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# Variability of Marine Carbonate Systems in Seagrass and Coral Reef Ecosystems of Pari and Lombok Islands, Indonesia

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***Abstract***

*The increase in anthropogenic $CO_2$ emissions has induced significant physical and biogeochemical alterations in oceans worldwide, including warming, acidification, and oxygen depletion. Coastal areas are particularly vulnerable due to intensified human activities and terrestrial influences, resulting in increased coastal ocean acidification driven by atmospheric $CO_2$ absorption and regional biological and anthropogenic processes. However, research on the collective impact of land-sea interaction and air-sea $CO_2$ exchange on coastal ocean acidification in severely disturbed areas, such as the small islands of Lombok and Pari in Indonesia, remains limited. This study aims to investigate the daily fluctuations in marine carbonate systems and aragonite saturation (Ωarag) levels in the vicinity of seagrass and coral reef habitats in Pari Island and Sire Bay, Lombok. Seawater samples were collected from Sire Bay, Lombok, and the coastal waters of Pari Island to analyze the carbonate systems, $CO_2$ flux, and metabolic processes. The findings indicate that Pari Island's coastal waters are more susceptible to ocean acidification than Sire Bay, Lombok, showing significantly lower pH values and Ωarag ($P<0.05$), ranging from 7.60 to 8.00 and 1.04 to 2.54, respectively. This disparity arises from the decreased temperature and salinity in Pari Island's coastal waters during the northwest monsoon, coupled with the deteriorated state of the seagrass and coral reef ecosystems, altering the equilibrium of ecosystem productivity and calcification. The study underscores the necessity of adopting specific coastal management tactics to lessen the effects on fragile ecosystems, highlighting the urgency for additional studies to evaluate adaptive and conservation strategies to preserve coastal biodiversity and ecosystem services.*

***Keywords:*** *$CO_2$, ocean acidification, pH, aragonite saturation, Pari Island*

## Introduction

Anthropogenic $CO_2$ emissions have triggered substantial physical and biogeochemical alterations worldwide (Friedlingstein *et al*., 2022), leading to ocean warming, acidification, and deoxygenation (Doney *et al*., 2020). Growing evidence indicates that the concurrent impacts of global changes caused by human activities will have enduring adverse ecological effects on marine life (Ishii *et al*., 2020; Bednaršek *et al*., 2022). Coastal regions experience heightened consequences due to increased human activities and terrestrial inputs (Li *et al*., 2020). Coastal ocean acidification stems from atmospheric $CO_2$ absorption and regional biological and anthropogenic activities (Jiang *et al*., 2024). In contrast to the consistent decrease in pH observed in the open ocean, coastal waters display a variety of specific long-term pH trends (ranging from -0.023 to 0.023 per year) at different sites (Carstensen *et al*.,

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2018; Carstensen and Duarte, 2019). This study evaluates the combined effects of land-sea interactions and air-sea $CO_2$ exchange on coastal ocean acidification, using data from Sire Bay, Lombok Island, and Pari Island—both of which are influenced by human activities.

Monitoring marine carbonate systems is crucial due to their significant role in regulating Earth's climate and marine ecosystems. Recently, there has been an increased focus on ocean aragonite saturation state (Ωarag), with analysis methods progressing from qualitative parameter identification to quantitative estimation in certain areas. However, research on small islands impacted by severe human disturbance, particularly in Pari and Lombok, remains scarce. Aragonite, a prevalent carbonate mineral in shallow marine waters, serves as a key indicator of calcification changes and the effects of ocean acidification on calcifying marine organisms in coastal regions (Mostofa *et al*., 2016; Li *et al*., 2020; Arroyo *et al*., 2022). Previous studies have revealed that the coastal waters of Pari and Lombok islands in Indonesia exhibit lower Ωarag due to low salinity (Afdal *et al*., 2024), yet the influence of biological processes, particularly the balance between photosynthesis/respiration and calcification /dissolution on aragonite saturation changes, remains unexplored in this research. Additionally, prior studies have not explored the impact of environmental conditions and coastal ecosystem health variations, particularly concerning seagrass beds and coral reefs between the two islands.

Pari Island, located near Jakarta Bay, is experiencing heightened human-induced pressure, deteriorating its seagrass and coral reef ecosystems. Hazardous chemicals potentially contaminate the bay, and water quality monitoring has revealed inadequacies in supporting marine life, recreational activities, and port operations, classifying it as moderately polluted (Edward and Kusnadi, 2023). Eutrophication in the bay has increased over time, leading to elevated nutrient concentrations and phytoplankton biomass, resulting in ecological issues such as hypoxia and algal blooms (Prayitno and Afdal, 2019; Damar *et al*., 2020; Hayami *et al*., 2020). Mangrove communities, vital for coastal protection and ecosystem health, have suffered degradation due to pollution and human activities like reclamation, with heavy metal concentrations in water and sediment threatening these ecosystems (Sari *et al*., 2019). Coral reef degradation along the coast of Pari Island has been exacerbated by environmental stressors such as oil pollution, waste accumulation, nutrient influx (eutrophication), and compromised water quality (Corvianawatie and Abrar, 2018; Abrar *et al*., 2020). The abundance and physiology of soft corals are linked to water quality, with declining conditions contributing to a shift from hard to soft coral dominance (Baum *et al*., 2016). Slight variations in conditions are observed in Sire Bay, Lombok Island, where the environment remains relatively pristine with clear waters and minimal human influence. This area's coral reef and seagrass ecosystems are healthy (Afdal *et al*., 2023).

Given the differing conditions in both ecosystem and aquatic environments, it is believed that the seagrass and coral reef ecosystems along the coasts of Pari and Lombok islands play distinct roles. This research aims to analyze the dynamics of the marine carbonate system and organism metabolism in the waters surrounding the seagrass and coral reef ecosystems of Pari and Lombok islands during the northwest monsoon season. Additionally, the study aims to assess the extent of anthropogenic pressure on the marine carbonate system and the metabolism of organisms around these ecosystems. Furthermore, the results can guide policy development to minimize human impacts on seagrass and coral reef ecosystems, which play essential roles in coastal defense, supporting biodiversity, and carbon storage.

## Materials and Methods

Pari Island, positioned at coordinates 106°36'32.796" S - 5°51'46.332" E in the Northwest part of Jakarta Bay (Figure 1A), and Sire Bay, located at coordinates 8° 21' 26.9994" S, 8° 22' 21" S, and 116° 6' 27" E, 116° 7' 47.9994" E on the northwestern coast of Lombok Island, Indonesia (Figure 1B). Pari Island forms part of the Island Group within Seribu Islands, consisting of 105 small islands covering 50.8 hectares or 5.08 km², making it a tiny island (Abrar and Wouthuyzen, 2020). Pari Island houses a seagrass ecosystem spanning 272.94 hectares (Rahmawati *et al*., 2020) and coral reefs covering about 296.1 hectares (Wouthuyzen *et al*., 2008). The seagrass ecosystem, mainly dominated by the *Enhalus acoroides* species, remains relatively stable, while the coral reefs show moderate conditions, albeit with a declining trend in coral diversity (Rifai *et al.* 2021). The waters around Pari Island are affected by water masses from Jakarta Bay and the Java Sea, characterized by their shallow depth, low salinity, and high anthropogenic influence (Koropitan and Ikeda, 2016; Koropitan, 2021).

Sire Bay is in the northern region of Lombok Island, positioned directly across from the Lombok Strait, a significant pathway for the Indonesian Throughflow (ITF), facilitating the transfer of water masses from the Pacific Ocean to the Indian Ocean (Gordon, 2005; Susanto *et al*., 2007). Sire Bay constitutes a partially enclosed water expanse hosting diverse ecosystems. Coral reefs dominate the benthic habitat, comprising 70% of the total habitat, followed by seagrasses (11%), a transition zone between seagrass and coral reef (9.63%), and sand (9.2%) (Afdal *et al*., 2023). Compared to Pari Island, the seagrass ecosystem in Sire Bay on Lombok Island is more diverse with nine species, namely *E. acoroides, T. hemprichii, Cymodocea rotundata, Cymodocea serrulata, Halodule univervis, Halodule pinifolia, Halophila ovalis, Halophila major,* and *Syringodium isoetifolium*. These beds are dense (4,326.36 stands.m$^{-2}$) with a coverage area of 75%, primarily dominated by *T. hemprichii* and *E. acoroides* (Afdal *et al*., 2023).

According to (Aldrian and Dwi Susanto, 2003), Pari Island and Lombok Island fall within the same climatic region. The monsoon wind's shift influences precipitation in both Pari and Lombok waters. The monsoon in Indonesian waters is divided into four periods: the west/northwest monsoon (December, January, February, and March), the first transition monsoon (April and May), the east/southeast monsoon (Jun, July, August, and September), and the second transition monsoon (October and November) (Alifdini *et al*., 2021; Monerie *et al*., 2021; Wahyudi *et al*., 2023). Pari and Lombok experience its rainy season from November to April, peaking in December to February, while the dry season lasts from May to October, with a peak in June to August (Aldrian and Dwi Susanto, 2003; Hendon, 2003; As-Syakur *et al*., 2011).

### *Sample collection and in-situ measurement*

Sampling and in-situ measurements of seawater properties were carried out during the northwest monsoon in both coral reef and seagrass ecosystems on Pari Island from February 16 to 17, 2021, and in the Sire Bay coastal waters on March 13 to 14 and March 14 to 15, 2021, for coral reef and seagrass ecosystems respectively. Sampling conducted during the northwest monsoon, which overlaps with the rainy season, seeks to examine the influence of land-sea interaction on the carbonate system in the waters of Pari Island and Sire Bay, Lombok. This is due to heavy rainfall, which increases land-derived input and reduces water salinity. The sampling occurred every 4 hours over 24 hours, covering daytime, nighttime, and various tidal conditions, with specific sampling times at 8 a.m., 12 p.m., 4 p.m., 8 p.m., 12 a.m., 4 a.m., and 8 a.m. The tides around Pari Island's waters follow a diurnal pattern, with one high and one low tide each day. The lowest tide, reaching 0.3 m, occurs at 6 pm, while the highest tide, at 0.8 m, occurs at 10 am (Figure 2). In contrast, Lombok's waters in Sire Bay exhibit a mixed tidal pattern, characterized by two high tides and two low tides of varying heights. The lowest tides occur at 5:13 am and 4:50 pm, measuring 0.5 m and 1.0 m, respectively, whereas the highest tides are recorded at 11:45 am and 10:56 pm, with heights of 1.5 m and 1.8 m, respectively (Figure 2). Daily sampling investigates diurnal variations in carbonate parameters, including pH, total alkalinity (TA), and dissolved inorganic carbon (DIC). This is crucial as biological processes like photosynthesis, respiration, and calcification can significantly influence the daily cycle. Additionally, daily data establish a baseline for

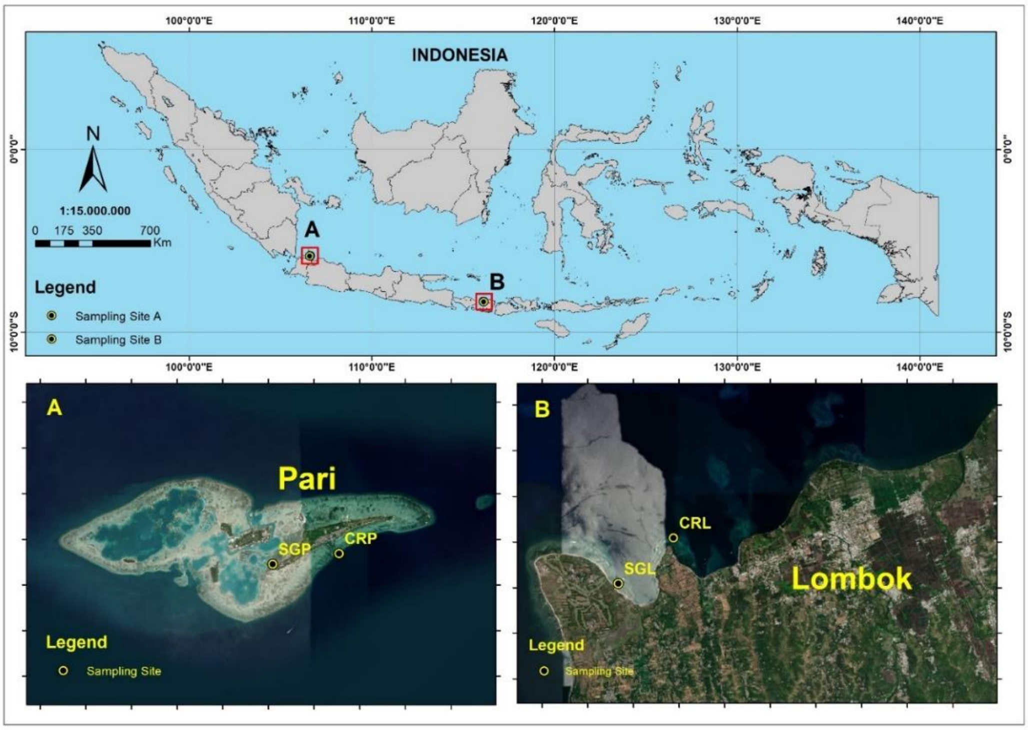


**Figure 1.** Sampling locations in seagrass (SGP) and coral reef (CRP) ecosystems of Pari Island and in seagrass (SGL) and coral reef (CRL) ecosystems of Sire Bay Lombok, February and March 2021.

identifying long-term trends, such as the effects of climate change or anthropogenic disturbances on marine carbonate systems. Monitoring daily fluctuations also helps assess the role of seagrasses in buffering ocean acidification, primarily to support the health of surrounding coral reefs.

Seawater samples were gathered to analyze the carbonate system (specifically total alkalinity), nutrients (phosphate, nitrate, silicate), and chlorophyll-a content. Simultaneously, on-site measurements were conducted to assess another aspect of the carbonate system, pH, and atmospheric $CO_2$ concentration, alongside various seawater physicochemical parameters, including temperature, salinity, and dissolved oxygen (DO). In-situ pH measurements were carried out using a Mettler Toledo Portable Single-Channel pH meter, calibrated with 7.00 and 10.00 pH buffers manufactured by Merck KGaA via EMD Millipore Corporation, ensuring accuracy within ±0.01 pH. Calibration was performed at a consistent temperature of 25°C. Atmospheric $CO_2$ partial pressure was determined using a Lutron GC-2028 $CO_2$ meter, which also integrated a thermometer with a measuring range of 0 to 4000 ppm, offering one ppm resolution and an accuracy of ±40 ppm, concurrently with surface water $pCO_2$ measurements. The Conductivity Temperature Depth – SeaBird Electronic (CTD SBE) 19plusV2 device recorded physical properties of seawater such as temperature (range: -5 to 35°C, accuracy: 0.005°C) and salinity (range: 0 - 45, accuracy: 0.003). Dissolved oxygen (DO) was assessed using a Hanna HI98194 multiparameter DO meter, with a range of 0.00 to 50.00 ppm ($mg.L^{-1}$) and accuracies of 0.0 to 500.0% and 0.0 to 300.0% of saturation.

Seawater samples were collected from the surface layer using a Niskin water sampler, given the relatively shallow waters around the seagrass and coral reef ecosystems. The water column can be relatively homogeneous in shallow waters, particularly in areas with strong mixing due to tides, currents, and wind-driven turbulence. Carbonate system parameters (pH, DIC, TA, Ωarag) may not differ significantly between surface and bottom layers (Hofmann *et al.*, 2011). The seawater sample intended for total alkalinity (TA) analysis was transferred to a 300 ml Duran sample bottle, adding 60 microliters of $HgCl_2$ solution to prevent biological activity, as the DOE (1994) recommended. Meanwhile, seawater samples for nutrient and chlorophyll analysis were transferred to 1 L polyethylene bottles. These bottles were then stored in a cool, dark box to maintain a low temperature. Subsequent analysis was conducted at the Marine Biogeochemistry laboratory at the Research Center for Oceanography, Indonesian Institute of Sciences.

### *Sample analysis*

TA was determined by incrementally introducing acid into seawater using specified flow rates in the alkalinity titrator setup (Kimoto *et al.*, 2001). Two high-precision valveless piston pumps pumped seawater and an HCl solution into a mixing coil. The resulting acidic solution (pH ranging from 3.5 to 3.9) was subsequently directed through a flow cell to measure TA. Before conducting measurements, the instrument underwent calibration using certified reference material (CRM) obtained from Dickson Laboratory, identified by batch number 156. This CRM possesses a precisely known total alkalinity value of 2236.51 ± 0.57 $\mu mol.kg^{-1}$.

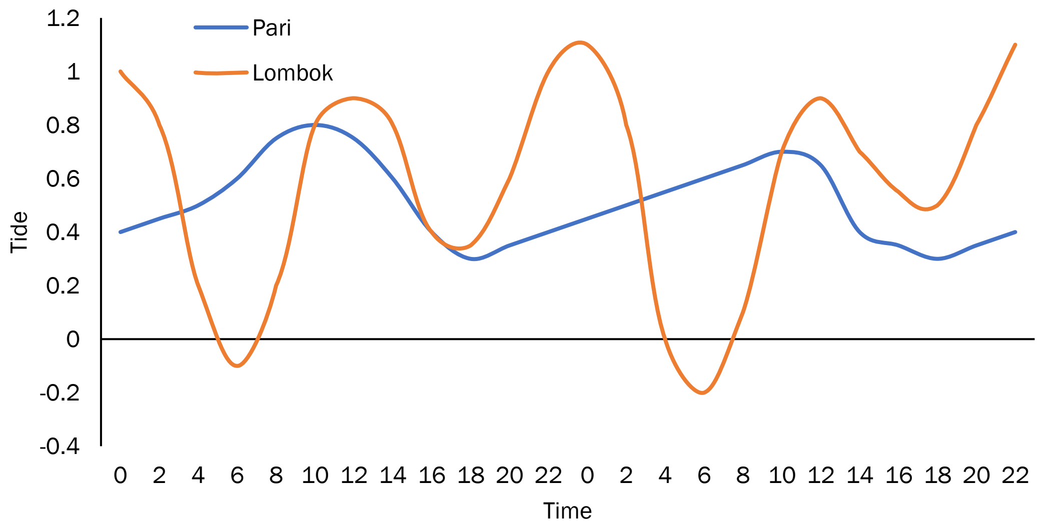


**Figure 2.** Tidal patterns in the waters of Pari Island on February 16-17, 2021, and in Sire Bay, Lombok, on March 13-14, 2021.

Other carbonate parameters, such as dissolved inorganic carbon (DIC), aragonite saturation state (Ωarag), and partial pressure of $CO_2$ ($pCO_2$), were computed utilizing the CO2SYS software package (Pierrot *et al.*, 2006). The $CO_2$ system coefficient utilized was initially derived from (Mehrbach *et al.*, 1973) and subsequently refined by (Dickson and Millero~ 1987). Nutrient concentrations ($PO_4$, $NO_3$, and $SiO_4$) were quantified employing a spectrophotometric technique (Strickland and Parsons, 1968). Chlorophyll-a levels were determined fluorometrically using a Trilogy fluorometer (Trick *et al.*, 2010).

To differentiate the effects of biological or chemical factors from those of physical processes on the marine carbonate system, dissolved inorganic carbon (DIC) and total alkalinity (TA) were standardized using a consistent salinity value of approximately 35, following the method outlined in Equation (1) by Chen and Millero (1979):

$$NP = \frac{P^{obs}}{S^{obs}}\ x\ S^{ref} \quad (1)$$

Here, NP represents salinity-adjusted TA and DIC, with $P^{obs}$ denoting the observed TA and DIC measurements, $S^{obs}$ indicating the measured salinity, and $S^{ref}$ representing the average oceanic salinity of 35.

### *$CO_2$ flux*

The calculation of the flux or exchange of $CO_2$ between the air and sea is determined by the subsequent formula:

$$CO2\ flux = K\ .\ \alpha\ .\ \Delta pCO2_{sw-atm} \quad (2)$$

$$\Delta pCO2 = pCO2_{sw} - pCO2_{atm} \quad (3)$$

Where: K= the gas transfer velocity, which is dependent on wind speed, has been derived using wind speed data retrieved from the ECMWF (European Centre for Medium-Range Weather Forecasts) website and selected based on latitude, longitude, and sampling time; α= the coefficient of solubility, which varies with temperature and salinity $\Delta pCO_2$ sw–atm= the difference between the partial pressure of $CO_2$ in surface water and the atmosphere indicates whether water acts as a source or sink of $CO_2$. If the seawater $pCO_2$ exceeds atmospheric levels (resulting in a positive value), it functions as a source, emitting $CO_2$ into the atmosphere. Conversely, if seawater $pCO_2$ is lower than atmospheric $pCO_2$ (leading to a negative value), it acts as a $CO_2$ sink, absorbing $CO_2$ from the atmosphere.

### *Net Ecosystem Calcification (NEC) and Net Ecosystem Production (NEP)*

Calcification, which involves the precipitation or dissolution of $CaCO_3$, was assessed utilizing the alkalinity anomaly technique as outlined in studies by (Longhini *et al.*, 2015) and Smith and Kinsey (1978). NEC was determined using the subsequent formula:

$$NEC = -0.5\ .\ \Delta TA\ .\ z\ .\ \rho/\Delta t \quad (4)$$

In the equation provided, ΔTA represents the alteration in total alkalinity ($\mu mol.kg^{-1}$), while z denotes the mean water depth (m). ρ signifies the density of seawater ($kg.m^{-3}$), and Δt represents the duration of the sampling interval measured in hours.

NEP (Net Ecosystem Production) was computed by measuring the alteration in total inorganic carbon concentration throughout the incubation period while disregarding fluctuations in total alkalinity resulting from the precipitation or dissolution of $CaCO_3$. The metabolic processes of organic matter within the aquatic environment can be described as the equilibrium between photosynthesis and respiration (Smith and Kinsey, 1978; Longhini *et al.*, 2015).

$$NEP = [(\Delta DIC\ .\ z\ .\ \rho/\Delta t) - G - F] \quad (5)$$

Where: NEP = Net Ecosystem Production ($mmol.m^{-2}.h^{-1}$); ΔDIC = the alteration in dissolved inorganic carbon concentration ($\mu mol.kg^{-1}$); P= seawater density ($kg.m^{-3}$); t= the duration of the sampling interval in hours; G = signifies the carbonate calcification rate ($mmol.m^{-2}.h^{-1}$); F= the air-sea $CO_2$ flux ($mmol.m^{-2}.h^{-1}$); Z= the average water depth (m).

### *Statistical analysis*

The Shapiro-Wilks test revealed non-normal data with a $P< 0.05$. Consequently, the Anova-one way test was employed to assess disparities in various factors, including physicochemical parameters, carbonate systems, NEP, calcification rates, and $CO_2$ fluxes across different categories of both locations (Pari and Lombok), and ecosystem type (seagrass and coral reefs). Multivariate analysis employing Partial Least Squares was utilized to pinpoint the primary factors influencing Ωarag at Sire Bay Lombok and Pari Island coastal waters.

## Result and Discussion

### *Hydrography*

The coastal waters between the islands of Pari and Lombok exhibit significant differences in sea surface temperature and salinity during the northwest monsoon ($P< 0.05$). However, their daily patterns remain consistent (Figure 3). Lombok's coastal waters consistently register higher temperatures and salinity than those around Pari Island, regardless of whether in the coral reef or seagrass ecosystems. Specifically, in Sire Bay, Lombok, the range of sea surface temperatures fluctuates between 28.14°C to 31.26°C, with an average of 29.23 ± 0.96°C. The highest temperature is usually detected in the seagrass ecosystem around 4 pm, whereas the lowest temperature occurs approximately at 8 am near the coral reef ecosystem. These temperatures are cooler than those experienced during transition season 1 (April) but warmer compared to transition season 2 (October) at the same site (Afdal *et al*., 2023). The higher sea surface temperature in Sire Bay, particularly around the seagrass ecosystem, is attributed to the shallowness of the waters and increased sunlight during the day, resulting in higher sea surface temperature and salinity due to intense evaporation. Salinity in Sire Lombok Bay varies from 29.30 to 33.05, with the highest salinity (33.05) recorded at 4 pm in the seagrass ecosystem.

In Pari Island waters, the low sea surface temperature observed in February aligns with findings from prior studies (Corvianawatie, 2019). This research indicates that February and August typically experience the lowest sea surface temperatures around the island, coinciding with the peak periods of the northwest and southeast monsoons. This phenomenon is attributed to strong surface winds in the region, leading to the thorough mixing of water masses both horizontally and vertically (Corvianawatie, 2019). Salinity in Pari Island waters is relatively lower, ranging from 28.74 to 30.90, likely due to significant rainfall during the sampling period.

The notable variations in temperature and salinity between the two sites did not correlate with differences in the biological chemical composition of the water. Parameters such as dissolved oxygen (DO), chlorophyll-a, phosphate, and nitrate showed no significant variance between the two research locations ($P>0.05$). The TRIX index, derived from measurements of dissolved oxygen, phosphate, nitrate, and chlorophyll-a concentrations during observation, indicates that both sites exhibit oligotrophic or less productive conditions with an average TRIX consistently below four units (Giovanardi and Vollenweider, 2004). However, the TRIX index for Pari Island's waters is generally slightly higher than that of Sire Bay, Lombok. The observed low TRIX index value in the waters of Pari Island is believed to stem from rainwater dilution in the upper layer, resulting in diminished concentrations of nutrients and chlorophyll.

Variations are evident in DO, chlorophyll-a, phosphate, and nitrate distribution patterns across different ecosystems (Figure 4). The daily DO fluctuations indicate that the seagrass ecosystem in Sire Bay, Lombok, significantly impacts changes in dissolved oxygen levels. Daytime levels of DO peak at 10.20 $mg.L^{-1}$, attributed to photosynthesis, while nighttime levels drop to 3.84 $mg.L^{-1}$ due to respiration processes. The daily dissolved oxygen (DO) pattern in the waters surrounding the coral reef ecosystem of Sire Bay Lombok displays similarity without significant fluctuations. Conversely, the DO patterns around the seagrass ecosystem and coral reefs of Pari Island exhibit distinct variations, likely influenced by tidal changes, with the impact of organism metabolism on DO concentrations less evident.

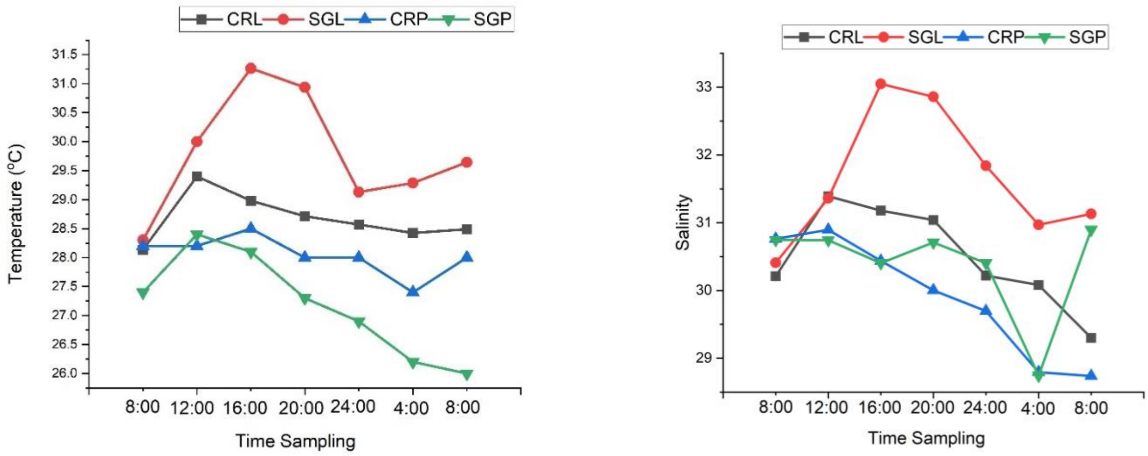


**Figure 3.** The daily variations in sea surface temperature and salinity within the seagrass and coral reef ecosystems surrounding Pari Island and Sire Bay Lombok, February and March 2021, respectively. CRL=Coral Reef of Lombok, SGL=Sea Grass of Lombok, CRP=Coral Reef of Pari, SGP=Sea Grass of Pari

### *Carbonate system, aragonite saturation state (Ωarag), and $CO_2$ flux*

Like temperature and salinity, the coastal regions of Sire Bay, Lombok, and Pari Island exhibit notable discrepancies in carbonate system parameters, including Ωarag and $CO_2$ flux, which are statistically significant ($P < 0.05$). Daily fluctuations across ecosystems and locations vary, as depicted in Figure 5. Sire Bay in Lombok displays heightened pH, total alkalinity (TA), and Ωarag levels. At the same time, Pari Island showcases increased partial pressure of $CO_2$ ($pCO_2$) in its coastal waters, leading to continuous $CO_2$ emission into the atmosphere throughout the observation period. Notably, nocturnal $CO_2$ flux is pronounced within the seagrass ecosystem, contrasting with minimal flux during daylight hours within the same ecosystem. In Sire Bay, Lombok, pH levels range from 7.7 to 8.3, peaking at 4 pm and reaching a nadir at 8 am, particularly near the seagrass ecosystem. Likewise, the aragonite saturation state fluctuates between 1.73 and 4.37. Comparable trends are observed within the seagrass ecosystem of Pari Island, although with slightly diminished pH levels ranging from 7.60 to 8.00 and Ωarag ranging from 1.04 to 2.54. These values are notably lower than the aragonite saturation threshold for tropical coastal waters in the West Pacific, which stands at 3.8 (Kuchinke *et al*., 2014), and below the optimal average for tropical coral reef growth (>3.3) (Xue *et al*., 2017; Albright *et al*., 2018; Hall-Spencer and Harvey, 2019). This suggests that Pari Island's coastal waters are more susceptible to ocean acidification than those of Sire Bay, Lombok. The acidification of Pari Island's coastal waters arises not

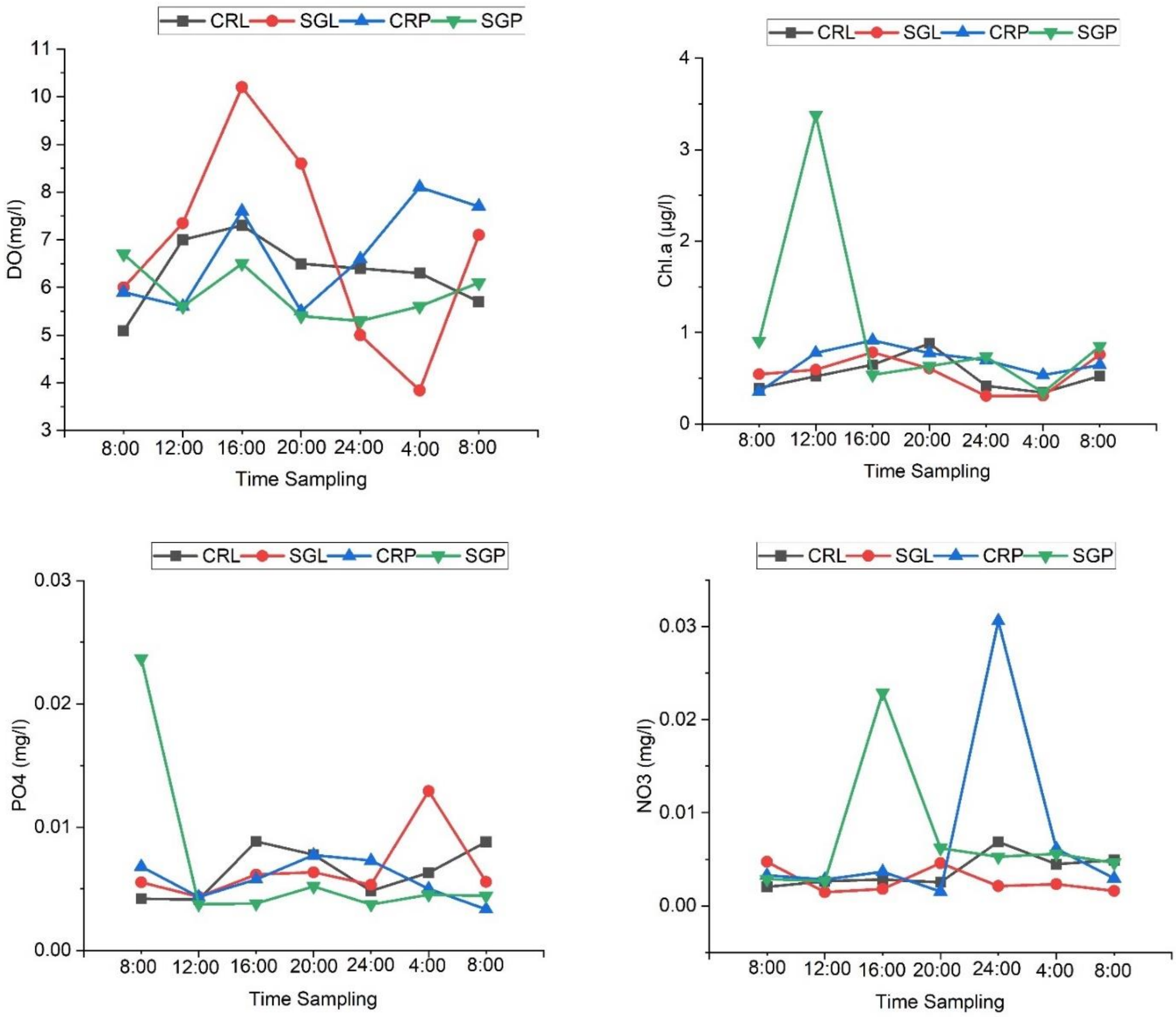


Figure 4. The daily changes in seawater chemistry parameters within the seagrass and coral reef ecosystems surrounding Pari Island and Sire Bay, Lombok, February and March 2021, respectively. CRL= Coral Reef of Lombok, SGL= Sea Grass of Lombok, CRP= Coral Reef of Pari, SGP= Sea Grass of Pari

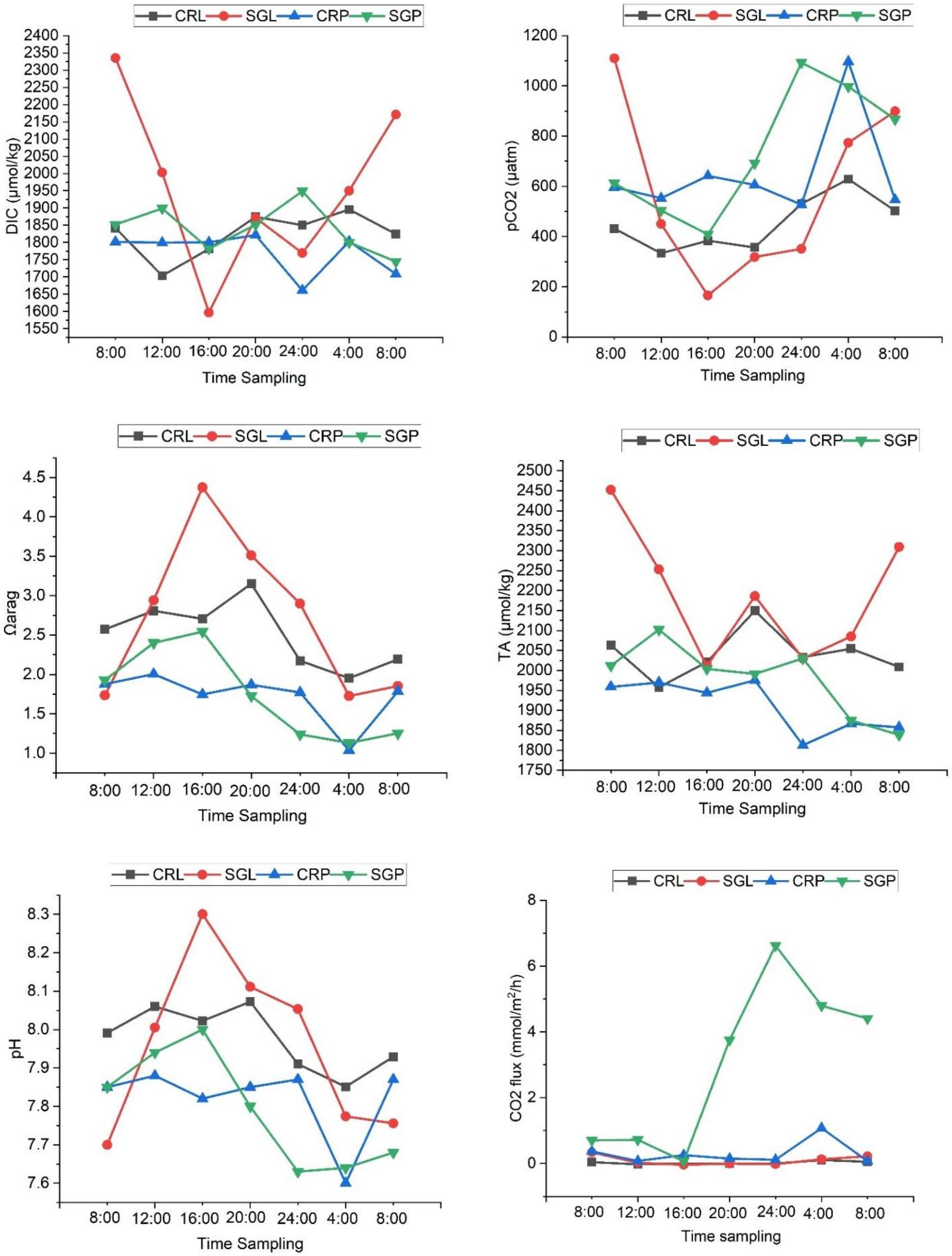


**Figure 5.** The daily variations in carbonate systems and $CO_2$ flux within the seagrass and coral reef ecosystems surrounding Pari Island and Sire Bay Lombok, February and March 2021, respectively. CRL= Coral Reef of Lombok, SGL= Sea Grass of Lombok, CRP= Coral Reef of Pari, SGP= Sea Grass of Pari

solely from increased $CO_2$ levels in the atmosphere. Still, it is believed to also stem from the interaction between oceanic and terrestrial water masses, particularly from Jakarta Bay, and the limited capacity of benthic ecosystems to mitigate $CO_2$ levels in the water. Although Pari Island's waters are nourished by benthic ecosystems like seagrass and coral reefs, these ecosystems are in poor health. Seagrass is limited to two species, and coral reefs are declining due to environmental pressure (Abrar *et al*., 2020; Rifai *et al*., 2021). Several types of benthic ecosystems are crucial in reducing $CO_2$ levels through various biological and chemical processes. Seagrass meadows, mangrove forests, and macroalgal beds are well-known for absorbing and storing $CO_2$ through photosynthesis, contributing to the 'blue carbon' ecosystem (Duarte and Macreadie, 2022). Seagrass and macroalgae actively take up dissolved inorganic carbon (DIC) and convert it into organic matter, which can be buried in sediments or exported to adjacent ecosystems (Longhini *et al*., 2015; Duarte and Krause-Jensen, 2017; Macreadie *et al*., 2017; Hasselström and Thomas, 2022). Additionally, coral reef ecosystems contribute to $CO_2$ reduction through calcification, where calcium carbonate ($CaCO_3$) formation binds carbonate ions and reduces free $CO_2$ in the water column. However, calcification can also release $CO_2$, making the net effect dependent on the balance between photosynthesis, respiration, and carbonate precipitation (Frankignoulle *et al*., 1994; Gattuso *et al*., 1998; Davis *et al*., 2021). Environmental conditions, anthropogenic stressors, and seasonal variability influence the capacity of these ecosystems to mitigate ocean acidification and $CO_2$ levels.

Evidence from a multivariate analysis using PLS suggests that lower temperatures and salinity play a significant role in driving low pH and aragonite saturation in Pari Island coastal waters. Both Pari Island and Sire Bay in Lombok are influenced mainly by temperature, salinity, and dissolved oxygen (DO), impacting aragonite saturation. In the waters of Pari Island, temperature accounts for approximately 36.37% of the variability in aragonite saturation, followed by salinity (16.69%) and DO (16.12%). Conversely, temperature has a more significant influence in Sire Bay, Lombok, contributing around 41.75%, followed by DO (15.4%) and salinity (13.94%) (Figure 6). Similar patterns are observed in Aceh coastal waters in the southwest monsoon (Afdal *et al*., 2024). Temperature and salinity emerge as crucial factors affecting the aragonite saturation state (Ωarag) of coastal waters because they influence the solubility of $CO_2$ and measure the water's capacity to sustain calcium carbonate structures vital for marine organisms. The solubility of gases like carbon dioxide ($CO_2$) decreases with rising temperatures, potentially leading to higher Ωarag in warmer waters (Jiang *et al*., 2015). Moreover, elevated temperatures can enhance biological activity, depleting dissolved inorganic carbon (DIC) and elevating Ωarag. Freshwater input, which has lower salinity, can suppress aragonite saturation states. This is because freshwater typically has lower levels of carbonate ions, which are necessary for aragonite formation. In coastal regions with significant freshwater influence, Ωarag can be higher during productive seasons due to the net removal of DIC from the water column (Harris *et al*., 2013). However, during the sampling period, the water conditions in the coastal waters of Pari Island were not particularly conducive to productivity, resulting in very low aragonite saturation levels (within the tropical coastal waters classification).

### *Impact of anthropogenic and metabolic processes on aragonite saturation*

This research employed a multivariate analysis using Partial Least Square methods to assess the influence of human activities and metabolic processes on variations in aragonite saturation in the coastal areas of Pari Island and Sire Bay, Lombok, as illustrated in Figure 7. The findings indicate that metabolic activities (namely NEP and NEC) exert a more substantial effect on the fluctuations in aragonite saturation than human-induced factors, based on the NDIC and NTAlk measurements, in both Pari Island and Sire Bay, Lombok. Nonetheless, the influence patterns differ between the two areas; in Pari Island, NEP affects aragonite saturation changes more than NEC, whereas in Sire Bay, Lombok, the reverse is true. Additionally, NDIC and NTALk are more significant in influencing aragonite saturation shifts in Pari Island’s waters than in Sire Bay, Lombok, suggesting that Sire Bay's marine environment is healthier than Pari Island. In Sire Bay, Lombok, the calcification processes outpace dissolution, and photosynthesis rates exceed respiration rates, as evidenced by positive NEC and NEP values, particularly around the seagrass ecosystem areas, as shown in Figure 8. Photosynthesis happens faster than respiration when an ecosystem has a positive net ecosystem production (NEP). This leads to photosynthetic organisms using up dissolved inorganic carbon (DIC), which in turn causes dissolved oxygen (DO) to increase and the partial pressure of carbon dioxide ($pCO_2$) to decrease. This confirms the role of ecosystem metabolism, especially that of seagrass ecosystems, which exert a sufficiently strong influence on modifying carbonate chemistry dynamics in shallow waters (Ganguly *et al*., 2017). According to (Li *et al*., 2020), biological processes contribute 50–70% to changes in aragonite saturation in coastal waters. Biological processes, especially primary production, produce oxygen, reduce CO2, and increase aragonite saturation. Aragonite saturation values often represent an increased calcification rate (Chou *et al*., 2013). An increase in carbonate ions usually creates higher aragonite saturation. These are favourable for calcification since aragonite saturation is the main controlling variable for calcium carbonate deposition (Gattuso *et al*., 1998).

Figure 5 also illustrates the inverse relationship between pH and Ωarag, linked to fluctuations in DIC concentration and $pCO_2$ driven by metabolic processes, particularly photosynthesis and respiration. Specifically, DIC and $pCO_2$ levels are low during the day but increase at night, especially in the seagrass ecosystem in Sire Bay, Lombok. Generally, the waters of Sire Bay, Lombok, and Pari Island act as $CO_2$ sources to the atmosphere, with fluxes varying from -0.04 to 0.34 $mmol.m^{-2}.h^{-1}$ and 0.07 to 6.62 $mmol.m^{-2}.h^{-1}$, respectively. $CO_2$ flux was typically low, except near the seagrass ecosystem of Pari Island, where there was notable $CO_2$ exchange, particularly at night, reaching up to 6.62 $mmol.m^{-2}.h^{-1}$. Changes in the $CO_2$ flux between the air and sea will lead to changes in the carbonate system of marine ecosystems, such as seagrass beds and coral reefs. When $CO_2$ is absorbed by seawater, it increases dissolved inorganic carbon (DIC) levels and lowers the pH. Conversely, when $CO_2$ is released from seawater to the atmosphere reduces DIC and raises the pH (Longhini *et al*., 2015). The direction of $CO_2$ flux across the sea surface is primarily determined by the difference in partial pressure of $CO_2$ between the air and sea ($pCO_2$). In coastal areas around seagrass and coral reefs, this $pCO_2$ is influenced by processes such as organic carbon metabolism, referred to as net ecosystem production (NEP), and the processes of calcification and dissolution of calcium carbonate, known as net ecosystem calcification (NEC). NEP indicates whether an ecosystem is a net producer or consumer of organic carbon based on whether it releases more organic carbon than it consumes (net autotrophic; NEP > 0) or vice versa (net heterotrophic; NEP < 0). NEC is vital for maintaining a balance between the ecosystem's creation and the breakdown of carbonate. In coral reefs, most carbonate formation happens through calcareous organisms in the benthic zones, especially scleractinian corals. In contrast, carbonate dissolution occurs above the reef when the Aragonite saturation state drops below 1. Additionally, loose sediments in shallow reef areas and their surroundings significantly influence carbonate dynamics.

In the coastal waters of Sire Bay, Lombok, during the northwest monsoon, the minimal reduction in aragonite saturation value due to low salinity is attributed to a healthy seagrass ecosystem. This ecosystem effectively decreases the dissolved inorganic carbon (DIC) concentration in the water column, particularly during daylight hours. Seagrass habitats have been considered a possible approach for localized ocean acidification mitigation due to their large standing stocks of organic carbon and high

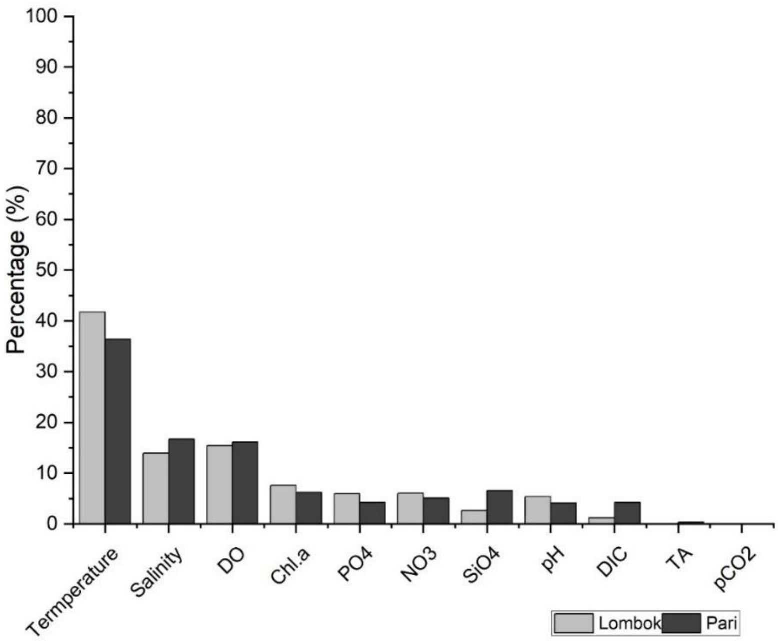


**Figure 6.** Key parameters contribute to changes in Ωarag at Pari Island and Sire Bay Lombok in February and March 2021, respectively.

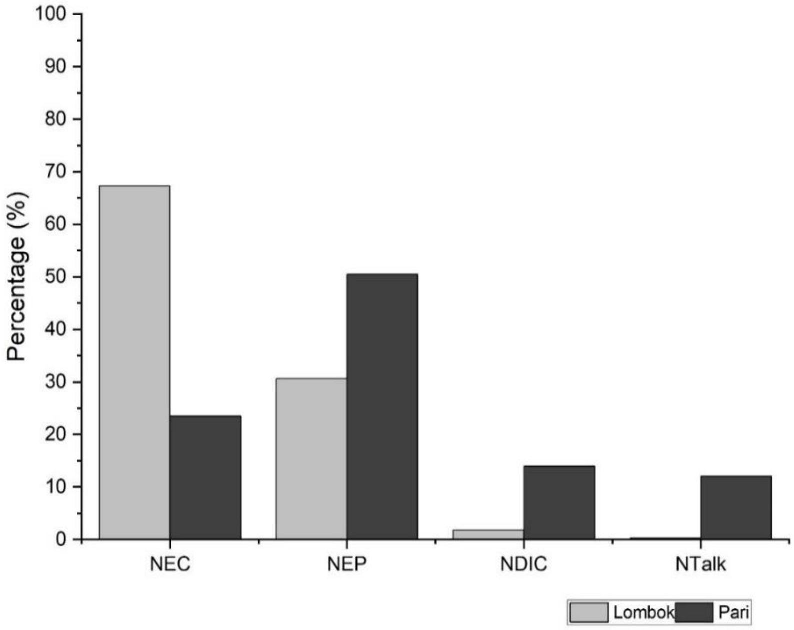


**Figure 7.** Metabolic processes (NEC and NEP) and anthropogenic impacts (NDIC and NTAlk) contribute to changes in aragonite saturation in the coastal waters of Pari Island and Sire Bay, Lombok, February and March 2021, respectively.

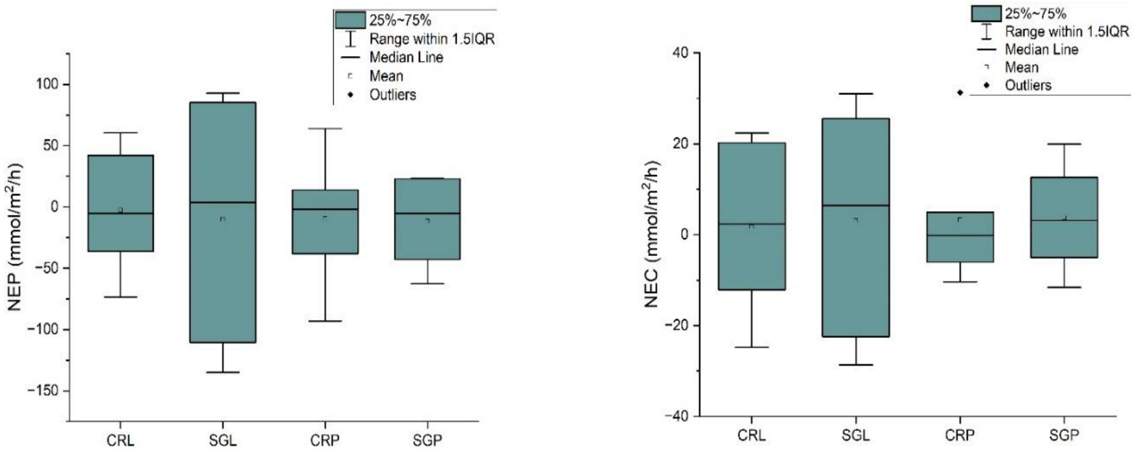


**Figure 8**. The average Net Ecosystem Productivity (NEP) and Net Ecosystem Calcification (NEC) within the seagrass and coral reef ecosystems surrounding Pari Island and Sire Bay, Lombok, February and March 2021, respectively.

productivity (Koweek *et al*., 2018). However, a study found that seagrass metabolism in Tomales Bay would not provide long-term ocean acidification mitigation (Koweek *et al*., 2018). On the other hand, a global study highlighted the potential for seagrasses to increase their capacity to sequester carbon under ocean acidification, providing a positive story for the impact of ocean acidification on seagrass ecosystems. Additionally, a coast-wide study spanning seven meadows and 1000 km of the U.S. west coast over six years found that seagrass meadows can locally alleviate low pH conditions for extended periods, indicating their potential to mitigate the impact of ocean acidification on coastal ecosystems (Ricart *et al*., 2021). Seagrass ecosystems have been demonstrated to counteract the effects of ocean acidification by increasing seawater's pH through their photosynthetic activity. This improvement is observed about 65% of the time, resulting in sustained pH increases of more than 0.1 units, equivalent to a 30% reduction in hydrogen ion concentration and lasting up to 21 days (Ricart *et al*., 2021). The most significant pH elevations typically occur during the seagrass growth season, particularly in meadows at higher latitudes. These discoveries suggest that seagrass meadows can locally mitigate low pH conditions over prolonged periods, which has significant implications for the conservation and management of coastal ecosystems.

Seagrass communities increase aragonite saturation through photosynthetic activity, leading to carbonate modifications within their canopy and beyond (Hendriks *et al*., 2014). The metabolic rates of seagrass communities, particularly gross primary production (GPP) rates, tend to be significantly higher than respiration rates, resulting in a positive net community production (NCP) and a mean P/R ratio above 1, indicative of metabolic balance (Duarte *et al*., 2010). Seagrass beds also contribute to oceanic carbonate lime mud production by providing a habitat for calcifying organisms and acting as efficient sediment traps, directly implicating seagrass in the precipitation of aragonite needles (Enríquez and Schubert, 2014). Additionally, seagrass habitats have been observed to experience an overall elevation in mean pH relative to adjacent outer reefs, with periods of high and low pH, which can sustain the calcification of corals within the habitat (Camp *et al*., 2016). These findings suggest that seagrass communities significantly increase aragonite saturation and maintain favorable chemical conditions for calcifying organisms.

## Conclusion

Pari Island's coastal waters are highly vulnerable to ocean acidification, as reflected in low pH levels and decreased aragonite saturation. Daily variations in pH, total alkalinity (TA), total inorganic carbon (DIC), and aragonite saturation reflect the influence of local oceanographic conditions and biological activity. Changes in aragonite saturation at both locations are driven by temperature, salinity, and dissolved oxygen (DO), with distinct environmental factors affecting each ecosystem. Differences in Net Ecosystem Production (NEP) and Net Ecosystem Calcification (NEC) between Pari and Lombok suggest variations in ecosystem productivity and calcification potential. The decline in aragonite saturation around Pari Island is associated with the deteriorating condition of its seagrass and coral reef ecosystems, which diminishes their ability to regulate carbonate balance. Variations in ocean acidification levels between Pari and Lombok highlight the need for location-specific mitigation strategies. Conservation and restoration of seagrass and coral reef ecosystems, particularly in the coastal waters of Pari Island, are essential to enhancing their resilience against ocean acidification.

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