

Macrobiofouling Communities on Concrete Piers across Coastal Aceh, Indonesia: Spatial Variation and Environmental Conditions

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ABSTRACT

Macrobiofouling is a major problem for maritime infrastructure, as it can cause structural fragility and corrosion of concrete substrates. This study aims to analyse the species diversity, density, and abundance of macrobiofouling on concrete piers, and descriptively examine their association with water quality parameters in the coastal waters of West Aceh (Kuala Bubon Port and Jetty Port) and Aceh Jaya (Calang Port). Sampling was conducted using a purposive sampling method, with two stages of data collection. The first stage was an analysis of species density and diversity index (H') using a 20×90 cm quadrat transect, conducted at 10 stations in Kuala Bubon Port to describe the distribution pattern of macrobiofouling communities. The second stage was an analysis of macrobiofouling abundance using a 30×30 cm quadrat transect, conducted at three stations representing Kuala Bubon Port, Jetty Port, and Calang Port, while also examining the environmental conditions co-occurring with abundance patterns, based on water quality parameters (temperature, salinity, pH, DO, BOD, clarity, nitrate, phosphate, and current) measured directly on site. The research results identified ten macrobiofouling species, dominated by *Balanus* sp. The diversity index (H') ranged from 1.67–1.68 (low category), with densities ranging from 3.11–3.33 individuals/ m^2 . The abundance of macrobiofouling ranged from 2,011–5,955 individuals/ m^2 , with the highest value found at Calang Port, which also exhibited relatively higher current velocity and greater water clarity than the other stations, describing the spatial variation in macrobiofouling abundance and environmental conditions among sampling stations without implying any statistical association or causal relationship.

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INTRODUCTION

Biofouling is the process by which organisms attach and grow on the surface of objects or materials submerged in the sea. Biofouling generally originates from bacteria, plants, and animals. Biofouling can attach to natural substrates and man-made facilities submerged in the sea, including ships and coastal structures. When a hard

substrate is submerged in seawater, it cannot avoid biofouling attachment. The biofouling attachment process occurs very quickly at a microscopic scale on the substrate (Al-Kautsar et al., 2020). West Aceh Regency and Aceh Jaya Regency are two coastal areas in Aceh Province closely linked to Indian Ocean dynamics and offer important geographical characteristics for studying

marine ecology and biofouling. Meulaboh, the center of coastal activities in West Aceh Regency, has port infrastructure consisting of two main ports: Jetty Port in Suak Indrapuri and Kuala Bubon Port (Kuswati et al., 2018). Meanwhile, Aceh Jaya Regency is a coastal area in western Aceh, located between 04°22'–05°16' N and 95°10'–96°03' E. This regency also has a major port, Calang Port, located in Krueng Sabee District (BPS Aceh Jaya, 2024).

The selection of Jetty Port in Meulaboh, Kuala Bubon Port in West Aceh, and Calang Port in Krueng Sabee was intended to represent different port settings along the west coast of Aceh and to enable the assessment of macrobiofouling communities associated with concrete pier structures under varying levels of coastal and maritime activity (BPS Aceh Barat, 2024; Zakia et al., 2023).

Previous studies reported that the Meulaboh ferry port serves ferry activities on the Meulaboh–Sinabang route and that the Meulaboh pier serves as key infrastructure supporting regional shipping and trade activities (Kuswati et al., 2018). Kuala Bubon Port was selected because it functions as a ferry facility and maritime hub in southwest Aceh, supporting community shipping and passenger and logistics transport, which can increase the availability of submerged artificial substrates and anthropogenic inputs in the surrounding waters (Zakia et al., 2023). Calang Port was selected to represent other strategic coastal ports in the southwest Aceh corridor, allowing comparison of macrobiofouling conditions among port areas with different local activity characteristics but similar exposure to coastal and maritime processes (BPS Aceh Jaya, 2024). Therefore, the port areas of West Aceh and Aceh Jaya are relevant locations to observe the presence and distribution of macrobiofouling, especially on hard substrates associated with shipping activities and dock infrastructure.

On ships, biofouling is a significant problem because organisms attached to the hull can increase surface roughness, increase frictional resistance during ship movement, and reduce hydrodynamic efficiency

(Oliveira & Granhag, 2020; Valchev et al., 2022). This condition can lead to increased fuel consumption, decreased operational speed, increased maintenance costs, and the need for regular hull cleaning (Pavin & Knežević, 2023; Degiuli et al., 2025). Beyond technical and economic impacts, biofouling on ships can also facilitate the movement of marine organisms from one water area to another, potentially disrupting local ecosystem balance by introducing non-native or invasive species (International Maritime Organization, 2023; Davidson et al., 2018). These technical, economic, and ecological consequences underscore the importance of documenting macrobiofouling communities on artificial structures in coastal environments.

Although biofouling studies on artificial substrates have been widely conducted in various regions, data on macrobiofouling communities associated with concrete pier structures along the western coast of Aceh remain limited. In particular, baseline information on species diversity and density at Kuala Bubon Port, as well as species abundance and its descriptive association with water quality conditions across coastal ports in West Aceh and Aceh Jaya, has not been sufficiently documented. This gap matters because coastal port environments have variable local conditions that may influence the development and distribution of macrobiofouling communities. Previous studies have examined biofouling on artificial structures in other settings, such as the protected waters of the Seribu Islands (Rombe et al., 2023) and bridge pillars in the Madura Strait (Al-Kautsar et al., 2020). Beyond its descriptive value, establishing baseline density and diversity data is also relevant for future ecological monitoring of macrobiofouling communities on coastal infrastructure.

This study's primary novelty lies in three complementary contributions. First, it provides a geographical contribution by establishing baseline macrobiofouling data from concrete pier structures at coastal locations in West Aceh and Aceh Jaya that have not been previously documented,

thereby providing a regional reference point rather than proposing a new methodological or theoretical framework. Second, the study provides a descriptive comparison of macrobiofouling communities and measured water quality conditions across three coastal ports, allowing examination of spatial patterns in community abundance alongside differences in environmental conditions. However, the present study did not statistically test the relationship between water quality parameters and macrobiofouling abundance; therefore, the observed associations are interpreted descriptively rather than as evidence of causal or statistically supported relationships. Third, the study combines two complementary spatial scales of ecological observation within a single regional assessment: fine-scale, species-level density and diversity data from 10 stations at Kuala Bubon Port and broader comparisons of macrobiofouling abundance and water quality across three coastal ports. This multi-scale approach provides a regional ecological baseline that can support future studies with greater spatial and temporal replication, consistent species-level observations across sampling locations, and statistical analyses designed to test relationships between environmental

variables and macrobiofouling community patterns.

Together, these datasets contribute to a regional baseline for understanding macrobiofouling communities associated with concrete pier structures and provide a reference for future ecological monitoring in coastal Aceh. Future research can build on this baseline by applying replicated, hypothesis-driven designs to quantitatively test the influence of water.

RESEARCH METHODS

Study Site

The study was conducted at three representative port areas in West Aceh and Aceh Jaya Regencies, Aceh Province, Indonesia: Kuala Bubon Port, Jetty Port, and Calang Port a) Regional map showing the three surveyed ports along the coast of West Aceh and Aceh Jaya Regencies (Jetty Port, Kuala Bubon Port, and Calang Port) for assessing macrobiofouling abundance and monitoring water quality; (b) Regional map showing the 10 sampling stations at Kuala Bubon Port for assessing macrobiofouling species diversity and density. These locations represent macrofouling communities associated with concrete pier structures in different coastal settings.

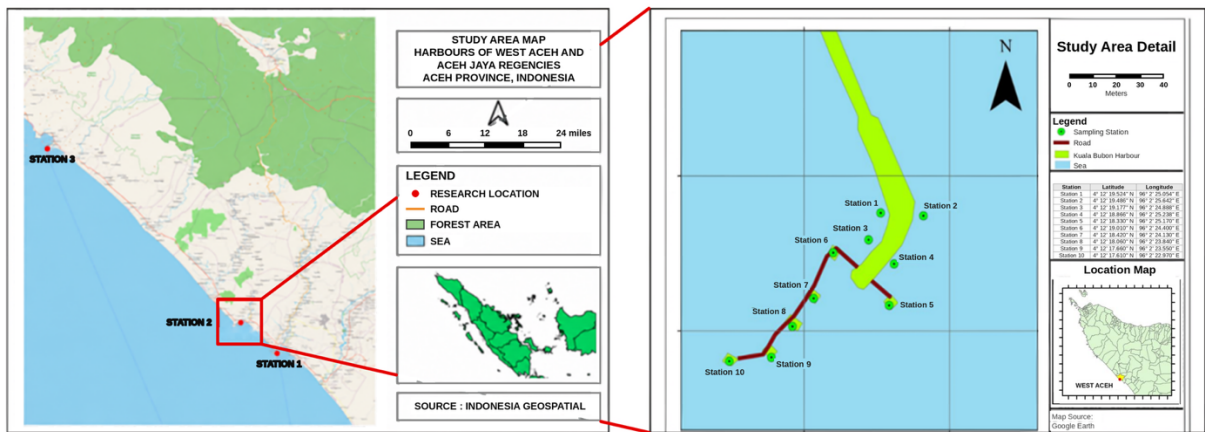


Figure 1. Research Study Map (a) Regional map showing the three surveyed ports along the coast of West Aceh and Aceh Jaya Regencies (Jetty Port, Kuala Bubon Port, and Calang Port) for assessing macrobiofouling abundance and monitoring water quality; (b) Regional map showing the 10 sampling stations at Kuala Bubon Port for assessing macrobiofouling species diversity and density (Source: Data Research, 2025)

This study employed a quantitative descriptive approach based on macrobiofouling observation data collected from concrete pier structures in West Aceh

and Aceh Jaya Regencies, Aceh Province. The study was conducted in two observation stages with different sampling periods, spatial coverage, and observation objectives. The first stage was conducted from March to May 2022 at 10 stations in Kuala Bubon Port, West Aceh Regency, to assess species diversity and density. Each station was represented by a single concrete pier pillar, with one 20 × 90 cm quadrat placed on each pillar; quadrats were not repeated within a station. We selected stations based on the observable level of macrobiofouling attachment and the degree of sunlight exposure at each sampling location. We identified and recorded macrobiofouling organisms within each quadrat to species level. For each station, we used the total number of individuals recorded within the single quadrat to calculate species density and the Shannon-Wiener diversity index (H'), yielding one density and one H' value per station.

The second stage was conducted in February 2025 at three stations, namely Jetty Port and Kuala Bubon Port in West Aceh Regency and Calang Port in Aceh Jaya Regency, to assess macrobiofouling abundance and monitor water quality. We deliberately selected these locations because they represent active coastal and port environments along the west coast of Aceh and have concrete pile structures that provide a hard substrate for macrobiofouling attachment.

At each station, we assessed macrobiofouling abundance on 15 concrete pier pillars, with one 30 × 30 cm quadrat placed on each pillar, resulting in 15 quadrats per station. Individuals of each taxon recorded across the 15 quadrats were summed and used to calculate abundance per unit area according to the abundance formula. The quadrats were not repeated on individual pillars.

To achieve the objectives of this study, we followed a series of systematic procedures, beginning with study area selection and preliminary surveys in West Aceh and Aceh Jaya, followed by field sampling, laboratory analysis, and data analysis (Figure 2). We conducted

macrobiofouling sampling in situ at low tide to ensure we could properly observe and collect organisms attached to the concrete pier structure. We then collected organisms attached to the substrate surface by scraping the transect area with a knife. We placed the collected samples in sample bottles or plastic sample containers and preserved them in 70% alcohol for further observation and identification.

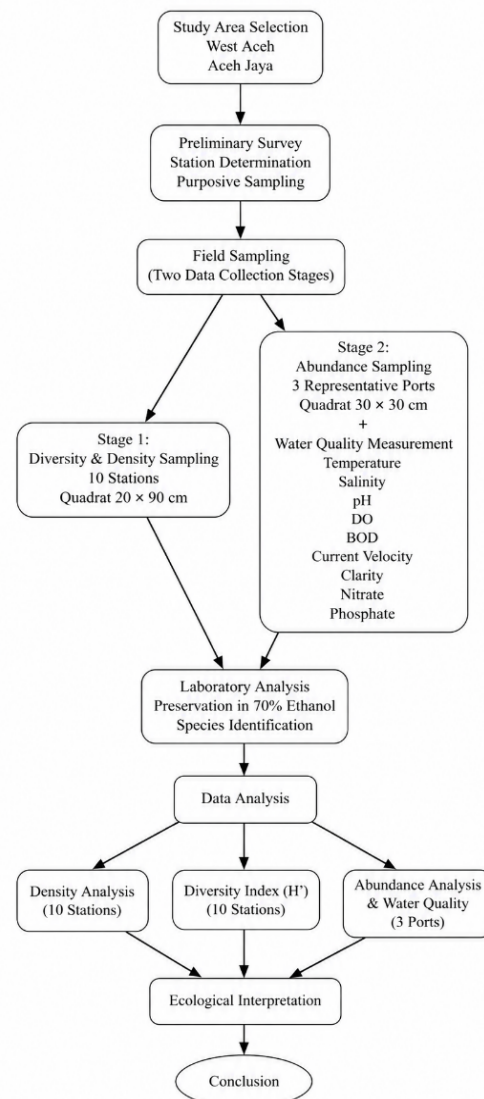


Figure 2. Flowchart of research stages
 (Source: Data Research, 2025)

The tools and materials used in this study consisted of field equipment, documentation tools, identification tools, and sample preservatives. Field equipment included basic diving equipment, GPS, quadrant transects, writing instruments,

sample bottles, plastic sample containers, and a knife for scraping organisms from the substrate. The preservative used was 70% alcohol (ONEMED). We documented observations using an underwater camera.

Specimens were identified at the Marine Science Laboratory, Faculty of Fisheries and Marine Sciences, Teuku Umar University. We identified them based on external morphological characteristics observed under a microscope and by comparing them with diagnostic descriptions and illustrations in taxonomic references. We identified molluscs primarily following (Dharma, 1988, 1992), macroalgae following (Atmadja, W. S. et al., 1996), and Porifera following (Hooper et al., 2002). We identified barnacles (Cirripedia) based on relevant taxonomic descriptions. Specimens were identified to the lowest practical taxonomic level supported by the observable morphological characters. We did not cross-check nomenclature against an online taxonomic database, which we acknowledge as a limitation of the present study.

We conducted water quality measurements at each sampling location to characterize environmental conditions during macrobiofouling observations. Measured parameters included physical and chemical variables.

Physical parameters included in situ temperature (thermometer), water clarity (Secchi disk), and current velocity (current meter). We also measured chemical parameters in situ, including salinity using a refractometer (MASTER-53M), pH using a pH meter (ATC), and dissolved oxygen (DO) using a DO meter (Darmasakti). Nitrate, phosphate, and BOD₅ analyses followed the procedures described (Vanri et al., 2020). Nitrate was analyzed using a spectrophotometric method according to SNI 06-6989.79-2011. Phosphate was analyzed using a spectrophotometric method according to SNI 06-6989.31-2005. BOD₅ was determined using the titrimetric Winkler method following APHA (2012), Method 5210. Each water quality analysis was performed in triplicate. For sample preservation, water samples were collected in dark bottles, transported in a cool box,

and stored at 4 °C until analysis. The samples were analyzed within a holding time of 2 × 24 h (48 h) after collection. All analyses were conducted at the Integrated Laboratory Unit (UPT Laboratorium Terpadu), Universitas Syiah Kuala. This study did not apply formal quality assurance and quality control (QA/QC) procedures, which is a limitation of the analytical procedure. These measurements characterized environmental conditions at each station and assessed their relationship with macrobiofouling abundance.

Macrobiofouling Density was calculated using the formula (Krebs, 1989):

$$D = \frac{n_i}{A}$$

Information:

D= species density (individuals/m²)

n_i= total number of i-th individuals (ind)

A= total cross-sectional area (m²)

The level of diversity of macrobiofouling species was analyzed using the Shannon-Wiener diversity index, as given by the formula, referring to Odum & Odum, 2003.

$$H' = -\sum \left(\frac{n_i}{N} \right) \ln \left(\frac{n_i}{N} \right)$$

Information:

H'= Shannon-Wiener Diversity Index

n_i= number of individuals of species i

N= total number of individuals of all species

Species abundance was calculated using the formula (Brower et al., 1998):

$$A = \frac{X_i}{n_i}$$

Information:

A= abundance

X_i= number of individuals of the i-th species

n_i= area of the i-th type quadrant found (m²)

Water quality conditions and macrobiofouling abundance taken at 3 locations of Jetty Port, Kuala Bubon Port and Calang Port were evaluated descriptively by comparing the value of each water quality

parameter to the macrobiofouling abundance pattern between locations.

RESULTS AND DISCUSSION

Macrobiofouling Density on Concrete Pier at Kuala Bubon Port

Macrobiofouling observations conducted at 10 stations in Kuala Bubon Port

showed combined, all-taxa densities ranging from 3.11 ind/m² to 3.33 ind/m² (**Figure 3**), calculated as described in the Methods (total individuals of all taxa recorded in the single 0.18 m² quadrat at each station, divided by quadrat area). The highest density was 3.33 ind/m² at stations 4 and 9, and the lowest was 3.11 ind/m² at stations 5 and 10.

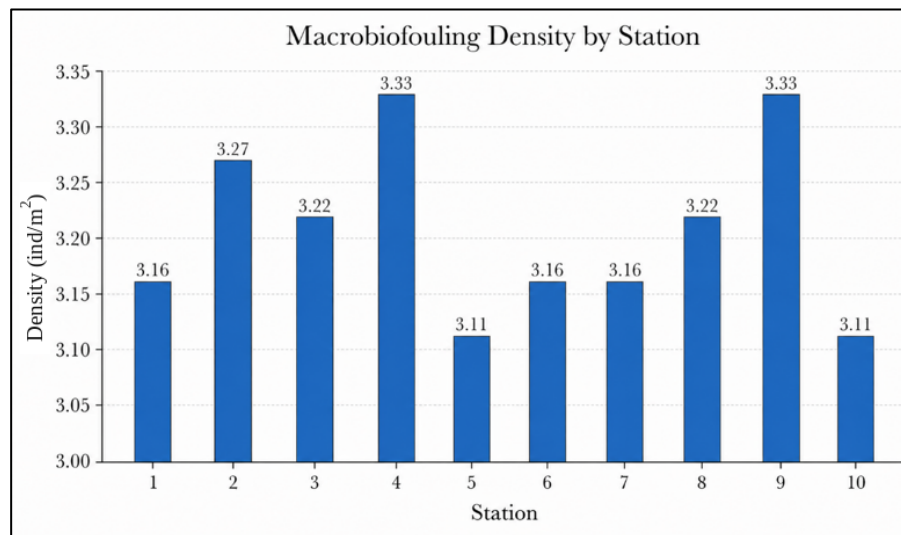


Figure 3. Macrobiofouling Density at Kuala Bubon Port, West Aceh (Source: Primary research data, 2022)

The study found 10 species (**Figure 4**): Balanus sp., Clathria sp., Isognomon sp., Codium sp., Lottia gigantea, Littorina sp.,

Thais sp., Sargassum sp., Padina sp., and Caulerpa taxifolia.

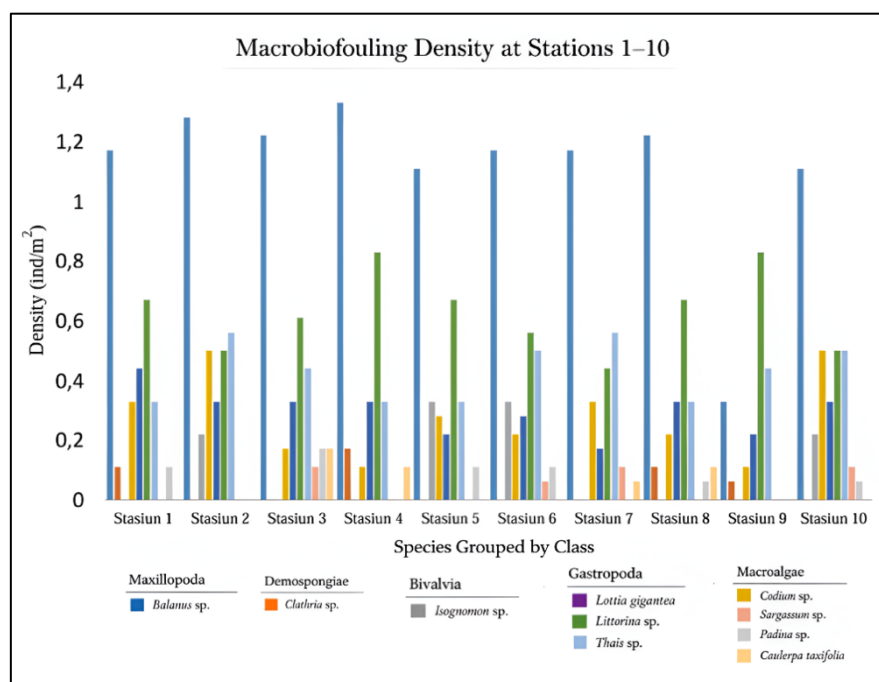


Figure 4. Macrobiofouling Species Community Grouped According to Taxonomic Class in Kuala Bubon Port, West Aceh (Source: Primary research data, 2022)

The macroalgae group had the highest species richness, comprising four species: *Codium* sp., *Sargassum* sp., *Padina* sp., and *Caulerpa taxifolia*. Gastropoda comprised three species, *Lottia gigantea*, *Littorina* sp., and *Thais* sp. In contrast, Maxillopoda, Demospongiae, and Bivalvia were each represented by one species, namely *Balanus* sp., *Clathria* sp., and *Isognomon* sp., respectively. Gastropoda had the highest average density (1.36 ind/m²), followed by Maxillopoda (1.21 ind/m²), macroalgae (0.42 ind/m²), Demospongiae (0.08 ind/m²), and Bivalvia (0.08 ind/m²). Thus, the group with the highest species richness was not the group with the highest density. At the species level, *Balanus* sp. was the most dominant species, occurring at all observation stations and exhibiting a relatively high density on the concrete pier pillars at Kuala Bubon Port.

The occurrence of *Balanus* sp. on the concrete pier in this study is consistent with [Alwi et al. \(2021\)](#), who recorded *Balanus crenatus* on concrete, iron, and wooden pier structures in Daruba Waters, Morotai Island, Indonesia. The highest number of *Balanus crenatus* individuals was recorded on concrete (324 individuals), compared with 83 on iron and 53 on wood, indicating that concrete can provide a suitable substrate for barnacle colonization.

A contrasting pattern was reported by [Dewi et al \(2026\)](#), at Kamal Port, Bangkalan, where Gastropoda was the most abundant macrobiofouling group on concrete substrates (106 individuals), followed by Bivalvia (33 individuals) and Amphibalanus sp. (26 individuals). This comparison indicates that although concrete can support

barnacle colonization, it does not necessarily make barnacles the dominant macrobiofouling group in every setting.

A different community composition was also reported by [Rombe et al. \(2023\)](#) on a concrete pier at Harapan Island, Seribu Islands, where Bivalvia was the dominant group at an average density of 50.173 ind/m², compared with the *Balanus* sp. (Maxillopoda)-dominated community in the present study (mean density 1.21 ind/m²). Taken together, these comparisons suggest that the composition and density of macrobiofouling communities on concrete pier structures can vary considerably among locations, plausibly reflecting differences in local environmental characteristics, oceanographic conditions, substrate properties, larval availability, and the degree of water exposure or protection; the present descriptive dataset cannot distinguish among these candidate explanations and formal comparative testing was beyond its scope.

Macrobiofouling Species Diversity Index in Kuala Bubon Port

The macrobiofouling species diversity index results from observations at Kuala Bubon Port, West Aceh, at 10 stations showed that the index ranged from 1.67 to 1.68, all in the low category (**Figure 5**). Stations 1, 2, 3, 5, and 6 had a species diversity index of 1.68, while stations 4, 7, 8, 9, and 10 had 1.67. Based on these results, the species diversity index values between stations showed very little difference. All stations were in the low category because the H' values obtained were less than 2.0.

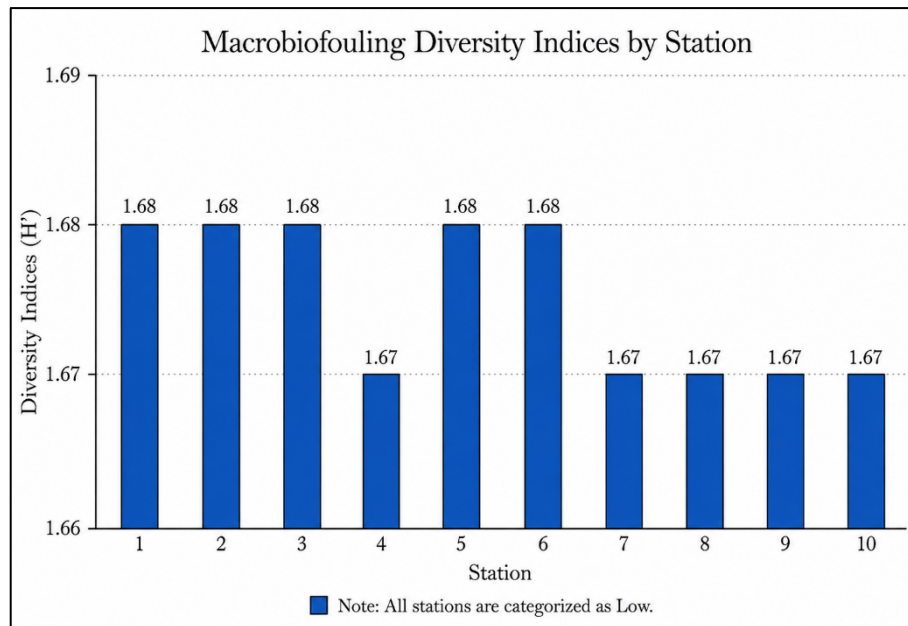


Figure 5. Diversity of Macrobiofouling Species in Kuala Bubon Port, West Aceh
 (Source: Primary research data, 2022)

The macrobiofouling community on the concrete pier pillars at Kuala Bubon Port showed an uneven distribution of individuals across species, despite a relatively high number of species recorded at some stations. We identified ten macrobiofouling species overall: *Balanus* sp., *Clathria* sp., *Codium* sp., *Lottia gigantea*, *Littorina* sp., *Thais* sp., *Padina* sp., *Isognomon* sp., *Sargassum* sp., and *Caulerpa taxifolia*. Pier surfaces varied in texture (smooth and rough) across stations. Several station-level patterns emerged: Stations 1 and 6, with a mix of smooth and rough surfaces, supported a greater variety of attached organisms, although the diversity index remained low because *Balanus* sp. continued to dominate. Station 2, with a relatively smooth substrate, recorded the lowest *Isognomon* sp. density among the stations (0.22 ind/m²) alongside high *Balanus* sp. density (1.28 ind/m²). Stations 4 and 9, both sheltered by neighboring pier pilings, recorded high *Balanus* sp. density (1.33 ind/m² at Station 4) and high overall macrobiofouling density. Conversely, Stations 5 and 10, the outermost and most current wave-exposed pillars, supported fewer organisms overall, with the community dominated by *Balanus* sp. Stations 3, 6, 8, and 10 recorded a

comparatively higher number of species due to macroalgae (*Sargassum* sp., *Padina* sp., and *Caulerpa taxifolia*), although this did not translate into a higher diversity index, since *Balanus* sp. remained numerically dominant.

The pattern of macroalgae occurring alongside sessile invertebrates on concrete substrates has also been reported elsewhere in Indonesian waters [Isdianto et al \(2020\)](#), where brown algae (Phaeophyta), together with green and red algae, were found among ten macrobiofouling taxa on a concrete artificial reef at Damas Beach, Trenggalek. This supports the general observation that concrete substrates can support macroalgal attachment, consistent with the pattern observed here; a high species count did not necessarily correspond to a high diversity index when one taxon numerically dominated the assemblage. Similarly, the tendency for more sheltered locations to support denser attachment is consistent with [Al-Kautsar et al \(2020\)](#), who reported that oceanographic factors, including current velocity, influence the degree of macrofouling attachment on pile structures, with more sheltered locations generally more supportive of successful attachment. For *Isognomon* sp. specifically, [Agostini & Ozorio \(2016\)](#), reported that *Isognomon*

bicolor is able to colonize both natural (rocky shore) and artificial hard substrates elsewhere, while [Dias et al \(2013\)](#) & [\(Tëmkin & Printragoon, 2016\)](#) documented *Isognomon* sp. attaching to natural coral crevices and the rough, porous surfaces of mangrove support roots, surface characteristics broadly similar to the rough concrete microhabitats observed at some stations in the present study.

Thus, the low diversity of macrobiofouling species in Kuala Bubon Harbor likely reflects a combination of substrate characteristics, protection from currents and waves, and the dominance of *Balanus* sp. Stations with smooth and rough substrate surfaces allow various organisms to attach according to their adaptation mechanisms, while stations more protected from currents and waves tend to support attachment for better survival. Conversely, stations with substrates that are too smooth or too exposed to currents and waves can limit attachment success for certain organisms, such as *Isognomon* sp.

These interpretations are constrained by the descriptive nature of the substrate texture, which was described qualitatively (smooth versus rough) rather than quantitatively measured, and no statistical test was applied to relate substrate characteristics, shelter, or current exposure to species composition or density. The mechanistic explanations above are therefore drawn from the broader literature on attachment biology rather than tested directly against the data collected here, and should be treated as hypotheses to guide future studies incorporating quantitative substrate characterization and replicated sampling.

Water Quality at Jetty Port, Kuala Bubon Port and Calang Port

Table 1 presents the water quality measurement results from Jetty Port, Kuala Bubon Port, and Calang Port **Table 1**. The measured parameters included temperature, water clarity, nitrate, phosphate, dissolved oxygen (DO), pH, salinity, biochemical oxygen demand (BOD), and current velocity. Physical parameters varied across

the three locations, with temperature ranging from 29.5 to 32.1 °C, water clarity from 0.96 to 2.06 m, and current velocity from 0.007 to 0.24 m/s. Chemical parameters ranged from 0.0082 to 4.3 mg/L for nitrate, 0.002 to 0.006 mg/L for phosphate, 4.6 to 5.4 mg/L for DO, 7.25 to 9.0 for pH, 23 to 33 ppt for salinity, and 1.10 to 1.33 mg/L for BOD.

In terms of macrobiofouling abundance, Station 3 (Calang Port) recorded the highest abundance (5,955 individuals/m²), followed by Station 2 (Kuala Bubon Port; 5,688 individuals/m²), whereas Station 1 (Jetty Port) recorded the lowest abundance (2,011 individuals/m²). The highest abundance at Station 3 coincided with the highest current velocity (0.24 m/s), water clarity (2.06 m), and phosphate concentration (0.006 mg/L). Station 2 had an intermediate abundance and the highest temperature (32.1 °C), whereas Station 1 had the lowest abundance and the lowest current velocity (0.007 m/s) and water clarity (0.96 m).

These spatial patterns broadly align with previous studies showing that environmental conditions can influence processes associated with organism attachment, growth, and distribution. Temperature has been reported as an important factor affecting organism distribution because it influences attachment and growth processes ([Zhang et al., 2025](#)). Salinity can also affect the osmotic conditions experienced by marine larvae, including bivalves, and changes in seawater salinity may consequently influence larval physiological responses ([Nogata et al., 2011](#); [Zhang et al., 2025](#)).

A plausible explanation for the observed pattern is that differences in hydrodynamic conditions may contribute to variation in macrobiofouling abundance among the sampling locations. Current velocity may facilitate larval transport and the delivery of oxygen and nutrients, potentially increasing the likelihood that larvae reach and attach to suitable substrates. Similarly, greater water clarity and phosphate concentrations at Station 3 may coincide with environmental conditions that support biofouling development.

However, the present study did not directly measure or experimentally test these mechanisms.

Other environmental or biological factors may also contribute to the observed differences in macrobiofouling abundance. For example, variation in substrate characteristics, larval supply, food availability, species composition, and other unmeasured environmental conditions may influence community abundance among the three ports. Therefore, the higher abundance observed at Station 3 cannot be attributed to current velocity, water clarity, phosphate, or any single water quality parameter.

A limitation of the present study is that

we evaluated the association between water quality conditions and macrobiofouling abundance descriptively rather than statistically. The observed correspondence between environmental parameters and abundance therefore does not demonstrate a significant relationship or causal effect. In addition, the limited number of sampling locations restricts the ability to quantitatively assess the contribution of individual environmental variables to macrobiofouling abundance. Future studies with greater spatial and temporal replication and appropriate statistical analyses are needed to test these relationships more rigorously.

Table 1. Results of water quality measurements at each station

Parameter	S1	S2	S3
Temperature (°C)	32	32.1	29.5
Water clarity (m)	0.96	1.2	2.06
Nitrate (mg/L)	0.7	4.3	0.0082
Phosphate (mg/L)	0.002	0.003	0.006
DO (mg/L)	4.9	4.6	5.4
pH	7.6	9	7.25
Salinity (ppt)	30	23	33
BOD (mg/L)	1.16	1.1	1.33
Current (m/s)	0.007	0.18	0.24

(Source: Primary research data, 2025)

Macrobiofouling Abundance at Jetty Port, Kuala Bubon Port, and Calang Port

Results show that macrobiofouling abundance varies across the three stations. Abundance values ranged from 2,011–5,955 individuals/m² (**Figure 6**). Station 3, Calang Port, had the highest abundance (5,955 individuals/m²). Furthermore, Station 2, Kuala Bubon Port, had an abundance of 5,688 individuals/m². Station 1, Jetty Port, had the lowest abundance (2,011 individuals/m²).

The station with the highest macrobiofouling abundance (Station 3) also exhibited the highest current velocity (0.24 m/s) among the three stations. This spatial correspondence is consistent with previous studies reporting potential effects of hydrodynamic conditions on larval

supply and the distribution of sessile organisms on hard substrates, although this descriptive study cannot infer causality. The relatively higher current velocity may facilitate the transport of larvae and suspended food particles to the concrete substrate, potentially contributing to the occurrence of filter-feeding organisms such as *Balanus* sp. Study [Firth et al., \(2020\)](#) emphasized that current velocity is a major hydrodynamic factor influencing the availability of larvae and the distribution of sessile organisms on hard structures in coastal waters, a pattern also supported by [\(Johansen, 2014\)](#), who noted that current velocity has major implications for the abundance and settlement success of aquatic organisms.

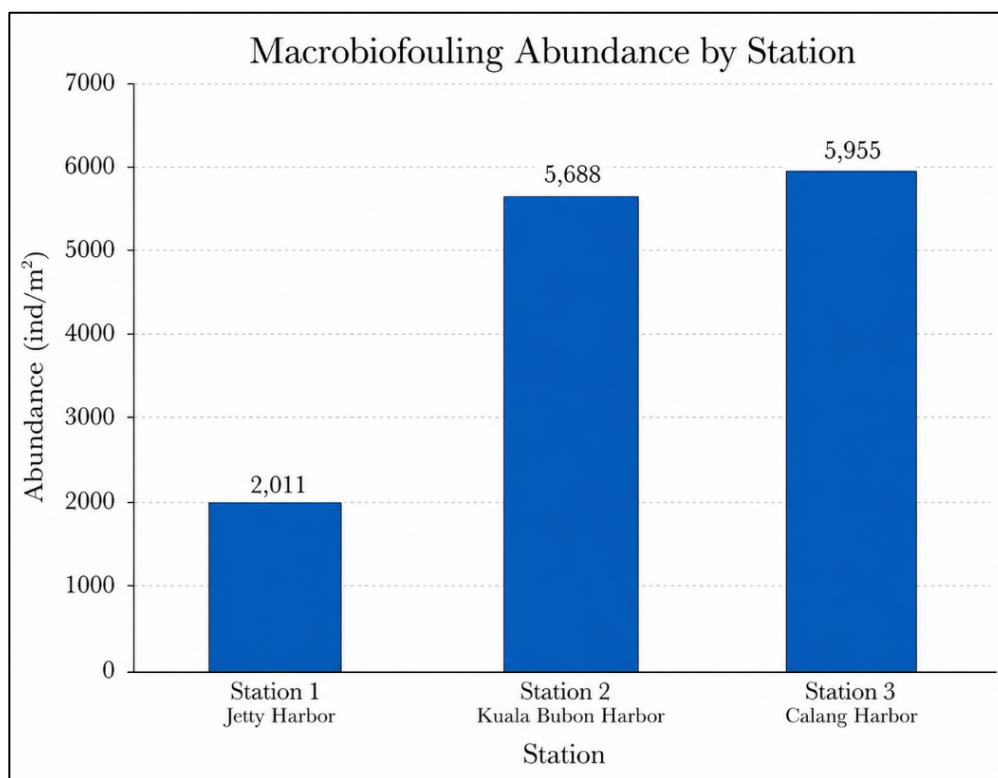


Figure 6. Macrobiofouling Abundance at Station 1 at Jetty Port, West Aceh, Station 2 at Kuala Bubon Port, West Aceh, and Station 3 at Calang Port
(Source: Primary research data, 2025)

Water clarity at Station 3 (2.06 m) was higher than at Station 2 (1.20 m) and Station 1 (0.96 m). This condition may have contributed to different macrobiofouling taxa at this station, particularly macroalgae such as *Sargassum* sp. and *Padina* sp., which require sufficient light penetration for photosynthesis. Light availability is a major limiting factor for photosynthetic organisms living on hard substrates in the intertidal zone, and differences in water clarity among locations may contribute to variation in biofouling community composition (Arboleda-Baena et al., 2022). Low water clarity may also directly affect filter-feeding taxa. According to Abdul Wahab et al., (2017), elevated suspended particulate loads can clog the feeding apparatus of filter feeders such as barnacles, reducing their survival and growth. This suggests that the comparatively lower clarity at Stations 1 and 2 may have similarly constrained filter-feeding efficiency relative to Station 3. The DO level at Station 3 was also the highest recorded (5.4 mg/L), indicating more favorable oxygenation to support the

metabolism and respiration of macrobiofouling organisms.

The salinity at Station 3 (33 ppt) was within the marine salinity conditions reported for biofouling communities. Lapuasa & Doni (2025), reported that a salinity range of 30–33 ppt supported the occurrence of fouling organisms, including barnacles and mussels. The highest phosphate concentration at Station 3 (0.006 mg/L) indicates available dissolved nutrients that may support aquatic productivity and early biofilm development, potentially contributing to subsequent larval attachment. Study Davidson et al., (2018) stated that stable oceanographic conditions, including salinity and nutrient availability, significantly influence the initial colonization success of biofouling organisms on hard substrates. Stable substrate conditions, suitable water quality, and favorable currents can increase larval attachment and development on the substrate surface. According to Cima (2023), biofouling larval attachment is closely related to substrate characteristics, as

texture, microstructure, roughness, color, and surface chemical composition can influence settlement success. Taken together, these findings indicate that the concrete surface at Calang Port provides favorable space and environmental conditions for macrobiofouling development.

The relatively high abundance of macrobiofouling organisms at Station 2 coincided with the presence of a stable concrete jetty structure, which provides a fixed hard substrate for sessile organisms to attach to and develop on. Concrete surfaces can provide suitable attachment sites for larvae and other macrobiofouling organisms because they offer more stable surfaces than unconsolidated substrates. Lower human activity around Kuala Bubon Port than at Jetty Port may also contribute to differences in local environmental conditions; however, the present study does not establish a causal relationship between human activity and macrobiofouling abundance.

Conversely, the relatively low macrobiofouling abundance at Station 1 coincided with the lowest current velocity (0.007 m/s) among the three stations. Hydrodynamic conditions, including current velocity, can influence the structure and development of biofouling communities on artificial substrates (Portas et al., 2023). The low current velocity may have limited the transport of larvae and suspended food particles to the concrete substrate. Station 1 also had the lowest water clarity (0.96 m) and phosphate concentration (0.002 mg/L), which may have influenced light and nutrient availability and potentially affected early biofilm development. Phosphate availability has been reported to influence biofilm formation (Pinel et al., 2020), while phosphate has also been associated with the abundance of epiphytic microalgae on artificial substrates (Sugiana et al., 2022). However, these factors should be considered potential explanations rather than demonstrated causes because the present study did not directly measure larval supply or biofilm development.

Together, the density and diversity dataset from Kuala Bubon Port and the

abundance dataset from the three ports reflect two complementary spatial scales of the same phenomenon: fine-scale variation in colonization intensity within a single port and broader-scale variation in abundance across ports with different current velocities and water clarity. Both datasets showed spatial variation in macrobiofouling patterns alongside differences in current velocity and water clarity. This pattern is consistent with previous findings that current velocity is an important determinant of macrofouling attachment success (Al-Kautsar et al., 2020) and that water clarity shapes both larval settlement and filter-feeding efficiency (Johansen, 2014; Abdul Wahab et al., 2017). Together, these observations highlight current velocity and water clarity as environmental conditions that varied alongside macrofouling patterns across the two spatial scales examined in this study, without implying a statistical or causal relationship.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

MS. Conceptualization & Writing the Original Draft. **IK.** Statistical Analysis & Writing the Original Draft. **SW.** Conducting the Research. **RIG.** Conducting the Research. **NL.** Conducting the Research. **DA.** Statistical Analysis. **DI.** Review & Editing. **FS.** Review & Editing. **UFM.** Review & Editing.

CONCLUSION

Based on the research findings, macrobiofouling diversity on concrete pier piles at Kuala Bubon Port is relatively low, with a Shannon-Wiener index of 1.67 to 1.68 and a species density ranging from 3.11 to 3.33 ind/m². At the inter-port scale, macrobiofouling abundance varies significantly, ranging from 2,011 to 5,955 ind/m², with the highest value at Calang Port (Station 3), followed by Kuala Bubon Port (Station 2), and the lowest at Jetty Port (Station 1). Descriptive measurements of water parameters show that Calang Port,

which has the highest abundance, simultaneously recorded relatively higher current speed and water clarity values compared to other stations. These results illustrate a pattern of co-existence between ambient water environmental conditions and macrobiofouling abundance on concrete piles, without implying a statistical causal relationship.

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