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Seasonal soil greenhouse gas dynamics: Do mangroves contribute to warming or cooling effect? A case study from Benoa Bay, Indonesia

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ABSTRACT

Mangrove ecosystems are crucial blue carbon sinks, yet limited studies have quantified greenhouse gas (GHG) fluxes, particularly from sediments, in Indonesia. This study addresses that gap by measuring sediment-based fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) across mangrove zones in Benoa Bay, South Bali during wet and dry seasons. GHG fluxes ranged from 164.7–6529.9 $\mu gmol \cdot m^{-2} \cdot h^{-1}$ for CO_2, 27.6–166.8 $\mu gmol \cdot m^{-2} \cdot h^{-1}$ for CH_4, and 4.1–4.4 $\mu gmol \cdot m^{-2} \cdot h^{-1}$ for N_2O. CO_2 consistently acted as a source, while CH_4 and N_2O fluctuated between sources and sinks, particularly during the wet season. Although no significant seasonal or spatial differences were observed, fluxes were strongly influenced by soil properties (pH, bulk density, total Kjeldahl nitrogen) and porewater characteristics (salinity, redox potential, and dissolved oxygen). These findings highlight the dominant role of sediment and water chemistry in regulating GHG emissions. The study provides essential baseline data for national carbon accounting and underscores the need for integrating sediment management in mangrove restoration. Long-term monitoring is recommended to capture interannual variability and land-use change impacts.

Keywords: mangrove ecosystems, GHG fluxes, sources, sinks, emissions.

INTRODUCTION

Global climate change is a pressing issue driven by increased atmospheric greenhouse gas (GHG) concentrations, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Montzka et al., 2011; Kweku et al., 2018). Since the pre-industrial era, CO_2 concentrations have risen to 409.9 ppm, while CH_4 and N_2O have increased at rates of 5–10 ppb and 1 ppb per year, respectively (IPCC, 2021; Reay et al., 2018). Although CH_4 and N_2O are emitted in lower quantities than CO_2, their global warming potential (GWP) over a 100-year period is 29.8 and 273 times greater than CO_2, respectively (IPCC, 2021). This underscores the necessity of quantifying GHG emissions across diverse ecosystems, including coastal wetlands such as mangroves.

Mangrove forests have a complex role in climate dynamics, functioning as both carbon sinks and sources of GHG emissions. These ecosystems are globally significant in carbon sequestration and export to coastal waters (Dittmar et al., 2006; Alongi, 2014), yet they also contribute to atmospheric GHG fluxes through soil respiration and organic matter decomposition (Bouillon et al., 2008; Mcleod et al., 2011; Duarte et al., 2013). Mangrove forests sequester carbon at an estimated rate of 1110–1363 g C m^{-2} yr^{-1}, with approximately 70% stored in biomass (Bouillon et al., 2008; Alongi, 2009). However, studies estimate that soil carbon burial rates range between 163–226 g C m^{-2} yr^{-1}, highlighting the significance of soil carbon storage in climate mitigation efforts (Mcleod et al., 2011; Breithaupt et al., 2012; Alongi, 2014).

Despite their carbon sequestration potential, mangrove soils are also sources of atmospheric GHGs, with emissions influenced by anthropogenic nutrient inputs and environmental factors (Muñoz-Hincapié et al., 2002; Kreuzwieser et al., 2003; Allen et al., 2007; Chen et al., 2011). Soil CO_2 emissions account for approximately 20% of the net primary production (NPP) in mangroves, offsetting some of their carbon sequestration benefits (Bouillon et al., 2008). Moreover, CH_4 and N_2O, though emitted in lower amounts than CO_2, possess significantly higher radiative forcing potentials and can substantially contribute to atmospheric warming (Chen et al., 2010; Myhre et al., 2013). Environmental parameters such as salinity, oxidation-reduction potential (ORP), and soil organic carbon content play a crucial role in regulating these emissions (Chen et al., 2010, Chen et al., 2014; Welti et al., 2017). For example, CH_4 production is more prevalent in low-salinity environments due to reduced competition from sulfate- and nitrate-reducing bacteria, which are more energy-efficient than methanogenic bacteria (Purvaja and Ramesh, 2001; Biswas et al., 2007).

In addition to these environmental controls, seasonal variations significantly influence GHG fluxes in mangrove ecosystems. The rainy season generally enhances soil microbial activity and organic matter decomposition, leading to increased GHG emissions (Kristensen et al., 2008; Tang et al., 2018; Otero et al., 2020; Kitpakornsanti et al., 2022). Conversely, during the dry season, lower water levels and reduced organic matter input may alter soil redox conditions, potentially affecting CH_4 and N_2O fluxes (Padhy et al., 2020; Cameron et al., 2021). The seasonal impact on GHG emissions remains understudied in Indonesia's mangroves, highlighting the need for further research.

Indonesia holds the world's largest mangrove area, covering approximately 19.5% of the global total (Bunting et al., 2018). However, the country also faces one of the highest rates of mangrove deforestation (Richards and Friess, 2016), contributing to significant GHG emissions (Maiti and Chowdhury, 2013). Understanding the balance between carbon sequestration and GHG emissions in Indonesian mangroves is critical for developing effective climate mitigation strategies, particularly within the FoLU (forestry and other land use) Net Sink 2030 framework.

Benoa Bay, located in Bali, is one of Indonesia's most impacted mangrove ecosystems, facing threats from nutrient pollution (Raharja et al., 2018; Rahayu et al., 2018) and sedimentation due to land reclamation. The ecological degradation in this area raises concerns about whether these mangroves serve as net carbon sinks or potential contributors to global warming through soil GHG emissions. Given the critical role of mangroves in carbon cycling, it is essential to quantify the net warming or cooling effect of these ecosystems. Previous studies by Sugiana et al. (2023) have measured GHG fluxes across landward, middle, and seaward zones, but no significant differences were found among these zones. Similarly, Sugiana et al. (2024) conducted measurements across different mangrove species zones, yet the results also showed no significant differences in GHG fluxes. However, seasonal variations may still influence GHG fluxes, making this study essential. If seasonal variations also fail to show significant differences in GHG fluxes, these factors can be disregarded in future research.

This study aims to determine whether seasonal variations significantly influence soil GHG fluxes in mangrove ecosystems and assess whether the mangroves of Benoa Bay act as a net source or sink of warming potential. Unlike previous studies that mainly explored spatial differences across zones or vegetation types, this research focuses on seasonal drivers of GHG emissions – an aspect still underexplored in Indonesian mangroves. By integrating soil and porewater characteristics with GHG flux measurements, this study seeks to reveal how seasonal environmental changes shape the role of mangroves in climate regulation. The findings are particularly relevant to Indonesia's FoLU Net Sink 2030 target, which aims to achieve net-zero emissions in the land-based sector by enhancing carbon sinks and reducing emissions. Improving our understanding of the seasonal balance between GHG emissions and carbon sequestration from mangrove soils directly supports this national strategy. A clearer understanding of seasonal GHG dynamics in mangrove ecosystems can support more accurate carbon budgeting and inform national policy on sustainable coastal land use and blue carbon strategies.

METHOD

Study site and sampling design

This research was conducted in the mangrove forests of Benoa Bay, Bali, Indonesia (coordinates: 8°44’21.3”S, 115°12’35.2”E). Benoa Bay, situated in the southern part of Bali Island, is a semi-enclosed bay encompassing a mangrove area of 1168.06 hectares (As-syakur et al., 2025). The study area consists of three distinct intertidal zones: landward, middle, and seaward (Figure 1). Each zone was represented by one station, and within each station, three sub-stations were established to measure soil GHG fluxes. These zones were selected to represent varying tidal gradients and ecological functions in mangrove ecosystems – ranging from land-influenced conditions (inland direction) to ocean-dominated conditions (ocean direction) – which affect factors such as root oxygenation, organic matter input, and hydrological exchange, all known to influence GHG flux dynamics (Chen et al., 2010, Chen et al., 2014; Welti et al., 2017; Cameron et al., 2021). The dominant mangrove genera in the study area include *Rhizophora* and *Bruguiera* in the landward zone, *Rhizophora* in the middle zone, and *Sonneratia* in the seaward zone (Sugiana et al., 2022). The landward zone has the highest mangrove density (2.540 individuals per hectare), while the seaward zone has the lowest density (1.750 individuals per hectare). The average mangrove health index around the stations is categorized as moderate (Sugiana et al., 2022). Soil texture is primarily composed of fine sand, while porewater salinity and pH vary depending on proximity to the sea (Prinasti et al., 2020; Imamsyah et al., 2020; Sugiana et al., 2021). The variation in environmental conditions may indicate differences in GHG fluxes, as they show a significant relationship (Chen et al., 2014; Sugiana et al., 2024). Field sampling was conducted during the peak of the wet (January 2024) and dry seasons (August 2024) to account for seasonal variability in GHG emissions.

GHGs data collection and calculations

Each sampling plot consisted of three subplots designated as measurement points for GHG fluxes. Gas samples were collected using a 10 mL syringe after incubation within an acrylic chamber (20 × 20 × 25 cm), which was placed with 10 meters between chambers at each station and was submerged approximately 2 cm into the soil to ensure a gas-tight seal. The gas sampling occurred at four-time intervals (0, 10, 20, and 30 minutes), following the methodology of Chen et al. (2016). To minimize variability, chambers were placed in areas free of crab burrows and debris. A total of 36 gas samples were collected from 9 plots during the wet season and 36 during the dry season. Samples were stored in 10 mL vacutainer tubes before transportation for laboratory analysis.

GHG concentrations were analyzed at the Agricultural Environmental Research Institute in Pati, Central Java, using a gas chromatograph (450-GC Varian) equipped with a flame

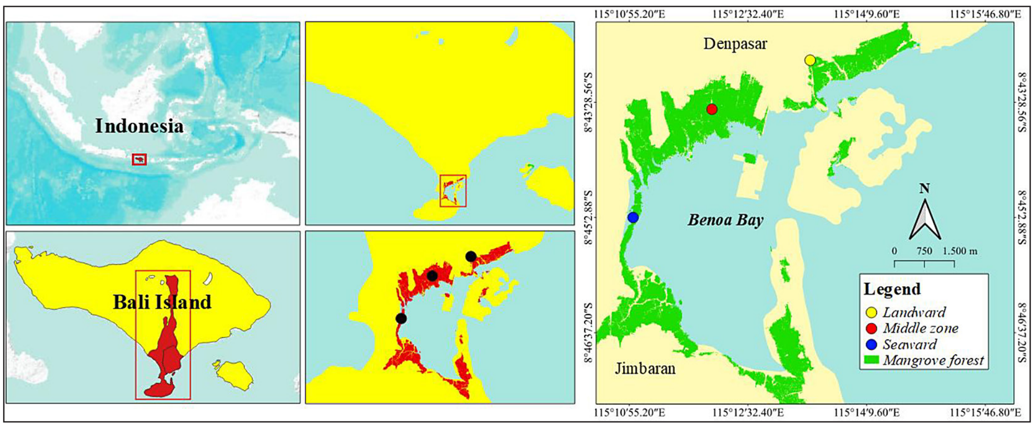

Figure 1. Location and distribution of sampling sites in Benoa Bay

ionization detector (FID), thermal conductivity detector (TCD), and a 63Ni electron capture detector (μECD). The chromatograph was fitted with a PAL autosampler injector and operated at 25 °C. Carrier gases included Ar, H_2, He, and N_2. The GHG concentrations were determined by comparing peak areas to a standard calibration curve, ensuring measurement accuracy.

The collected data were transformed into flux values using the equation from Chen et al. (2015):

$$Fm = \frac{V \times \Delta M \times 10^6}{A \times P} \quad (1)$$

where: Fm represents GHG fluxes (μgm^{-2}h^{-1}), ΔM is the slope of the linear regression of GHG concentration changes (ppm) over time (converted to per hour), V is the chamber volume (L), A is the chamber area (m^2), and P is the gas constant (22.414 Lmol^{-1}). To standardize the warming/cooling impact, CH_4 and N_2O fluxes were converted into CO_2-equivalent fluxes using:

$$Fe = Fm \times M \times GMP \quad (2)$$

where: Fe *is* the warming effect in CO_2-equivalent fluxes (gCO_2m^{-2}h^{-1} converted to MgCO_2ha^{-1}year^{-1}), M is the molecular weight (CH_4: 16.04 gmol^{-1}, N_2O: 44.013 gmol^{-1}), and GMP represents the global warming potential of CH_4 (29.8) and N_2O (273) over a 100-year period (IPCC, 2021).

Measurement of soil and porewater properties

Environmental condition measurement was categorized into two main components: soil and porewater properties, which were measured during each season. Parameters such as temperature, soil pH, salinity, and ORP were selected because they strongly influence microbial activity, redox balance, and nutrient cycling, all critical drivers of GHG production and consumption in mangrove soils (Chen et al., 2010; Koebsch et al., 2013; Welti et al., 2017). Soil samples were collected using a soil auger (5 cm diameter) at depths of 0–50 cm. The collected soil was homogenized, and 300 g was stored in plastic containers for further analysis. Soil pH was measured in situ using a Lutron 212 pH meter. To determine water content, 100 g of soil was dried at 70 °C until a constant weight was achieved (approximately 48 hours). An additional 100 g of soil was dried at 105 °C to measure bulk density. The dried soil from water content analysis was further used for grain size analysis (10 g), soil organic carbon (SOC) measurement (3 g), and the remaining portion (approximately 100 g) was used for total Kjeldahl nitrogen (TN) and total phosphorus (TP) analysis.

Grain size analysis was conducted using the dry sieve and the hygrometer methods. The loss on ignition (LOI) method was used to determine SOC content, with samples incinerated at 550 °C (Chen et al., 2014). TN analysis was performed using the flow injection analyzer (FIA) method to quantify nitrogen content in the soil.

Porewater samples were primarily found at depths of 50–100 cm from the soil surface, as data collection was conducted during low tide. Several parameters were measured, including temperature, pH, salinity, and ORP, using the Multimeter COM-600 Water Quality Tester. Dissolved oxygen (DO) was measured separately using a Lutron DO-5519 meter. To minimize disturbances that could affect GHG data, soil sampling for these measurements was conducted only after GHG sampling had been completed.

Statistical analysis

To examine differences in GHG fluxes and environmental variables (soil and porewater properties) across zones and seasons, we performed an ANOVA analysis. The Shapiro-Wilk normality test confirmed that all data were normally distributed ($\rho > 0.05$). However, no significant variations were found in GHG fluxes and environmental conditions, so further analysis using Tukey's honestly significant difference (HSD) test was not conducted. To assess seasonal differences in GHG fluxes and environmental conditions, we applied a t-test. Additionally, Pearson correlation analysis was conducted to evaluate the relationship between GHG fluxes and environmental parameters. All statistical analyses were performed using R Studio version 4.0.2.

RESULT AND DISCUSSION

GHGs fluxes

The CO_2, CH_4, and N_2O fluxes varied across different zones and seasons, with the highest CO_2 flux recorded in the seaward zone during the dry season, while the landward and middle zones showed lower and more stable values (Figure 2). On average, CO_2 fluxes were higher in the wet season than in the dry season for the middle and seaward zones, but in the landward zone, CO_2 fluxes were slightly higher during the dry season. CH_4 fluxes were also highest in the seaward zone during the dry season, while the middle and landward zones exhibited more variable values, with some negative fluxes recorded (Figure 2). During the wet season, CH_4 fluxes increased in the middle and seaward zones but remained low in the landward zone. N_2O fluxes showed a mixed pattern, with the highest flux observed in the landward zone during the dry season and the lowest flux in the seaward zone during the wet season (Figure 2). The middle and seaward zones generally exhibited low and stable N_2O fluxes across both seasons, with some negative values indicating possible N_2O sinks. Despite these variations, ANOVA results showed no significant differences in CO_2, CH_4, and N_2O fluxes among seasons and locations, indicating that seasonal and spatial factors did not have a statistically significant impact on greenhouse gas emissions in this mangrove ecosystem.

The absence of significant seasonal and spatial differences in GHG fluxes may reflect the relatively uniform environmental conditions across the study zones, including similar vegetation composition and sediment characteristics. The three zones in Benoa Bay are predominantly covered by *Rhizophora* and *Sonneratia* species and exhibit consistent canopy cover (Sugiana et al., 2024; As-syakur et al., 2025). Both dominant species are known for their similar root structures and microbial interactions, while the uniform canopy cover may contribute to relatively consistent levels of organic matter input that influence gas emissions (Srikanth et al., 2016; Lai et al., 2022: Adame et al., 2024). Furthermore, the hydrological conditions in the study area, characterized by moderate tidal influence and relatively subtle microtopographic variation within zones, may buffer environmental fluctuations between seasons, thereby contributing to the uniformity observed in greenhouse gas emissions throughout the mangrove ecosystem (Cameron et al., 2021; Castellón et al., 2022). It is also possible that prior land use changes, reclamation activities, or pollutant inputs (As-syakur et al., 2025; Suteja and Dirgayusa, 2018) may have altered site dynamics over time, resulting in a more homogenised biogeochemical environment. These factors could result in a more stable GHG emission pattern, regardless of seasonal shifts. The short sampling duration may also contribute to the lack of detected differences, as it may not fully capture

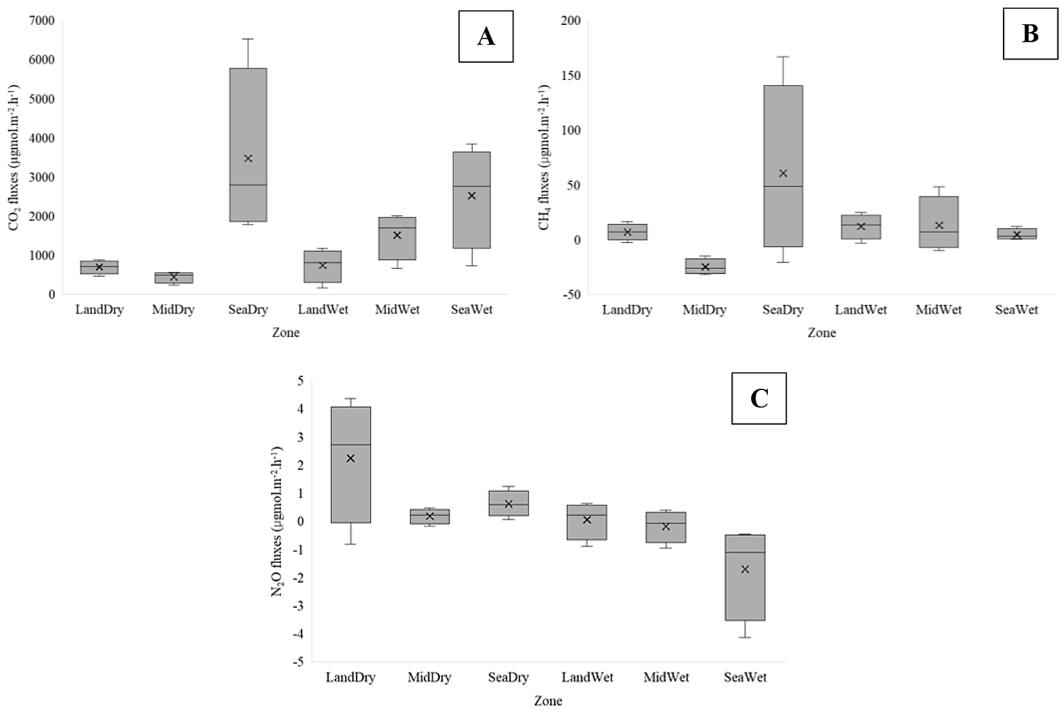

Figure 2. Fluxes of CO_2 (A), CH_4 (B), and N_2O (C) in grams molecule per m^2 over 1 h of each mangrove zone and season (LandDry: landward on dry season, MidDry: middle zone on dry season, SeaDry: seaward on dry season, LandWet: landward on wet season, MidWet: middle zone on wet season, and SeaWet: seaward on wet season)

episodic variations driven by extreme weather or ecological changes. Therefore, the observed stability might not imply actual uniformity year-round, but rather the limitation of the temporal resolution of the dataset.

GHG fluxes in mangrove soils can act as both sources (positive values) and sinks (negative values), as observed in previous studies (Konnerup et al., 2014; Atwood et al., 2017; Cabezas et al., 2018; Romero-Uribe et al., 2022). In this study, CO_2 fluxes exhibited positive values across all zones and seasons, indicating continuous emissions of CO_2 from mangrove soils to the atmosphere. The highest CO_2 flux was recorded in the seaward zone during the dry season, whereas the lowest values were found in the middle and landward zones, with no significant seasonal variations detected. CH_4 and N_2O fluxes, on the other hand, demonstrated both positive and negative values, highlighting inconsistencies in their emission trends. The highest CH_4 flux was observed in the seaward zone during the dry season, whereas negative values were more frequently recorded in the landward and middle zones, suggesting possible CH_4 oxidation processes. Similarly, N_2O fluxes fluctuated between positive and negative values, with the highest emission found in the landward zone during the dry season and the lowest in the seaward zone during the wet season. The presence of negative flux values for CH_4 and N_2O in certain zones aligns with findings from studies in North Sulawesi, Indonesia (Chen et al., 2014) and Tampamachoco coastal lagoon, Mexico (Romero-Uribe et al., 2022), where microbial activity and environmental conditions were identified as key factors influencing GHG dynamics.

While the GHG fluxes in Benoa Bay showed limited seasonal and spatial variation, contrasting patterns have been reported in other mangrove ecosystems. For instance, studies in the Ayeyarwady Delta, Myanmar (Cameron et al., 2021) and the Sundarbans, India (Padhy et al., 2020) found clear seasonal shifts in CH_4 and N_2O emissions, often attributed to monsoonal intensity, salinity gradients, and sediment characteristics. Similarly, mangroves in subtropical regions such as Florida (Liu et al., 2020) and China (Chen et al., 2014) exhibited strong spatial heterogeneity in GHG fluxes due to variations in species composition and tidal inundation regimes. In contrast, ANOVA results from this study showed no significant differences in CO_2, CH_4, and N_2O fluxes across seasons and locations, suggesting that temporal and spatial factors did not substantially affect GHG emissions in Benoa Bay. This relative stability may be influenced by consistent tidal exchange, minimal anthropogenic disturbance, and homogeneous vegetation dominated by *Rhizophora* and *Sonneratia* species, which may support similar microbial and biogeochemical processes. Although prior research has emphasized the importance of mangrove species and climatic factors, the findings of this study suggest that site-specific environmental and microbial conditions may exert a stronger influence on GHG dynamics in Benoa Bay. These comparisons highlight the need for more regionally nuanced studies to inform global carbon models and support accurate climate mitigation strategies.

Environmental conditions (soil and porewater properties)

Soil properties varied significantly across the different zones, with notable differences in soil pH, bulk density, SOC, total Kjeldahl nitrogen (TN), and water content. The dominant soil type in the landward and middle zones was sand, while the seaward zone consisted of sandy loam. Soil pH was significantly lower in the middle zone compared to the landward and seaward zones, indicating variations in soil acidity influenced by environmental conditions (Table 1). Bulk density showed a decreasing trend from landward to seaward, likely due to higher organic matter accumulation in the latter. SOC values followed a similar pattern, with the seaward zone exhibiting the highest organic carbon content, suggesting greater carbon sequestration potential. TN content was significantly higher in the landward and middle zones, with the lowest values observed in the seaward zone (Table 1). Seasonal variations were also evident, as soil water content increased in the wet season across all zones.

Porewater properties also demonstrated substantial spatial and seasonal variations. Water temperature remained relatively consistent across zones and seasons, with minor fluctuations. Porewater pH was significantly higher in the seaward zone compared to the middle and landward zones, suggesting different biogeochemical conditions that influence alkalinity (Table 1). Salinity increased towards the seaward zone, reflecting its proximity to marine influence, whereas the middle and landward zones exhibited lower salinity levels due to freshwater input. Oxidation-reduction potential (ORP) values varied significantly, with the middle zone showing the most negative values, indicative of more reduced conditions, while the seaward zone exhibited higher oxidation potential (Table 1). DO concentrations were highest in the seaward zone during the dry season, possibly due to better water exchange with the marine environment.

The soil properties of each mangrove zone exhibited significant differences, as indicated by the ANOVA test results. The predominant soil type in the landward and middle zones was sand, while the seaward zone was classified as sandy loam. Soil pH showed a notable trend, with the highest values recorded in the seaward zone and the lowest in the middle zone, suggesting varying acidity levels likely influenced by proximity to seawater and organic matter decomposition. Water content followed a similar pattern, with higher values observed in the middle zone, which is known for its muddy substrate that retains more moisture compared to the sandy seaward zone (Shepard, 1954). The bulk density was significantly lower in the seaward zone, which can be attributed to its higher organic matter content, as observed in previous studies where SOC is inversely related to bulk density (Perie and Ouimet, 2008; Matus, 2021). The highest SOC values were found in the seaward zone, aligning with findings that finer soil particles, such as those found in sandy loam, enhance carbon sequestration by binding organic matter more effectively than coarser soil types (Matus, 2021; Amorim et al., 2023). Additionally, TN values varied significantly among zones, with the highest concentrations recorded in the landward and middle zones. This variation may be attributed to differences in microbial activity related to nitrification and denitrification processes, which regulate nitrogen availability in mangrove soils (Lovelock et al., 2006; Inoue et al., 2011; Zhu et al., 2013; Queiroz et al., 2019; Dharmayasa et al., 2024). Seasonal fluctuations were also observed, with water content and SOC increasing during the wet season, further highlighting the influence of hydrological conditions on soil properties.

Porewater properties also demonstrated significant spatial and seasonal variability. Water temperature remained relatively stable across all zones, with minor fluctuations attributed to environmental exposure and tidal dynamics.

Table 1. Soil and porewater properties in each mangrove zone across different seasons

Media	Parameter	Season	Zone			
			Landward	Middle	Seaward	Average
Soil	Dominant soil type	Both	Sand	Sand	Sandy Loam	Sand
	Soil pH	Dry	6.08±0.28	5.98±0.18	6.35±0.51	6.14±0.35[a]
		Wet	6.31±0.46	5.97±0.21	6.20±0.17	6.16±0.31[a]
	Water content (%)	Dry	40±8	37±7	47±6	41±7[a]
		Wet	42±10	49±14	44±8	45±10[a]
	Bulk density (gr cm^{-3})	Dry	0.77±0.01	0.78±0.02	0.65±0.12	0.73±0.09[a]
		Wet	0.76±0.04	0.73±0.04	0.69±0.07	0.73±0.05[a]
	Soil organic carbon (SOC) (%)	Dry	3.7±0.4	3.8±1.2	4.4±1.7	4.0±1.1[a]
		Wet	3.8±1.3	3.9±1.0	4.4±0.8	4.0±1.0[a]
	Total Kjeldahl nitrogen (TN) (%)	Dry	0.06±0.02	0.05±0.01	0.04±0.01	0.05±0.02[a]
		Wet	0.05±0.01	0.04±0.01	0.03±0.02	0.04±0.01[a]
Porewater	Temperature (°C)	Dry	28.8±0.6	29.0±0.6	28.3±0.8	28.7±0.7[a]
		Wet	28.0±0.9	28.9±0.4	28.7±0.9	28.5±0.8[a]
	pH	Dry	6.44±0.29	6.34±0.19	6.61±0.33	6.47±0.27[a]
		Wet	6.62±0.42	6.33±0.22	6.58±0.18	6.51±0.29[a]
	Salinity (ppt)	Dry	23.9±1.9	25.5±3.0	21.7±1.4	23.7±2.5[a]
		Wet	26.2±1.3	25.7±2.4	26.0±0.8	26.0±1.5[b]
	Oxidation-reduction potential (ORP) (mV)	Dry	47±51	-68±19	34±69	4±70[a]
		Wet	-9±66	-12±28	25±85	2±59[a]
	Dissolved oxygen (DO) (mg L^{-1})	Dry	1.64±0.91	1.54±0.75	2.68±0.85	1.95±0.91[a]
		Wet	1.34±0.73	1.70±0.50	1.25±0.46	1.43±0.54[a]

Note: [a,b] represents the statistic different between season by t-test at 95% or $\rho \leq 0.05$.

Porewater pH was highest in the seaward zone and lowest in the middle zone, a trend consistent with soil pH variations. The elevated pH in the seaward zone is likely due to seawater intrusion and tidal flushing, which can introduce alkaline conditions into the porewater (Dangremond et al., 2015). Salinity increased towards the seaward zone, reflecting stronger marine influence, whereas the middle and landward zones exhibited lower values due to freshwater input from runoff and precipitation. This is consistent with findings that mangroves in lower salinity environments, such as *Bruguiera*-dominated areas, exhibit distinct salinity gradients compared to zones dominated by *Sonneratia* (Hall et al., 2013). ORP and DO were significantly higher in the seaward zone, likely due to enhanced water exchange and lower organic matter decomposition rates. In contrast, the middle zone exhibited lower ORP and DO levels, indicating more reducing conditions driven by anaerobic microbial activity and organic matter degradation (Hall et al., 2013). The observed variations in porewater parameters emphasize the complex biogeochemical interactions in mangrove ecosystems and their dependence on both spatial distribution and seasonal dynamics.

GHGs fluxes relationship with environmental conditions

The correlation analysis of soil properties with GHG fluxes showed several significant relationships. Soil pH had a positive correlation with both CO_2 and CH_4, indicating that higher soil pH levels were associated with increased emissions of these gases. Bulk density exhibited a negative correlation with both CO_2 and CH_4, suggesting that higher soil compaction was linked to lower gas fluxes (Table 2). SOC was positively correlated with CO_2, highlighting its influence on carbon dioxide emissions, while no significant relationship was found with CH_4 or N_2O. TN displayed a positive correlation with N_2O and a negative correlation with CO_2, suggesting that nitrogen availability played a role in the emission of these gases (Table 2).

The correlation between porewater properties and GHG fluxes also demonstrated notable patterns. Temperature showed a negative correlation with CO_2, indicating lower emissions at higher temperatures. Porewater pH was positively correlated with both CH_4 and CO_2, suggesting that pH variations influenced gas fluxes (Table 2). Salinity exhibited a negative correlation with both CH_4 and CO_2, indicating that higher salinity levels were associated with lower emissions. ORP had a positive correlation with both CO_2 and CH_4, while DO also showed a positive correlation with these gases, suggesting that oxidation conditions played a role in regulating GHG emissions in mangrove soils (Table 2).

The observed correlations between soil properties and GHG fluxes in mangrove ecosystems can be explained by various physicochemical interactions. The positive correlation between soil pH and both CO_2 and CH_4 suggests that microbial activity and organic matter decomposition processes are influenced by pH variations. Higher soil pH values may enhance microbial

Table 2. Pearson correlation coefficient values (r) among soil and porewater properties with greenhouse gases

Parameter	Pearson correlation coefficient		
	CO_2	CH_4	N_2O
Soil properties			
Soil pH	0.567*	0.706**	-0.096
Water content (%)	0.460	0.470*	-0.107
Bulk density (gr cm^{-3})	-0.692**	-0.786**	0.204
Soil organic carbon (%)	0.667**	0.460	-0.198
Total nitrogen Kjeldahl (%)	-0.565*	-0.325	0.758**
Porewater properties			
Temperature (°C)	-0.473*	-0.407	0.201
pH	0.493*	0.585*	-0.141
Salinity (ppt)	-0.487*	-0.593**	-0.086
Oxidation-reduction potential (ORP) (mV)	0.624**	0.566*	0.135
Dissolved oxygen (DO) (mg L^{-1})	0.469*	0.586*	0.379

Note: * – correlation coefficient at $\rho \leq 0.05$, while ** at $\rho \leq 0.01$.

respiration, leading to increased CO_2 emissions, while also affecting methanogenic pathways that contribute to CH_4 production (Koebsch et al., 2013; Ulumuddin, 2018). Conversely, bulk density exhibited a negative correlation with both CO_2 and CH_4, indicating that compacted soils limit gas diffusion and microbial activity, thereby reducing emissions (Chen et al., 2016; Yost and Hartemink, 2019; Sugiana et al., 2023). SOC showed a strong positive correlation with CO_2, suggesting that higher carbon availability supports microbial respiration, leading to greater CO_2 fluxes (Bouillon et al., 2008; Morell et al., 2011). Meanwhile, the significant positive correlation between TN and N_2O highlights the role of nitrogen availability in denitrification processes, where microbial conversion of nitrogen compounds results in N_2O emissions (Queiroz et al., 2019; Robertson and Groffman, 2024).

The relationship between porewater properties and GHG fluxes further emphasizes the role of environmental conditions in regulating gas emissions. Porewater pH was positively correlated with CO_2 but negatively correlated with CH_4, suggesting that variations in acidity influence microbial respiration and methanogenesis (Koebsch et al., 2013; Ulumuddin, 2018). In contrast, salinity showed a negative correlation with CH_4, indicating that higher salinity levels may suppress methanogenic activity due to competition with sulfate-reducing bacteria (Chen et al., 2014; Welti et al., 2017; Sugiana et al., 2023). The significant positive correlations between ORP and both CO_2 and CH_4 suggest that redox conditions play a crucial role in determining whether carbon is released as CO_2 or CH_4 (Marton et al., 2012; Megonigal et al., 2013). Similarly, DO exhibited a positive correlation with CO_2, reinforcing the idea that aerobic respiration dominates in environments with higher oxygen availability, while its negative correlation with CH_4 suggests that anaerobic conditions favor methanogenesis (Hall et al., 2013; Ulumuddin, 2019).

The overall trends observed in Benoa Bay's mangrove soils align with findings from other studies, where soil physicochemical characteristics are key drivers of GHG emissions. The increasing CH_4 flux in areas with lower salinity and ORP supports the idea that methanogenesis thrives under reducing and low-salinity conditions (Wang et al., 2009; Gao et al., 2019; Liu et al., 2020; Matus, 2021). Meanwhile, CO_2 emissions are closely tied to SOC availability and redox conditions, where organic carbon decomposition occurs through aerobic and anaerobic microbial processes (Bouillon et al., 2008; Morell et al., 2011). The significant correlation between TN and N_2O suggests that nitrogen cycling processes, including nitrification and denitrification, are actively contributing to N_2O emissions (Robertson and Groffman, 2024). These results reinforce the complex interplay between soil and porewater properties in regulating mangrove GHG fluxes, highlighting the need for further research to quantify the long-term impact of these interactions on coastal carbon dynamics.

Warming and cooling effect

The warming effect of CO_2, CH_4, and N_2O varies across mangrove zones and seasons, demonstrating differences in greenhouse gas dynamics. During the dry season, the highest warming effect was observed in the seaward zone, followed by the landward zone, while the middle zone exhibited a cooling effect (Table 3). In contrast, during the wet season, the overall warming effect decreased, with the landward zone still contributing to atmospheric warming, whereas the middle and seaward zones showed a net cooling effect (Table 3). This seasonal shift suggests that environmental factors influence the balance between emissions and sequestration, with the wet season exhibiting lower warming effects compared to the dry season.

A positive warming effect indicates that a zone is a net GHG source, contributing to atmospheric warming, whereas a negative value suggests that the area acts as a net carbon sink, providing a cooling effect. In the dry season, CH_4 emissions in the middle zone showed a significant cooling effect, indicating its potential role as a methane sink (Table 3). Similarly, during the wet season, a notable cooling effect was observed in the middle and seaward zones, particularly for N_2O, suggesting that environmental conditions in these areas may suppress emissions (Table 3). Overall, most zones contributed to warming in the dry season, while the wet season saw a shift where some zones acted as carbon sinks, emphasizing the role of seasonal variability in determining GHG fluxes in mangrove ecosystems.

The warming effect observed in Benoa Bay varies across zones and seasons, with some areas acting as net carbon sinks, particularly in the middle and seaward zones during the wet season. When compared to other mangrove ecosystems,

Table 3. Warming and cooling of GHGs from several regions

Region	Condition	Warming effect ($MgCO_2ha^{-1}yr^{-1}$)			Net Total	References
		CO_2	CH_4	N_2O		
Benoa Bay where familiar with the name Ngurah Rai Forest Park, Bali, Indonesia	Dry season average	0.14±0.09	0.60±1.60	1.07±1.27	1.81±2.49	This study
	Landward	0.06±0.02	0.30±0.39	2.36±2.86	2.72±2.51	
	Middle zone	0.04±0.02	-1.03±0.38	0.20±0.35	-0.80±0.19	
	Seaward	0.30±0.23	2.54±4.01	0.66±0.61	3.50±4.71	
	Wet season average	0.14±0.08	0.42±0.71	-0.64±1.28	-0.08±1.41	
	Landward	0.07±0.05	0.51±0.59	0.05±0.87	0.63±0.53	
	Middle zone	0.13±0.06	0.55±1.28	-0.19±0.74	0.50±1.84	
	Seaward	0.22±0.14	0.20±0.26	-1.80±2.22	-1.37±1.86	
	Tropical area, across vegetation species on dry season	0.6±0.1	0.2±1.0	0.4±1.1	1.2±1.2	Sugiana et al. (2024)
	Wet season in general	0.2±0.1	0.6±0.4	1.1±0.4	1.9±0.7	Sugiana et al. (2023)
Ayeyarwady Delta, Myanmar	Dry season	8±0.5	0.2±0.1	1.6±0.3	9.8±0.9	Cameron et al. (2021)
	Wet season	78.5±16.2	0.3±0.1	NA	78.8±16.3	
North Sulawesi, Indonesia	Overall dry and wet season	25.7±2	3.1±0.5	0.7±0.3	29.5±2.8	Cameron et al. (2019)
South Sulawesi, Indonesia	Both seasons are in mangrove soil	16.7±0.8	1.4±0.2	1.3±0.1	19.4±1.1	Cameron et al. (2019)
	Both season on inudated and operating ponds	0.5±0.0	0.6±0.3	NA	1.1±0.2	
Perancak Estuary, Bali, Indonesia	Both dry and wet season	44.8±6.6	NA	NA	44.8±6.6	Sidik et al. (2019)
Northern Vietnam	All season	15.3±14.3	NA	NA	15.3±14.3	Hien et al. (2018)
Honday Bay, Philippines	All season	15.9±3.7	NA	NA	15.9±3.7	Castillo et al. (2017)
Global average of mangrove forest	Sum of autotrophic and heterotrophic respiration	17.6	19.5	NA	19.5	Alongi (2014)

Note: NA: data not available.

the net total warming effect in Benoa Bay is generally lower than that reported for Perancak Estuary, North Sulawesi, and South Sulawesi, which exhibit substantially higher emissions (Table 3). The Ayeyarwady Delta in Myanmar also shows significantly greater warming effects, particularly during the wet season, suggesting higher GHG emissions from sediment decomposition and organic matter turnover (Table 3). In contrast, the results from Benoa Bay align more closely with those found in South Sulawesi's inundated and operating ponds, as well as in Honda Bay, the Philippines, which both show relatively low emissions (Table 3). This variation may be attributed to factors such as vegetation composition, stable canopy cover, hydrological conditions, historical land use, and local microtopography, as discussed in the previous section, which may limit GHG production relative to more dynamic or disturbed sites. Additionally, the net total warming effect in Benoa Bay is lower than the global average for mangrove ecosystems, further emphasizing the variability of GHG emissions across different locations. This highlights the influence of site-specific environmental conditions and anthropogenic impacts on the balance between carbon sequestration and greenhouse gas emissions in mangrove ecosystems.

CONCLUSIONS

This study found that CO_2 was consistently emitted across all zones and seasons, indicating that mangrove soils in Benoa Bay function as persistent sources of carbon dioxide. In contrast, CH_4 and N_2O fluxes fluctuated between positive and negative values, suggesting that certain zones—particularly during the wet season – may act as temporary sinks for these gases. The overall warming effect varied both spatially and seasonally, with the highest warming potential observed in the seaward zone during the dry season, while middle and seaward zones exhibited cooling effects in the wet season. Despite these patterns, statistical analysis revealed no significant seasonal or spatial differences in GHG fluxes, underscoring the greater influence of local site-specific factors – such as soil organic carbon, salinity, redox potential, and microbial activity – over temporal factors. These findings have important implications for Indonesia's climate policy, especially within the framework of the FoLU Net Sink 2030 target, which aims to achieve net-zero emissions in the forestry and land-use sectors. The ability of mangrove zones to function alternately as GHG sources and sinks highlights the necessity of protecting and restoring these ecosystems to maximize their role in climate mitigation. Conservation efforts should be tailored to maintain or enhance the site-level environmental conditions that favor GHG sequestration, especially in zones with net cooling potential. While this study provides valuable baseline data, it is limited by its short-term sampling period and the restricted number of observation sites, which may not capture long-term trends or spatial variability at finer scales. Future research should incorporate longer-term, high-frequency monitoring across diverse tidal, seasonal, and climatic conditions. Broader spatial coverage – encompassing varied mangrove species, geomorphologies, and disturbance gradients – would improve the understanding of GHG flux drivers. The use of remote sensing technologies and ecosystem-scale modeling approaches, along with integration into national GHG accounting frameworks, is also recommended to support national GHG inventories and guide evidence-based conservation and climate strategies in Indonesia's coastal zones.

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