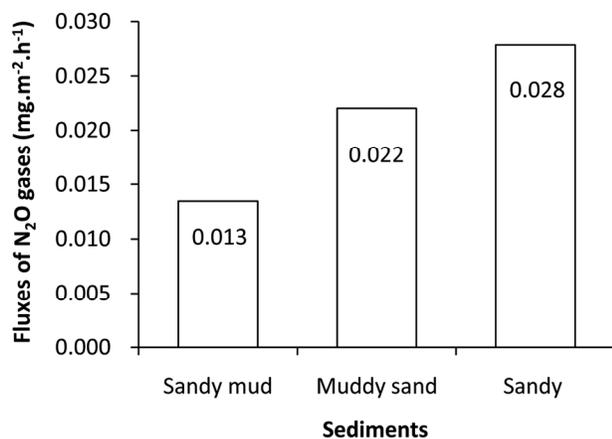


Fig. 6 — N₂O flux at different types of mangrove sediments in the study area

each type of mangrove sediment and were proportionally inverse the N₂O concentration. This is because different gas concentrations were produced at different time intervals (dc/dt).

Also, the higher N₂O gas flux (Fig. 6) compared to its concentration in sand sediments can be caused by several factors. The first is higher permeability: sandy sediments have larger and more open pores than silty sediments. It allows the gas trapped in the sediment to escape more easily into the atmosphere compared to silty sediments, which has smaller and more closed pores so that it can limit gas flow and reduce emissions¹⁰. Both are different biogeochemical activities: sandy sediments generally have a lower level of microbial life than silty sediments. Microbes in silty sediments play a role in the decomposition of

organic matter and produce greenhouse gases as a by-product. Therefore, silty sediments produce and store more methane, which can be trapped and not released into the atmosphere¹⁰. Third is the lower organic matter content: sandy sediments generally have a lower organic matter content than silty sediments. The source of organic matter in mangrove sediments comes from the production of mangrove litter and domestic waste from people who live in an around mangrove ecosystem areas²⁸⁻³⁰.

The total N₂O fluxes from mangrove sediments from the Waiheru coastal area was 0.063 mg.m⁻².h⁻¹. This value is lower than that found at Tallo River, Makassar²⁵, mangrove sediment at West Muna Regency²³, mangrove sediment at India³¹, mangrove sediment at South China³², and mangrove sediment at Colombia¹⁵ which were 0.286 mg.m⁻².h⁻¹, 3.36 mg.m⁻².h⁻¹, 0.188 mg.m⁻².h⁻¹, 0.527 mg.m⁻².h⁻¹, and 1.168 mg.m⁻².h⁻¹, respectively (Table 2).

The different values of N₂O fluxes occur due to different tide periods in the mangrove ecosystems³¹, the water content in mangrove sediment, soil temperature, oxygen concentration, ammonium (NH₄⁺), and nitrates (NO₃⁻)^{11,32-35}. All of these components support the nitrification and denitrification processes to produce N₂O, with the correlation value (r) varied from 0.764 to 0.816.

Global warming potential

N₂O is one of the greenhouse gasses that contribute to climate change⁹. The decomposition of organic matter produces increasing N₂O emission in the atmosphere. Carbon gas concentrations also increase in mangrove sediment through natural processes such as detritus degradation³⁶⁻³⁷. GWP of N₂O is the equivalent value of N₂O emissions, equivalent to 298 CO₂-eq emissions⁹.

The average GWP of N₂O in the mangrove sediment at the Waiheru coastal area was 6.29 CO₂-eq mg.m⁻².h⁻¹. The highest value of GWP was contributed by sandy sediment (8.30 CO₂-eq mg.m⁻².h⁻¹), and the lowest value of GWP was found in muddy sand sediment (4.01 CO₂-eq mg.m⁻².h⁻¹) (Table 3). It is probably caused by the

Table 3 — The values of GWP of N₂O for different types of mangrove sediment at Waiheru village, Inner Ambon Bay

Sediments	GWP (CO ₂ -eq mg.m ⁻² .h ⁻¹)
Muddy sand	4.01
Sandy mud	6.57
Sand	8.30
Average	6.29

high porosity of the sandy substrate compared to other substrates. The high porosity causes gas from the sediment to be emitted easily into the atmosphere.

This total value of GWP of N₂O emission was lower than that of N₂O gas emission from mangrove sediment at Tallo rives, Makassar²⁵, and mangrove sediment at South China³¹, which was 44.23 CO₂-eq mg.m⁻².h⁻¹ and 165.02 CO₂-eq mg.m⁻².h⁻¹, respectively. However, this GWP value is higher than that of mangrove sediment from an estuary in China (GWP = 0.18 mg.m⁻².h⁻¹)¹⁴.

Conclusion

The concentration of N₂O was significantly different among the types of mangrove sediments (*P-value* < 0.05) in the Waiheru coastal area. The highest N₂O flux was found in sandy sediment (0.0278 mg.m⁻².h⁻¹) and the lowest was in muddy sand sediment (0.0135 mg.m⁻².h⁻¹). The average GWP in mangrove sediment was 6.29 mg.m⁻².h⁻¹. GWP in muddy sand sediment was 4.01 CO₂-eq mg.m⁻².h⁻¹; in sandy mud sediment was 6.57 mg.m⁻².h⁻¹, and in sandy sediment was 8.30 CO₂-eq mg.m⁻².h⁻¹. These GWP values were relatively lower than the standard value given by IPCC (298 CO₂-eq mg.m⁻².h⁻¹). The results indicate that nitrification and denitrification processes in the mangrove sediments of the Waiheru coastal area are normal and do not produce air pollution.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

The work presented in this article is purely a numerical study. It is certified that the results reported

here are original and have not been published in any other journal.

Authors Contributions

The first author (IK) collected and analysed the data and wrote the manuscript. The second author (R) collected data, wrote the manuscript, and set the manuscript style.

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