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Functional Guild Responses of Megabenthos Under Sedimentation and Nutrient Enrichment in a Port-Influenced Tropical Reef System

Andik Isdianto[1,2*], Nuril Huda Al Maky[1], Dian Aliviyanti[1,2], Qurrota A'yun[1], Arief Setyanto[2], Uun Yanuhar[3], Nico Rahman Caesar[3], Aulia Lanudia Fathah[4], Muhammad Naufal Eka Putra[4], Berlania Mahardika Putri[5], Supriyadi Supriyadi[6], Oktiyas Muzaky Luthfi[7], Dwi Candra Pratiwi[8]

[1] Department of Marine Science, Faculty of Fisheries and Marine Sciences, Brawijaya University, Malang 65145, Indonesia
[2] Coastal Resilience and Climate Change Adaptation Research Group, Brawijaya University, Malang 65145, Indonesia
[3] Department of Fisheries Marine Resources Management, Brawijaya University, Malang 65145, Indonesia
[4] Master Program of Environmental Management and Development, Brawijaya University, Malang 65145, Indonesia
[5] Master Program of Environmental Science, Universitas Gadjah Mada, Yogyakarta 55284, Indonesia
[6] Doctoral Program in Ocean Resource and Environmental Changes, National Taiwan Ocean University, Keelung City 202301, China
[7] Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin 70383, Poland
[8] Earth and Atmospheric Sciences Department, University of Alberta, Edmonton T6G 2E3, Canada

Corresponding Author Email: andik.isdianto@ub.ac.id

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ABSTRACT

Port-adjacent coral reef systems are frequently exposed to multiple environmental pressures, including sedimentation, nutrient enrichment, runoff, tourism-related disturbance, and local hydrodynamic variability. However, functional biological responses under such cumulative pressure gradients remain insufficiently quantified. This study evaluates the association among sedimentation, nutrient enrichment, live coral cover, and megabenthos functional guild structure in the Sempu Strait, Indonesia. Megabenthos assemblages were surveyed using belt transects and classified into feeding guilds, while live coral cover was quantified using Underwater Photo Transects (UPT) across 15 station–period observations. Coral cover remained consistently low (10.28–16.37%), indicating persistent structural degradation. Although temperature, pH, and dissolved oxygen (DO) were within marine tolerance ranges, sedimentation rates were elevated across stations, with station means ranging from 58.12 ± 12.07 to 89.26 ± 14.57 mg/cm²/day and an overall mean of 73.73 ± 19.46 mg/cm²/day. Nutrient concentrations exceeded the national marine standards at some stations, with nitrate reaching 0.550 ± 0.026 mg/L and orthophosphate reaching 0.303 ± 0.015 mg/L. Carnivorous megabenthos showed a significant positive association with live coral cover ($r = 0.676$, $p = 0.006$), and exploratory regression further indicated this association ($R^2 = 0.457$). Other guilds showed weak or non-significant associations. Principal Component Analysis (PCA) indicated an integrated sedimentation–nutrient gradient explaining 46.2% of total variance, with the first two axes accounting for 71.4%. These findings suggest that guild-specific megabenthos analysis can provide a differentiated biological signal for interpreting habitat degradation under cumulative sedimentation and nutrient stress. Integrating environmental gradients, coral-cover condition, and feeding-guild responses may strengthen environmental impact diagnosis and monitoring in port-adjacent tropical reef systems.

1. INTRODUCTION

Coastal coral reef systems located adjacent to ports, fisheries infrastructure, tourism areas, and land-based runoff pathways are increasingly exposed to cumulative environmental pressures. These pressures commonly include sedimentation, nutrient enrichment, reduced water clarity, and physical habitat disturbance. Elevated sedimentation can reduce light penetration, impair coral photosynthesis, and inhibit larval settlement, ultimately constraining reef recovery trajectories [1]. Nutrient enrichment, particularly nitrate and phosphate loading, may promote algal proliferation and alter benthic competitive dynamics, contributing to reef degradation in nearshore environments [2, 3]. In port-adjacent reef systems, such stressors may arise from multiple interacting sources, including terrestrial runoff, coastal activity, maritime operations, tourism pressure, and local hydrodynamic resuspension [4]. In semi-enclosed port waters, altered water renewal time and contaminant accumulation have also been shown to amplify ecological stress and degrade

coastal ecosystem quality, reinforcing the vulnerability of adjacent reef habitats [5]. Recent environmental impact assessments further emphasize the importance of integrated, multiscale pollution characterization to improve situational awareness and ecological diagnosis in coastal systems exposed to anthropogenic pressure [6].

Indonesia, located within the Coral Triangle, harbors some of the world's most diverse coral reef ecosystems [7]. These reefs provide essential ecological services, including habitat provisioning, nursery grounds, trophic regulation, biodiversity maintenance, and coastal protection [8, 9]. However, increasing coastal development, fisheries expansion, tourism activity, and localized pollution have intensified environmental stress in many Indonesian reef systems [10, 11]. The Sempu Strait, East Java, represents a port-adjacent tropical reef system where coral habitats coexist with fishing-port activity, vessel movement, fish offloading, tourism use, and drainage inputs from surrounding coastal areas. Previous studies in this area have documented marine debris impacts, coral disease prevalence, and declining coral condition, indicating progressive ecosystem stress [4, 11, 12]. However, the present study does not assume that port activity is the sole causal driver of reef degradation. Instead, the Sempu Strait is treated as a coastal reef system exposed to multiple potential stressors that may interact through sedimentation, nutrient enrichment, reduced water clarity, and habitat simplification.

Megabenthos (>1 cm) are widely recognized as useful ecological indicators of reef condition because of their close association with benthic substrates, limited mobility, and relatively long life spans [13, 14]. Many megabenthic taxa, including echinoderms, gastropods, bivalves, and crustaceans, perform important ecological functions such as grazing, bioerosion, sediment reworking, filtration, and predator–prey regulation [15, 16]. However, megabenthos responses to environmental change are not uniform. Functional feeding groups, such as carnivores, herbivores, detritivores, and filter feeders, may exhibit distinct responses to habitat degradation, substrate alteration, water-column conditions, and physicochemical gradients [17]. For example, elevated sea urchin densities have been associated with degraded reef states and altered trophic structure [18], whereas coral-associated or structurally dependent taxa may decline when live coral cover and habitat complexity are reduced.

Despite the increasing use of megabenthos as reef-condition indicators in Indonesia [14, 19], empirical analyses explicitly linking functional guild structure with concurrent sedimentation, nutrient enrichment, and coral-cover decline remain limited. Most regional assessments emphasize abundance patterns or taxonomic composition without integrating environmental stress gradients within a functional framework. This limits their application for environmental impact diagnosis, because taxonomic abundance alone may not clearly indicate which ecological functions are most affected by sediment and nutrient pressure. In an environmental impact assessment context, feeding-guild structure can provide a practical biological signal because different guilds respond to environmental pressure through different ecological pathways. Herbivores and detritivores may respond to changes in algal availability, exposed substrate, and sediment-associated organic matter, whereas filter feeders may reflect changes in suspended particles and water-column conditions. Carnivorous and coral-associated taxa may be more sensitive to reduced habitat complexity, declining live coral cover, and altered trophic interactions. Therefore, integrating feeding-guild information with sedimentation, nutrient concentration, water clarity, and coral-cover data can improve the diagnosis of environmental pressure and support coastal monitoring, reef restoration planning, and management priority setting in port-adjacent reef systems.

Therefore, this study examines the association among sedimentation, nutrient enrichment, live coral cover, and megabenthos functional guild structure in the Sempu Strait, East Java, Indonesia. Specifically, this study aims to (1) quantify coral-cover condition and physicochemical characteristics across multiple station–period observations, (2) characterize megabenthos community structure by feeding guild, and (3) evaluate guild-specific associations with live coral cover under concurrent sedimentation and nutrient enrichment gradients. By linking environmental gradients, habitat condition, and functional megabenthos responses, this study contributes to environmental impact assessment by providing an integrated pressure–habitat–biological response framework for diagnosing reef degradation in a port-adjacent tropical coastal system.

2. MATERIALS AND METHODS

2.1 Study area

Surveys were conducted in December 2022, February 2023, and April 2023 at Sempu Strait, East Java, Indonesia. Sampling stations were established at five fixed stations, namely Rumah Apung, Jetty, Banyu Tawar, Waru-waru, and Watu Meja (Figure 1), with the unique characteristics of each research station (Table 1).

Table 1. Characteristics of each research station

Station	Coordinates	Description
Watu Meja	8°25'46.12"S, 112°41'51.24"E	Located in the east and directly facing the open sea.
Waru-waru	8°25'48.99"S, 112°41'37.03"E	The only location in the Sempu Strait that is commonly used as a tourist attraction.
Banyu Tawar	8°26'1.35"S, 112°41'19.65"E	This location receives runoff from a small river, resulting in lower seawater salinity.
Jetty Port	8°26'1.86"S, 112°41'3.22"E	This location is the busiest station with intensive fisheries activities, including fishing-boat docking, vessel transit, and fish offloading.
Rumah Apung	8°26'13.99"S, 112°40'48.14"E	Located at the western end of the Sempu Strait and directly adjacent to the Indian Ocean.

2.2 Megabenthos survey and identification

Megabenthos monitoring was conducted using a belt-transect approach commonly applied for assessing megabenthic assemblages in coral reef ecosystems [20]. Target taxa included sea urchins, sea cucumbers, giant clams, lobsters, lola, crown-of-thorns starfish (COT), drupella snails, and blue sea stars; additional taxa were also recorded to improve representativeness of the study area, consistent with prior work in the Sempu Strait [21]. Data collection used a visual census (Figure 2) with a belt transect method of 5 × 100 m (width × length), where the belt width was divided into 2.5

m on both the left and right sides of the transect line [22]. Divers swam in a zig-zag pattern and recorded all target occurrences within the belt transect [23]. Specimens were verified morphologically using field guides and relevant literature, and cross-checked using the World Register of Marine Species (WoRMS; https://www.marinespecies.org/). Megabenthos data were summarized as abundance. Each recorded genus was assigned to a feeding guild based on taxon-specific trophic roles reported in coral-reef megabenthos and relevant benthic ecological literature [15, 16, 20]. The guild assignment considered dominant feeding mode and ecological function, including grazing, corallivory, predation, detritus/deposit feeding, suspension feeding, and mixotrophy. For example, *Diadema* was classified as a herbivore/grazer because sea urchins commonly graze algal films and benthic turf; *Drupella* was classified as carnivore/corallivore because this gastropod feeds on coral tissue; *Tridacna* was classified as filter feeder/mixotroph because giant clams combine suspension feeding with photosymbiosis; *Comaster* was classified as filter/suspension feeder based on its crinoid feeding mode; and *Trapezia* was classified as carnivore/omnivore because coral-associated crabs consume animal material, mucus, detritus, and small particles. The genera were then grouped into herbivores/grazers, carnivores/corallivores or carnivores/omnivores, detritivores/deposit feeders, and filter/suspension feeders.

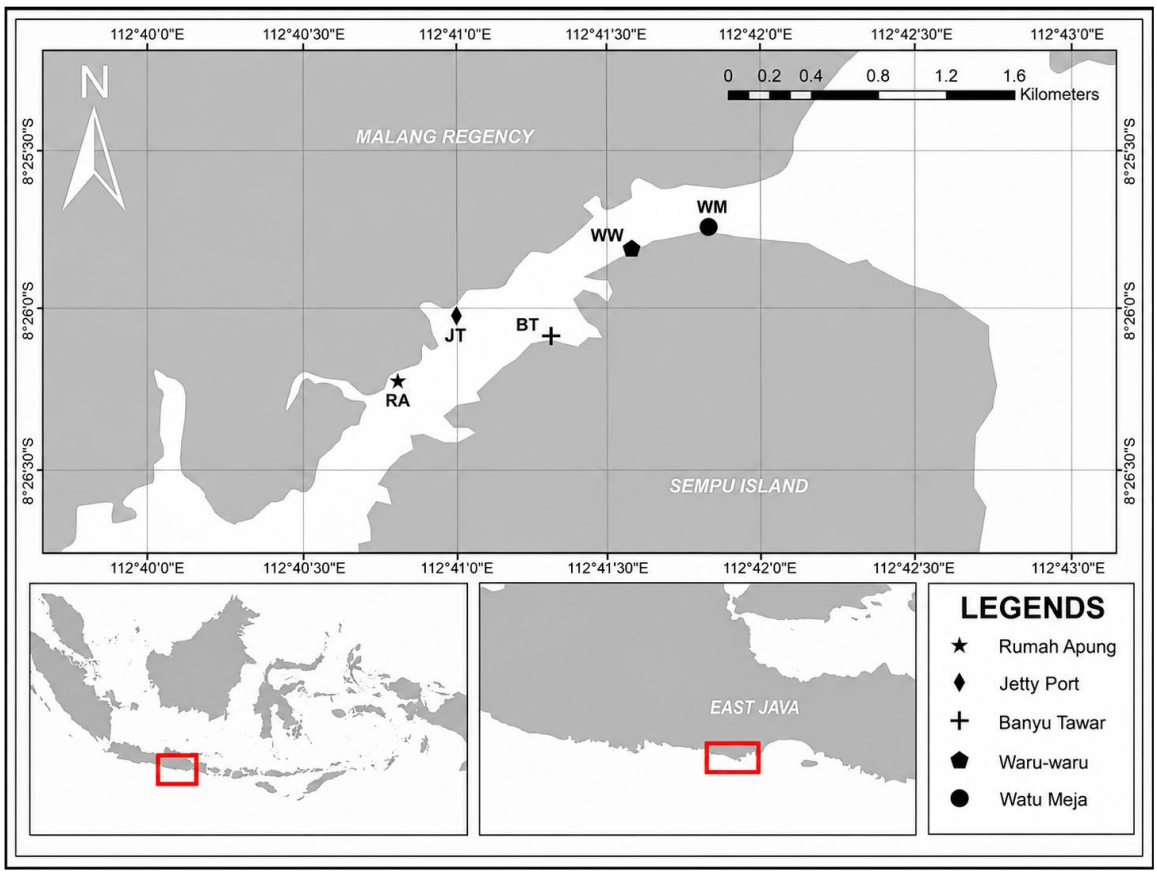

Figure 1. The five observation sites in Sempu Strait

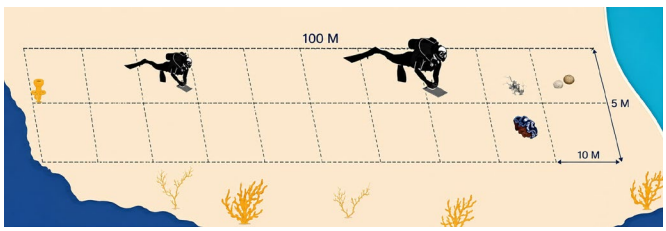

Figure 2. Belt transect for megabenthos monitoring

2.3 Live coral cover assessment

Live coral cover (%) was quantified using the Underwater Photo Transect (UPT) method [24] and analyzed using CPCe software [25]. Ten 1 × 1 m quadrats were placed at each station [26], with approximately 10 m spacing between quadrats.

2.4 Water quality measurements

Water quality metrics were measured to characterize physical and chemical conditions [27]. Temperature, dissolved oxygen (DO), salinity, and pH were recorded using an AAQ Rinko 1183s-F; light penetration was measured using a Secchi disk; sedimentation rate was measured using sediment traps; and current data were obtained from PODAAC. Nitrate and orthophosphate were analyzed in the laboratory and are reported as nitrate-nitrogen (NO_3–N) and orthophosphate-phosphorus (PO_4–P), respectively. These reporting units follow the Indonesian marine biota standards used for regulatory comparison. The values presented in Table 2 were expressed in the same units as the regulatory thresholds before exceedance ratios were calculated.

All in situ physicochemical parameters were measured in triplicate at each station during each sampling period to improve measurement reliability. For statistical analysis,

values were averaged per station–period combination and expressed as mean ± standard deviation (SD). Thus, the final dataset consisted of 15 station–period observations (5 stations × 3 sampling periods).

2.5 Statistical analysis

Association between megabenthos abundance and live coral cover (%) was initially tested using Pearson correlation. Correlation analyses used n = 15 station–period paired observations (5 stations × 3 sampling periods), where each observation represents paired values of live coral cover (%) and megabenthos abundance for the corresponding station and sampling period. Water-quality variables were first averaged from triplicate measurements prior to correlation and regression analyses to avoid pseudo-replication. Given the moderate sample size, statistical results were interpreted conservatively, emphasizing effect size (r and R^2) alongside *p*-values.

Table 2. Water quality parameters

Parameters	Unit	Station					Mean	Threshold (Indonesian Government, 2021)
		BT	WM	WW	JT	RA		
Temperature	°C	29.58 ± 0.058	29.71 ± 0.030	29.73 ± 0.049	29.42 ± 0.053	29.78 ± 0.188	29.64 ± 0.157	Natural condition; allowable deviation ≤ 2 °C from natural baseline
Salinity	‰ (psu)	32.06 ± 0.081	32.16 ± 0.038	32.10 ± 0.024	32.36 ± 0.051	32.40 ± 0.094	32.22 ± 0.152	Natural condition; allowable deviation ≤ 5% from seasonal mean salinity
pH	-	8.3 ± 0.175	8.0 ± 0.091	8.2 ± 0.051	8.3 ± 0.195	8.1 ± 0.154	8.2 ± 0.175	7.0–8.5
Dissolved Oxygen (DO)	mg/L	6.37 ± 0.012	6.35 ± 0.011	6.33 ± 0.006	6.37 ± 0.0114	6.32 ± 0.01	6.35 ± 0.023	> 5 mg/L
Water Clarity (Secchi Depth)	m	2.70 ± 0.495	2.19 ± 0.231	1.96 ± 0.444	2.99 ± 1.598	2.38 ± 1.352	2.44 ± 0.917	> 5 m (coral ecosystem)
Current Velocity	m/s	0.38 ± 0.312	0.45 ± 0.293	0.47 ± 0.421	0.49 ± 0.472	0.50 ± 0.487	0.45 ± 0.407	– (Not regulated under PP 22/2021)
Sedimentation Rate	mg/cm^2/day	89.26 ± 14.57	58.12 ± 12.07	61.05 ± 22.83	74.73 ± 3.891	85.49 ± 24.06	73.73 ± 19.46	– (No regulatory threshold)
Nitrate (NO_3–N)	mg/L	0.021 ± 0.002	0.027 ± 0.004	0.010 ± 0.001	0.550 ± 0.026	0.346 ± 0.011	0.205 ± 0.227	0.06 mg/L (as NO_3–N)
Orthophosphate (PO_4–P)	mg/L	0.011 ± 0.001	0.019 ± 0.001	0.008 ± 0.001	0.303 ± 0.015	0.286 ± 0.015	0.125 ± 0.143	0.015 mg/L (as PO_4–P)

Note: Nutrient concentrations are expressed as nitrate-nitrogen (NO_3–N) and orthophosphate-phosphorus (PO_4–P), consistent with Indonesian Government Regulation No. 22/2021, Appendix VIII, for marine biota standards. JT = Jetty, RA = Rumah Apung, BT = Banyu Tawar, WM = Watu Meja, and WW = Waru-waru.

Statistical significance was assessed using two-tailed *p*-values with $\alpha = 0.05$. Prior to Pearson correlation, assumptions were evaluated (normality, linearity, and homoscedasticity) using standard diagnostics (e.g., Shapiro–Wilk test for normality and residual inspection) [28]. When needed, data were transformed (e.g., arcsine–square-root for percentage coral cover and log(x+1) for abundance). If assumptions were not satisfied after transformation, Spearman's rank correlation was used as a non-parametric alternative.

In addition to correlation analysis, simple linear regression was applied to quantify the statistical association between live coral cover and carnivorous megabenthos abundance. Live coral cover (%) was treated as the independent variable and carnivore abundance as the dependent variable. The coefficient of determination (R^2) was calculated to estimate the proportion of variance in carnivore abundance accounted for by the regression model. Model significance was evaluated using an F-test at $\alpha = 0.05$. Regression diagnostics were inspected to verify linearity and homoscedasticity assumptions.

Principal Component Analysis (PCA) was performed in RStudio using R statistical software to explore the combined structure of environmental variables, live coral cover, and feeding-guild abundance. Before PCA, all variables were standardized using z-scores and analyzed using a correlation matrix to account for differences in measurement units. Environmental variables included sedimentation rate, nitrate (NO_3–N), orthophosphate (PO_4–P), water clarity, current velocity, and live coral cover, whereas biological variables included carnivore, herbivore, detritivore, and filter-feeder abundance. Variables were screened for extreme values and redundancy using descriptive statistics and inter-variable correlation patterns. Principal components were retained based on eigenvalues greater than 1, percentage of explained variance, and ecological interpretability. Because the dataset consisted of 15 station–period observations, PCA was interpreted as an exploratory gradient analysis rather than a confirmatory inferential test.

Because this study used 15 station–period observations, the correlation, regression, and PCA results were interpreted as exploratory evidence of association rather than proof of causality. Direct attribution of sedimentation, nutrient enrichment, or feeding-guild shifts to port activities would require additional operational and environmental data, such as vessel traffic, dredging records, discharge measurements, rainfall–runoff inputs, and longer-term temporal monitoring. Therefore, this study interprets the Sempu Strait as a port-adjacent reef system influenced by multiple potential stressors rather than attributing the observed patterns to a single source. Supporting station–period environmental and habitat data, together with summary statistics from the guild-level correlation, regression, and PCA analyses, are provided in

Tables A1–A3 in the Appendix. The environmental dataset comprises 15 observations from five stations and three sampling periods.

3. RESULTS AND DISCUSSION

Because this study was based on observational and correlational data, the results do not support causal inference. The patterns reported here should therefore be interpreted as empirical associations that are consistent with, but do not prove, the hypothesized stress-response pathways.

3.1 Water quality parameters in the Sempu Strait

Physical and chemical water quality parameters regulate habitat suitability, light penetration, and trophic processes that structure coral–megabenthos assemblages. In the Sempu Strait (Table 2), temperature ranged from 29.42 ± 0.053 to 29.78 ± 0.188 ℃, pH ranged from 8.0 to 8.3, and DO ranged from 6.32 ± 0.010 to 6.37 ± 0.012 mg/L. These values were within the marine biota standards stipulated in Indonesian Government Regulation No. 22 of 2021 (Appendix VIII) [29]. These ranges indicate that acute thermal stress, hypoxia, or acidification were not the dominant environmental constraints during the observation periods.

Salinity ranged from 32.06 ± 0.081 to 32.40 ± 0.094‰. Under PP 22/2021, salinity is regulated based on natural conditions, allowing deviations of ≤5% from the seasonal mean rather than fixed numeric thresholds. These values are close to the salinity of full seawater (±35‰), which indicates the dominance of marine influences, which is a common condition in open coastal areas far from large river estuaries [30]. Thompson et al. [31] used a long-term average (LTA) approach as a reference to assess salinity changes due to tropical cyclones, and concluded that a 13% decrease in average salinity due to tropical cyclones is generally within the tolerance range of most estuarine and coastal species. This approach is conceptually similar to the provisions of PP 22/2021, which allows a deviation of ≤5% from the seasonal average.

In contrast, water clarity (Secchi depth) ranged from 1.96 ± 0.444 to 2.99 ± 1.598 m, with an overall mean of 2.44 ± 0.917 m. These values were below the recommended threshold (>5 m) for coral ecosystems under PP 22/2021. Reduced light penetration indicates elevated suspended particulate matter and turbidity, conditions known to suppress zooxanthellae photosynthesis and reduce coral recruitment success [32]. Persistent low clarity therefore signals chronic depositional pressure in this nearshore system.

Current velocity ranged from 0.38 ± 0.312 to 0.50 ± 0.487 m/s, with an overall mean of 0.45 ± 0.407 m/s. Although hydrodynamic conditions are not directly regulated under PP 22/2021, current velocity may be associated with sediment resuspension, nutrient redistribution, and spatial variability in particulate conditions within coral habitats. In this study, the observed hydrodynamic pattern was consistent with spatial heterogeneity in sedimentation and nutrient conditions among stations [33].

Sedimentation rates were elevated across stations, with station means ranging from 58.12 ± 12.07 to 89.26 ± 14.57 mg/cm²/day and an overall mean of 73.73 ± 19.46 mg/cm²/day. While no regulatory threshold is specified for sediment deposition, these values indicate substantial particulate flux typical of inshore and nearshore reef systems exposed to terrestrial runoff, coastal activity, and local hydrodynamic resuspension. Drainage inputs from the Clungup and Kondang Butung estuaries and Tamban River likely contribute to sediment delivery [21]. High sediment deposition can smother coral tissue, reduce substrate suitability for larval settlement, and increase metabolic stress, thereby constraining reef structural recovery [34]. Sediment transport and depositional patterns can also be strongly influenced by catchment runoff and associated hydrological processes [35].

Nutrient concentrations revealed clear spatial exceedances of national marine standards. Nitrate (expressed as NO_3–N) reached 0.550 ± 0.026 mg/L at the Jetty and 0.346 ± 0.011 mg/L at Rumah Apung, exceeding the PP 22/2021 threshold of 0.06 mg/L by approximately nine-fold and six-fold, respectively. Orthophosphate (expressed as PO_4–P) reached 0.303 ± 0.015 mg/L and 0.286 ± 0.015 mg/L at the same stations, substantially exceeding the regulatory limit of 0.015 mg/L. These magnitudes indicate substantial nutrient enrichment relative to the regulatory thresholds.

Spatially, the Jetty and Rumah Apung showed the highest nutrient concentrations. The Jetty was additionally characterized by intensive coastal activity, sediment resuspension, and disturbed benthic substrate. The concurrent occurrence of low water transparency, elevated sediment deposition, and nutrient exceedance was consistent with a cumulative environmental stress gradient in this port-adjacent coastal reef system.

Overall, although core physicochemical parameters, including temperature, pH, and DO, were within acceptable marine ranges, sedimentation and nutrient enrichment appear to represent the dominant environmental gradients in the Sempu Strait. The magnitude and spatial concentration of these gradients suggest that reef degradation in this system is more closely associated with chronic depositional and enrichment processes than with acute oxygen depletion or thermal stress. This combined environmental gradient provides the structural context for interpreting the observed coral-cover condition and guild-specific megabenthos responses within an environmental impact assessment framework.

Because Table 2 summarizes station-based mean values across the three sampling periods, monthly variation in sedimentation and nutrient concentrations could not be fully separated in the main analysis. Nevertheless, the station-mean pattern indicates elevated sedimentation across several stations and localized nutrient enrichment at the Jetty and Rumah Apung. Future monitoring should include month-specific sedimentation and nutrient datasets to better distinguish seasonal effects, rainfall–runoff influence, and short-term coastal activity from persistent station-level environmental pressure.

3.2 Coral cover in the Sempu Strait

Live coral cover in the Sempu Strait ranged from 10.28% to 16.37% (Figure 3), indicating persistently poor reef condition. According to commonly applied reef-condition classifications, coral cover below 25% is consistent with a severely degraded structural state [36]. Substrate composition was dominated by abiotic components (68.31–80.22%), including dead coral fragments, rubble, sand, and rock, while algal cover ranged from 4.47% to 21.40%. The dominance of abiotic substrate suggests reduced structural complexity and limited habitat suitability for coral-dependent organisms.

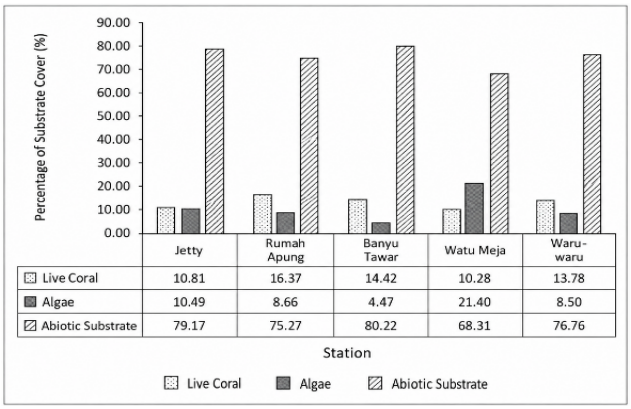

Figure 3. Substrate cover percentage

Comparisons with previous assessments in the same region indicate long-term structural instability. Coral cover in 2014 ranged from 6.94% to 42.4%, in 2016 from 10.62% to 33.75%, and in 2018 from 8% to 31% [12]. Although some historical observations reported moderate reef condition at certain sites, the present study documents consistently low coral cover across all stations. This pattern suggests that reef recovery has remained constrained over the past decade under persistent environmental pressure.

The low coral-cover condition observed in this study was consistent with reduced habitat structural complexity and refugia reported for degraded reef systems [37]. Such structural degradation has been associated with differences in megabenthos composition, coral-associated taxa abundance, and reef-fish assemblages [17, 38]. The observed dominance of abiotic substrate is consistent with reef flattening and competitive shifts associated with sedimentation and nutrient enrichment documented in nearshore reef systems exposed to cumulative environmental stress.

In addition to chronic sedimentation and nutrient enrichment (Section 3.1), episodic disturbances have likely contributed to reef degradation in the Sempu Strait. Historical port expansion activities (2006–2009), documented bleaching events (2010 and 2015), tourism pressure, and marine debris accumulation [4, 12] collectively represent cumulative anthropogenic stressors. Such multi-stressor exposure can suppress coral recruitment and delay structural recovery trajectories in marginal reef environments [9].

From an environmental impact perspective, the consistently low coral-cover values observed in this study represent a degraded baseline condition rather than short-term fluctuation. The structural simplification of the reef substrate provides the ecological context for interpreting functional megabenthos responses under sedimentation and nutrient pressure in subsequent analyses.

3.3 Megabenthos community in the Sempu Strait

A total of 801 megabenthos individuals representing 19 genera across seven taxonomic classes were recorded during the three sampling periods (Table 3). The community was strongly dominated by echinoderms, particularly the sea urchin *Diadema* (432 individuals), accounting for more than half of total observations. In contrast, several taxa such as lobsters and certain gastropods occurred at very low abundances.

The dominance pattern suggests a structurally simplified megabenthos assemblage rather than a balanced multi-taxa community. Elevated densities of *Diadema* have frequently been associated with degraded reef conditions, reduced predator abundance, increased algal resources, and altered trophic dynamics [39]. In the Sempu Strait, high *Diadema* abundance may reflect the combined influence of reduced live coral cover, exposed hard substrate, algal-film availability, and localized disturbance under chronic sedimentation and nutrient enrichment pressure.

The relative scarcity of coral-associated taxa and the low occurrence of some indicator organisms, such as blue sea stars, further suggest environmental stress. Megabenthos are substrate-associated and relatively sessile organisms, making them responsive to persistent changes in habitat structure and water quality [40]. Therefore, community composition can function as an integrative biological indicator of cumulative environmental pressure.

Table 3. Megabenthos composition

Class	Genus	Feeding Guild	Month			Total
			Dec 2022	Feb 2023	Apr 2023	
Echinoidea	*Diadema*	Herbivore/grazer	232	112	88	432
	Echinothrix	Herbivore/grazer	7	4	6	17
	Tripneustes	Herbivore/grazer	2	1	1	4
Crinoidea	*Comaster*	Filter/suspension feeder	35	29	37	101
Holothuroidea	*Holothuria*	Detritivore/deposit feeder	1	0	1	2
	Synapta	Detritivore/deposit feeder	1	0	0	1
Asteroidea	*Echinaster*	Carnivore/omnivore	5	8	7	20
	Culcita	Carnivore/omnivore	4	1	2	7
Gastropoda	*Charonia*	Carnivore	0	0	2	2
	Drupella	Carnivore/corallivore	29	36	28	93
	Trochus	Herbivore/grazer	7	0	3	10
	Phyllidiella	Carnivore/sponge feeder	0	2	0	2
	Phyllidia	Carnivore/sponge feeder	0	0	1	1
Bivalvia	*Tridacna*	Filter feeder/mixotroph	18	20	17	55
Malacostraca	*Stenopus*	Carnivore/omnivore	2	2	2	6
	Enoplometopus	Carnivore/omnivore	0	1	0	1
	Trapezia	Carnivore/omnivore	11	11	16	38
	Cymo	Carnivore/omnivore	2	3	1	6
	Odontodactylus	Carnivore	1	1	1	3
Total			**357**	**231**	**213**	**801**

Note: Feeding-guild assignment was based on dominant trophic roles reported for coral-reef megabenthos and taxon-specific ecological descriptions. Key examples include *Diadema* as herbivore/grazer, *Drupella* as carnivore/corallivore, *Tridacna* as filter feeder/mixotroph, *Comaster* as filter/suspension feeder, and *Trapezia* as carnivore/omnivore.

The observed assemblage structure, characterized by echinoderm dominance and uneven taxonomic distribution, is consistent with coral-degraded and sediment-impacted reef systems documented in other nearshore environments [41]. Given the low live coral cover documented in Section 3.2, the megabenthos community structure is consistent with habitat simplification and altered benthic resource pathways. The dominance of grazing echinoids, particularly *Diadema*, may reflect increased availability of exposed substrate and algal films under degraded reef conditions, whereas the low abundance of coral-associated taxa suggests reduced availability of structurally complex microhabitats.

From an environmental impact perspective, the megabenthos community reflects a stress-associated configuration linked to habitat degradation and altered benthic food resources. This pattern provides the foundation for evaluating guild-specific responses in subsequent analyses.

3.4 Megabenthos abundance in the Sempu Strait

Total megabenthos abundance across the three observation periods ranged from 0.0007 to 0.288 ind/m² (Figure 4). The highest density was recorded for the sea urchin *Diadema* (0.288 ind/m²), whereas several taxa, such as *Synapta*, *Phyllidia*, and *Enoplometopus*, exhibited minimal densities (0.0007 ind/m²). Spatially, relative abundance mapping revealed strong dominance of *Diadema* at the Jetty station, where this genus accounted for 90.26% of total individuals (Figure 5).

The strong dominance of *Diadema* at the Jetty coincided with the highest nitrate and orthophosphate concentrations and intensive coastal activity at this station. However, this co-occurrence should not be interpreted as evidence of a direct nutrient effect. The Jetty was also characterized by sediment resuspension, physical disturbance, exposed benthic substrate, and reduced live coral cover. These concurrent conditions may collectively be associated with the observed *Diadema* dominance. Therefore, the abundance pattern should be interpreted in relation to combined habitat disturbance, substrate condition, resource availability, and trophic interactions rather than nutrient enrichment alone.

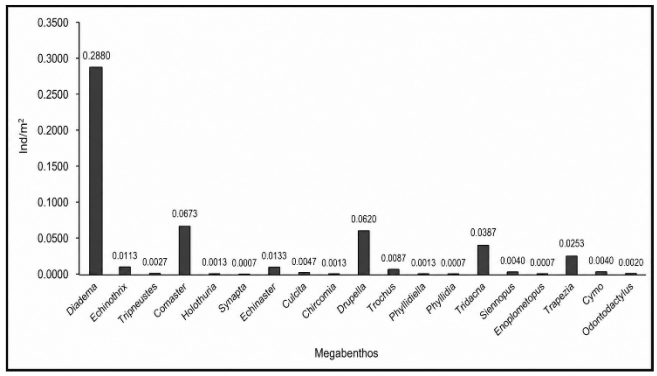

Figure 4. Abundance of megabenthos

The skewed abundance distribution indicates community imbalance rather than a heterogeneous multi-taxa structure. Elevated densities of sea urchins have been widely documented in degraded reef systems characterized by reduced predator pressure, increased algal substrate, and structural simplification [42, 43]. High *Diadema* abundance is frequently associated with coral mortality, algal proliferation, and sediment-disturbed habitats, particularly in nearshore environments exposed to anthropogenic activity.

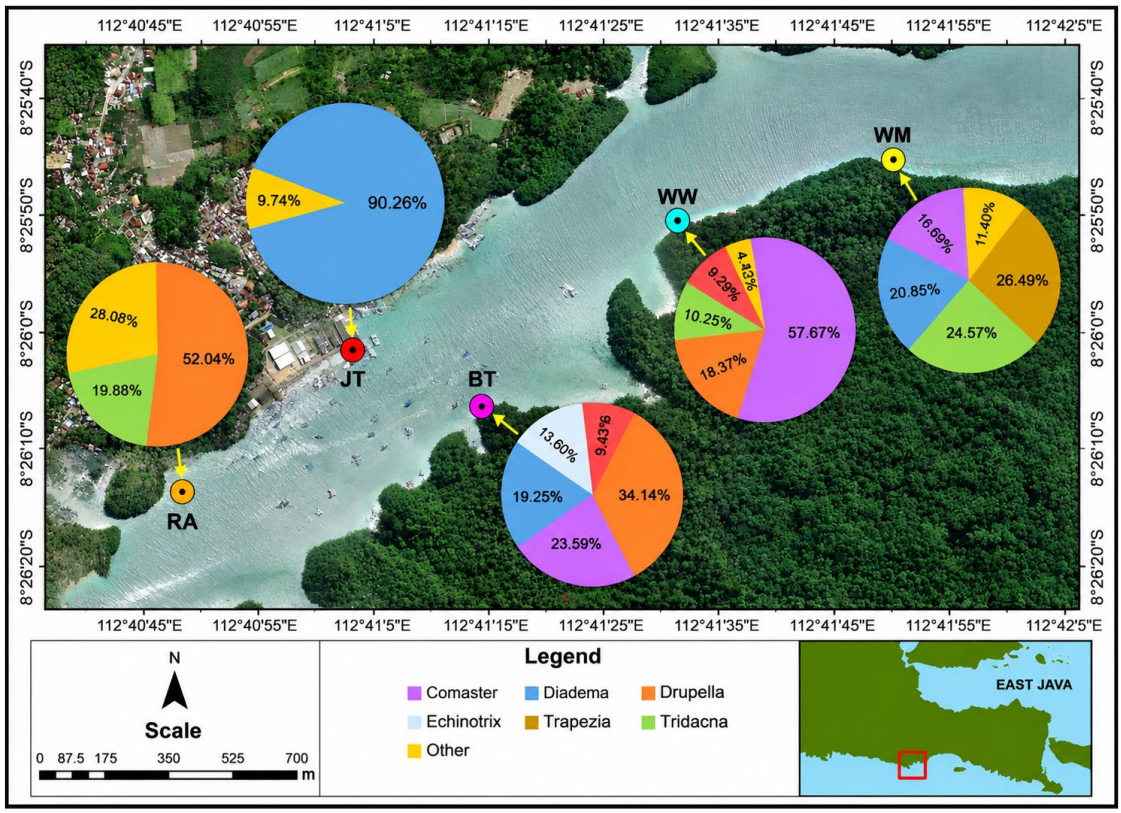

Figure 5. Spatial distribution of megabenthos based on relative abundance at each station
Note: JT = Jetty, RA = Rumah Apung, BT = Banyu Tawar, WM = Watu Meja, and WW = Waru-waru.

The dominance of echinoderms in reef gaps and unconsolidated substrates further supports the interpretation of localized habitat alteration under depositional pressure. Sea urchins can tolerate moderate turbidity and sediment flux and may proliferate where coral cover is reduced [44]. Given the low coral cover documented in Section 3.2 and the elevated sedimentation and nutrient exceedance described in Section 3.1, the observed abundance pattern is consistent with cumulative habitat degradation. However, *Diadema* dominance at the Jetty should not be interpreted as a direct response to nutrient enrichment alone. Instead, localized disturbance, sediment resuspension, exposed substrate, algal-film availability, and altered predator–prey interactions may have created suitable conditions for sea urchin aggregation.

Conversely, the relatively low abundance of coral-associated taxa, such as giant clams and certain crustaceans, may indicate limited availability of structurally complex microhabitats. Giant clams are known to prefer clear and stable substrates and may be sensitive to prolonged turbidity and nutrient imbalance [45]. Reduced densities of such taxa can therefore signal declining habitat quality and reduced reef structural suitability.

From an environmental impact perspective, the abundance pattern indicates localized dominance of stress-tolerant taxa, particularly Diadema, under degraded reef conditions. This pattern complements the community-level evidence in Section 3.3 and suggests that megabenthos abundance should be interpreted together with station-level habitat disturbance, substrate condition, and trophic interactions. Direct attribution to port operations requires additional operational data.

3.5 Guild-specific associations with coral cover

Megabenthos abundance may respond to habitat structure and benthic substrate composition through changes in food availability, refuge provision, and trophic interactions. Given the concurrent sedimentation and nutrient-enrichment gradients described in Section 3.1 and the low coral-cover condition described in Section 3.2, live coral cover was evaluated as a structural covariate potentially associated with guild-level megabenthos abundance. Pearson correlation analysis was conducted using n = 15 station–period paired observations (Table 4).

Table 4. Correlation between live coral cover and megabenthos

Diet	r	*p*-Value	Correlation
Carnivore	0.676	0.006	Strong
Herbivore	-0.22	0.43	Very weak
Filter Feeder	-0.253	0.362	Weak
Detritivore	-0.033	0.907	Very weak

Note: n = 15 station–period observations; *p*-values are two-tailed.

Table 5. Simple linear regression between live coral cover and carnivorous megabenthos abundance

Model	R	R^2	Adjusted R^2	F (1,13)	*p*-Value
Coral cover → Carnivore abundance	0.676	0.457	0.417	10.94	0.006

Carnivorous megabenthos exhibited a significant positive association with live coral cover (r = 0.676; n = 15; $p = 0.006$; two-tailed). Simple linear regression further supported this exploratory association ($F_{1,13} = 10.94$; $p = 0.006$; $R^2 = 0.457$; adjusted $R^2 = 0.417$) (Table 5). Given the limited number of station–period observations, this result should be interpreted as exploratory evidence of association rather than proof of a direct causal relationship. The pattern suggests that carnivorous megabenthos tend to be more abundant where live coral cover and reef structural condition are relatively higher.

From an environmental impact perspective, sedimentation and nutrient enrichment were correlated with reduced coral-cover condition in this dataset. This pattern was also consistent with an association between lower reef structural condition and reduced carnivore abundance, although the present analysis does not establish a causal pathway among these variables. Similar habitat-dependent regulation of predator abundance has been documented in structurally degraded reef systems where reef flattening constrains trophic organization [46, 47]. Therefore, carnivorous megabenthos may be more responsive to changes in reef structural condition than other feeding guilds under depositional and enrichment stress.

In contrast, herbivores (r = -0.22; $p = 0.43$), filter feeders (r = -0.253; $p = 0.362$), and detritivores (r = -0.033; $p = 0.907$) showed weak and statistically non-significant associations with live coral cover. These guilds are likely influenced by additional drivers beyond coral extent alone, including algal biomass, sediment-associated organic matter, suspended particles, substrate condition, and hydrodynamic transport processes. Elevated *Diadema* densities under degraded reef conditions have been reported in other systems experiencing sediment and nutrient stress [48, 49], which may partially decouple herbivore abundance from live coral cover.

The absence of strong associations for non-carnivorous guilds suggests that coral cover alone does not fully represent the environmental stress gradient influencing megabenthos distribution. Instead, guild composition in this port-adjacent reef system is likely associated with multiple interacting stressors, including sediment deposition, nutrient enrichment, localized anthropogenic activity, and hydrodynamic variability.

Overall, coral cover functioned as a significant structural covariate for carnivorous megabenthos but not for other feeding guilds. These findings indicate that guild-specific analysis may provide a useful differentiated ecological signal for interpreting megabenthos responses under sedimentation and nutrient stress. Integrating structural reef metrics with functional megabenthos responses may strengthen environmental impact diagnosis beyond single-indicator assessments and support targeted management prioritization in port-adjacent tropical reef systems.

While correlation analysis highlights guild-specific associations with coral cover, coral extent alone may not fully capture the integrated environmental stress context influencing megabenthos distribution. Therefore, a multivariate approach was applied to examine the combined structure of sedimentation, nutrient enrichment, habitat condition, and guild abundance.

3.6 Multivariate environmental–guild association

PCA extracted two dominant axes with eigenvalues greater than 1. PC1 had an eigenvalue of 4.62 and accounted for 46.2% of total variance, whereas PC2 had an eigenvalue of 2.52 and accounted for 25.2% of total variance. Together, PC1 and PC2 explained 71.4% of the total variance (Table 6; Figure

6). These two axes were retained because they showed the highest percentages of explained variance, met the Kaiser criterion, and provided interpretable environmental–guild gradients. PC1 was strongly structured by positive loadings of sedimentation rate, nitrate, and orthophosphate, and negative loadings of live coral cover and water clarity (Table 6). This axis represents a depositional–nutrient enrichment gradient. PC2 was primarily associated with megabenthos trophic differentiation, characterized by positive loading of carnivore abundance and moderate negative association with herbivore dominance.

Table 6. Principal component loadings

Variable	PC1	PC2
Sedimentation rate	0.82	0.21
Nitrate (NO_3–N)	0.87	0.18
Orthophosphate (PO_4–P)	0.84	0.24
Water clarity	-0.71	-0.12
Live coral cover	-0.76	0.41
Current velocity	0.33	-0.48
Carnivore abundance	-0.52	0.73
Herbivore abundance	0.61	-0.39
Detritivore abundance	0.44	-0.22
Filter feeder abundance	0.37	-0.31

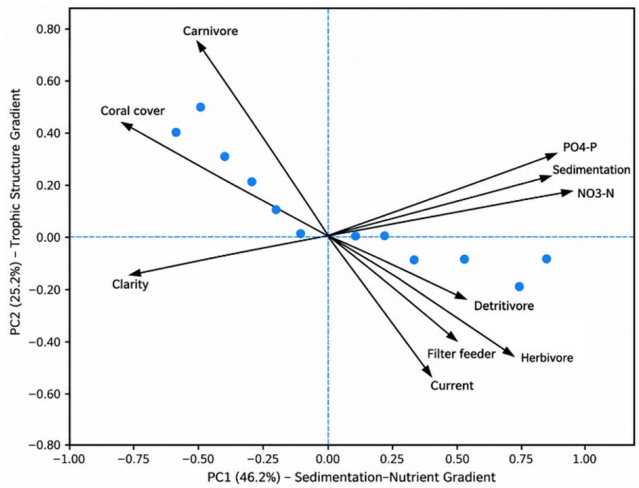

Figure 6. Principal Component Analysis (PCA) biplot of environmental variables, live coral cover, and megabenthos feeding guild abundance (n = 15)
Note: PC1 (46.2%) and PC2 (25.2%) represent the main ordination axes. Arrows indicate variable loadings.

Current velocity showed a moderate loading on PC1 (0.33; Table 6), indicating that hydrodynamic variability was associated with the sediment–nutrient ordination pattern. However, its loading was lower than those of sedimentation, nitrate, and orthophosphate, suggesting a comparatively weaker contribution to the observed multivariate gradient.

The ordination biplot (Figure 6) illustrates clear separation along the PC1 axis. Observations with elevated nutrient concentrations and sedimentation clustered along the positive side of PC1 and corresponded with reduced coral cover and lower water clarity. In contrast, station–period combinations with relatively higher coral cover aligned toward the negative PC1 region.

The inverse alignment between coral cover and the enrichment–sedimentation axis suggests that lower coral-cover conditions were associated with higher sedimentation and nutrient enrichment within the ordination space. This pattern was consistent with the association observed in the regression analysis (Section 3.5), although it should be interpreted as exploratory because the PCA was based on 15 station–period observations.

Guild positioning further reveals differentiated ecological sensitivity. Carnivorous megabenthos were associated with higher coral-cover conditions and positioned positively along PC2 (Figure 6), consistent with their greater abundance under relatively higher reef structural conditions. In contrast, herbivore abundance was more closely aligned with the enrichment-dominated end of the gradient, consistent with stress-tolerant proliferation patterns observed in degraded reef systems.

The ordination pattern indicates that sedimentation and nutrient enrichment co-vary as integrated environmental gradients rather than acting independently. Although exploratory, the PCA provides multivariate support for the interpretation that sedimentation and nutrient enrichment are associated with habitat condition and feeding-guild composition in this port-adjacent reef system. These results support the value of monitoring sediment and nutrient loads in coastal activity zones where chronic depositional conditions are associated with reduced reef structural integrity and functional stability.

Because this study used 15 station–period observations, the correlation, regression, and PCA results should be interpreted as exploratory evidence of association rather than proof of causality. Direct attribution of sedimentation, nutrient enrichment, or guild shifts to port activities would require additional operational and environmental data, such as vessel traffic, dredging records, discharge measurements, rainfall–runoff data, and longer-term temporal monitoring. Therefore, the present study interprets the Sempu Strait as a port-adjacent reef system influenced by multiple potential stressors rather than attributing the observed patterns to a single source.

4. CONCLUSION

This study indicates that the Sempu Strait reef system represents a structurally degraded tropical reef exposed to cumulative sedimentation and nutrient enrichment gradients in a port-adjacent coastal setting. Live coral cover remained low (10.28–16.37%), while sedimentation rates were elevated (58.12–89.26 mg/cm²/day). Nitrate and orthophosphate concentrations exceeded national marine standards by up to approximately nine-fold and twenty-fold, respectively, indicating substantial enrichment stress despite temperature, pH, and DO remaining within acceptable marine ranges.

Guild-level analysis showed differentiated association patterns. Carnivorous megabenthos had a significant positive association with live coral cover ($r = 0.676$), and exploratory regression further supported this association ($R^2 = 0.457$). In contrast, herbivore, detritivore, and filter-feeder guilds showed weak or non-significant associations with coral cover, indicating that coral cover alone did not account for their observed abundance patterns.

Multivariate analysis further indicated an integrated sedimentation–nutrient gradient, with PC1 explaining 46.2% of total variance and the first two axes accounting for 71.4%. Because the analysis was based on 15 station–period observations, these results should be interpreted as exploratory evidence of association rather than proof of causality. Direct attribution to port operations would require additional data on vessel activity, dredging, discharge, runoff, and longer-term

temporal variability.

From an environmental impact assessment perspective, the findings suggest that feeding-guild analysis can complement routine coral-cover and water-quality monitoring by providing a functional biological signal of habitat degradation. Nutrient-enrichment hotspots and stations with reduced water clarity should receive priority monitoring, while sediment and runoff inputs around coastal activity zones should be managed to reduce depositional pressure on reef habitats. Integrating sedimentation metrics, nutrient thresholds, coral structural condition, and guild-level megabenthos responses may strengthen environmental impact diagnosis and management prioritization in port-adjacent tropical reef systems.

AUTHOR CONTRIBUTIONS

Conceptualization, A.I.; methodology, A.I., N.H.A.M., and A.S.; software, A.I. and D.A.; validation, A.I., U.Y., N.R.C., and S.S.; formal analysis, A.I.; investigation, A.I., N.H.A.M., D.A., Q.A., A.S., A.L.F., M.N.E.P., and B.M.P.; resources, A.I., O.M.L., D.C.P., and S.S.; data curation, A.I. and D.A.; writing—original draft preparation, A.I.; writing—review and editing, A.I., N.H.A.M., U.Y., O.M.L., D.C.P., and S.S.; visualization, A.I. and D.A.; supervision, A.I.; project administration, A.I.; funding acquisition, none. All authors have read and agreed to the published version of the manuscript.

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APPENDIX

Table A1. Environmental and habitat variables for each station–period observation

Station	Sampling Period	Live Coral Cover (%)	Sedimentation Rate (mg/cm²/day)	Nitrate (NO_3–N, mg/L)	Orthophosphate (PO_4–P, mg/L)	Water Clarity (m)	Current Velocity (m/s)
JT	December 2022	14.60	71.34	0.520	0.320	4.829	0.49
JT	February 2023	8.92	78.98	0.570	0.290	2.300	0.49
JT	April 2023	8.92	73.89	0.560	0.300	1.855	0.49
RA	December 2022	19.80	113.23	0.340	0.290	3.895	0.50
RA	February 2023	20.39	73.04	0.360	0.300	1.295	0.50
RA	April 2023	8.92	70.21	0.340	0.270	1.950	0.50
BT	December 2022	13.20	96.82	0.019	0.011	2.200	0.38
BT	February 2023	13.40	98.51	0.024	0.010	2.720	0.38
BT	April 2023	16.66	72.47	0.021	0.012	3.190	0.38
WM	December 2022	10.20	60.58	0.023	0.018	2.215	0.45
WM	February 2023	10.85	68.79	0.031	0.019	2.400	0.45
WM	April 2023	9.80	45.01	0.028	0.020	1.940	0.45
WW	December 2022	13.60	71.90	0.009	0.007	2.265	0.47
WW	February 2023	15.45	76.43	0.010	0.008	1.450	0.47
WW	April 2023	12.30	34.82	0.012	0.009	2.165	0.47

Note: JT = Jetty, RA = Rumah Apung, BT = Banyu Tawar, WM = Watu Meja, and WW = Waru-waru.

Table A2. Guild-level Pearson correlations and simple linear regression statistics

Analysis	Guild / Model	r / R	*p*-Value	R^2	Adjusted R^2	F (1,13)
Pearson correlation	Carnivore	0.676	0.006	–	–	–
Pearson correlation	Herbivore	−0.220	0.430	–	–	–
Pearson correlation	Filter feeder	−0.253	0.362	–	–	–
Pearson correlation	Detritivore	−0.033	0.907	–	–	–
Simple linear regression	Coral cover → Carnivore abundance	0.676	0.006	0.457	0.417	10.94

Table A3. Principal Component Analysis (PCA) summary statistics

Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	4.62	46.2	46.2
PC2	2.52	25.2	71.4

Note: Environmental and habitat variables are reported for 15 station–period observations. Guild-level Pearson correlations and simple linear regression statistics correspond to the exploratory analyses reported in Tables 4 and 5. PCA statistics correspond to the ordination results reported in Table 6 and Figure 6.