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Integrated multimetric assessment of mangrove-seagrass-plankton systems across spatial gradients in Banyuwedang Bay, Bali, Indonesia

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Abstract. *Sugiana IP, Janaguna IMA, Alfatiha S, Wijaya IMS, Yasa IGA, Sutasoma IWG. 2026. Integrated multimetric assessment of mangrove-seagrass-plankton systems across spatial gradients in Banyuwedang Bay, Bali, Indonesia. Biodiversitas 27 (4): d270416. https://doi.org/10.13057/biodiv/d270416.* North Bali coastal waters host interconnected mangrove-seagrass-plankton systems that respond to spatial gradients in physicochemical conditions. This study provides a multimetric baseline assessment integrating environmental parameters with mangrove, seagrass, and plankton indicators across three stations (S1-S3) in Banyuwedang Bay (November 2025), emphasizing spatial ecological patterns rather than inferential relationships. The analysis integrates environmental parameters with ecological indicators of mangroves (Mangrove Health Index, MHI), seagrass (Seagrass Ecological Quality Index, SEQI), and plankton communities (diversity *H'*, evenness *J*, and dominance *C*). Environmental conditions varied spatially, with higher suspended solids at the inner bay and increasing temperature, salinity, and conductivity toward the outer bay. Mangrove ecosystems were consistently classified as excellent (MHI: 67.45-75.98), indicating structurally stable stands despite differences in species composition. In contrast, seagrass meadows exhibited moderate ecological condition (SEQI: 0.63-0.67), reflecting variation between species richness at the inner station and higher coverage at the mid-bay station. Plankton communities showed moderate diversity (phytoplankton *H'*: 1.31-1.75; zooplankton *H'*: 0.83-1.80) with localized dominance at the mid-bay station, indicating spatial heterogeneity in community structure. Diatoms dominated across stations, while cyanobacteria increased at one location, suggesting spatial variability associated with environmental gradients. Zooplankton communities displayed relatively high evenness across stations. Overall, the integrated multimetric approach reveals that coastal ecosystems in Banyuwedang Bay remain functionally intact but exhibit clear spatial heterogeneity along the inner-outer gradient. This study provides an integrated baseline framework linking benthic and pelagic indicators for future monitoring and adaptive coastal management in relatively low-disturbance tropical bays.

Keywords: Coupling, gradients, heterogeneity, monitoring, tropics

INTRODUCTION

Coastal ecosystems function as transitional zones where terrestrial and marine processes interact across spatial gradients. Mangrove forests, seagrass meadows, and plankton communities function as interconnected components linking benthic and pelagic processes across coastal environments (Nagelkerken 2009). These ecosystems influence sediment dynamics, habitat complexity, and energy transfer within coastal waters (Ayyam et al. 2019). In North Bali, Banyuwedang Bay represents a relatively low-disturbance coastal system where these interconnected ecosystems coexist, yet integrated ecological assessments across these components remain limited. The bay also supports fisheries, marine tourism, and conservation functions within the West Bali coastal region, highlighting its ecological and management importance. Mangroves contribute to shoreline stabilization, seagrasses enhance substrate stability, and plankton sustain primary productivity, indicating that ecosystem components may respond differently to environmental gradients (Sánchez-Núñez et al. 2019). Such variability may generate heterogeneous ecological responses across coastal systems (Hyman et al. 2019; Prowe et al. 2022).

North Bali coastal waters are influenced by natural oceanographic variability and localized anthropogenic activities, which together contribute to spatial differences in environmental conditions. Although development intensity remains relatively low compared to southern Bali, localized pressures such as small-scale fisheries, coastal infrastructure, and land-based runoff may still influence environmental variability. Seasonal monsoonal dynamics further influence temperature, salinity, and hydrodynamics, generating spatial variability in water characteristics (Naik et al. 2020). Physicochemical variability in water-column and sediment properties plays a central role in shaping biological communities across coastal gradients (Jaffar et al. 2020). Suspended solids affect light availability for seagrasses, while oxygen and redox conditions reflect sediment-water interactions influencing benthic and pelagic assemblages (Adams et al. 2016). Variations in substrate and water-column properties may also regulate mangrove distribution, seagrass structure, and plankton composition. These interactions emphasize the need for integrated ecosystem assessment.

Mangrove forests, seagrass meadows, and plankton communities provide complementary indicators of coastal ecosystem condition. Mangrove attributes such as species composition, density, canopy cover, and importance value index describe structural stability and regeneration (Wijaya et al. 2024; Qur'ani et al. 2026). Species dominance patterns may reflect environmental filtering associated with substrate and hydrological conditions (Sugiana et al. 2024). Regeneration patterns also provide insight into long-term stand stability (Dewi et al. 2021). Even when health classifications appear similar, differences in species composition may indicate ecological variability among sites (Sugiana et al. 2022). Seagrass indicators, including species richness and coverage, reflect habitat quality and sediment stability (Whitfield 2017). Seagrasses are sensitive to suspended sediments and water-column variability (Orth et al. 2020). Plankton communities respond rapidly to environmental fluctuations, and metrics such as diversity, evenness, and dominance describe trophic structure and ecological balance (Righetti et al. 2019; Boersma and Meunier 2020). Moderate diversity accompanied by localized dominance shifts may indicate environmental variability rather than ecosystem degradation (Suryani et al. 2025).

Despite increasing coastal ecosystem assessments in Indonesia, most studies evaluate mangroves, seagrasses, or plankton separately, or focus primarily on water quality parameters (Purnomo et al. 2017). Other studies emphasize individual ecosystem indicators without integrating benthic and pelagic components (Ma'ruf et al. 2022). Integrated assessments combining structural and functional indicators within a unified spatial framework remain scarce, particularly in relatively low-disturbance coastal systems. This limitation reduces the ability to understand cross-ecosystem responses to environmental gradients and to establish comprehensive ecological baselines. An integrated multimetric framework linking environmental parameters with mangrove structure, seagrass ecological quality, and plankton community indicators is therefore required to capture spatial ecological heterogeneity more effectively. Such an approach enables identification of ecological patterns that may not be detected when each ecosystem component is evaluated independently.

Based on the geomorphological setting of Banyuwedang Bay, spatial gradients between inner and outer bay areas are expected to generate different physicochemical conditions influencing ecosystem components unequally. Seagrass and plankton communities are likely more sensitive to environmental variability, whereas mangrove structural attributes are relatively stable. We hypothesize that physicochemical gradients from the inner to outer bay generate differential ecological responses among ecosystem components. Therefore, this study aims to assess the ecological condition of North Bali coastal waters using a multimetric framework integrating environmental parameters with mangrove structure, seagrass ecological quality, and plankton community indicators to provide a baseline ecological characterization of interconnected coastal ecosystems across spatial gradients in Banyuwedang Bay.

MATERIALS AND METHODS

Study area

This study was conducted in Banyuwedang Bay, Gerokgak Sub-district, Buleleng District, Bali, Indonesia (8.129398-8.145871°S; 114.546945-114.570598°E). Three sampling stations were selected to represent spatial positions within the bay (Figure 1, Table 1). Station characterization was based on field observations, including shoreline type, proximity to infrastructure, and visible activity, and is presented as contextual information rather than quantified disturbance metrics. These descriptors are qualitative and observational in nature and were not used as variables in any statistical or quantitative analysis.

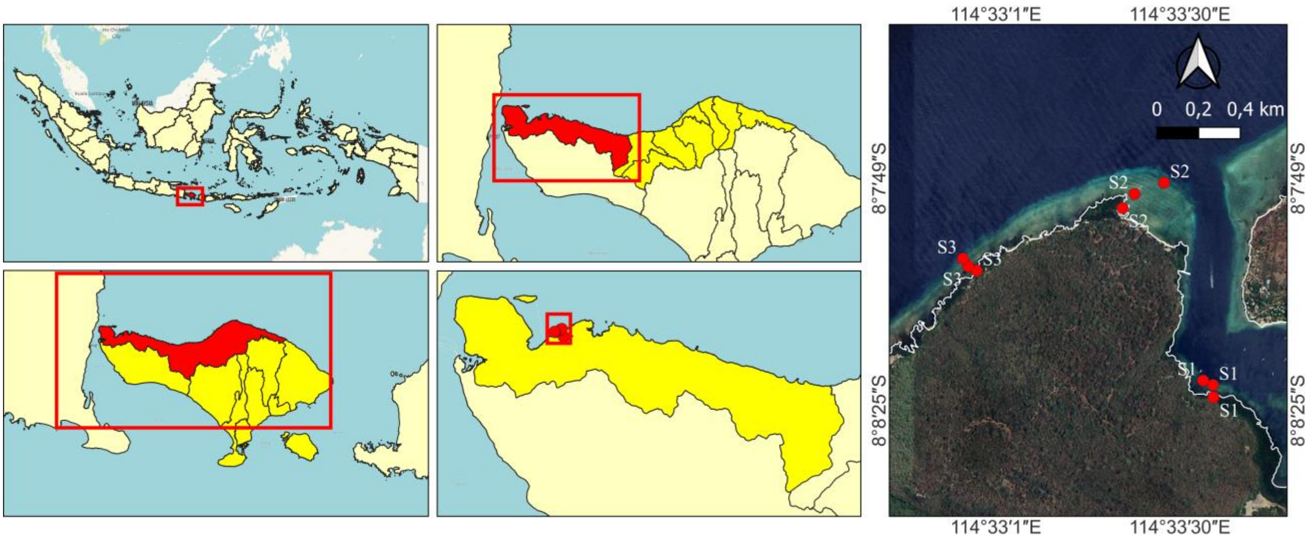

Figure 1. Distribution of data collection stations in Banyuwedang Bay, Gerokgak Sub-district, Buleleng District, Bali, Indonesia

Table 1. Coordinate the position of each station

Station	Ecosystems/object	Coordinate		Description
		Y	X	
S1	Mangrove	-8.139650°S	114.559858°E	Sheltered inner bay with muddy-sand substrate
	Seagrass	-8.13912°S	114.559834°E	
	Plankton	-8.138931°S	114.559406°E	
S2	Mangrove	-8.131515°S	114.555899°E	Transitional mid-bay near coastal infrastructure
	Seagrass	-8.130905°S	114.556413°E	
	Plankton	-8.130423°S	114.557707°E	
S3	Mangrove	-8.134204°S	114.549540°E	Exposed outer bay with gravelly-sand substrate
	Seagrass	-8.134014°S	114.549170°E	
	Plankton	-8.133686°S	114.548941°E	

S1 represents the inner bay, characterized by more sheltered conditions and muddy-sand substrate, while S3 is located toward the outer bay with greater exposure to open waters and gravelly-sand substrate. S2 is situated between these zones and is located near coastal infrastructure. Additional site descriptors, such as proximity to visible land-based inputs and boat activity, were recorded to support the interpretation of spatial patterns across stations. These qualitative descriptors are provided only for contextual interpretation and were not used as explanatory variables in the analysis or ecological comparisons. All data were collected in November 2025. Thus, the gradient interpretation is exploratory and limited to the three sampling stations.

Water quality and soil measurement

Water sampling was conducted at approximately 20-30 cm below the surface to represent near-surface water conditions. Triplicate measurements obtained using the multimeter (COM-600 Water Quality Tester) represent repeated instrument readings taken at the same sampling point, rather than independent field replicates. Sampling at all stations was performed within the same tidal phase during low tide and within a consistent time window between 07:00 and 12:00 local time to minimize diel variability in physicochemical parameters.

For laboratory analyses, approximately 1 L of seawater was collected three times at each station using pre-cleaned polyethylene bottles. These samples represent independent subsamples used as laboratory replicates for subsequent analysis. Samples for TSS analysis were filtered using a known volume of 500 mL per replicate through pre-weighed Whatman GF/C filters. Water samples designated for BOD_5 analysis were stored in airtight dark bottles to prevent oxygen exchange and transported in insulated cool boxes at approximately 4°C. TSS was analyzed using the gravimetric method following APHA 2540 D, while BOD_5 was determined according to APHA 5210 B. Laboratory analyses were initiated within 24 hours of sampling following standard procedures.

Sediment type at each station was determined using field-based visual assessment supported by texture classification, following standard sediment classification guidelines. Observations were conducted at each station to identify dominant substrate characteristics (e.g., muddy sand or gravelly sand). No granulometric laboratory analysis was performed to validate sediment texture, and classification is based solely on field observation. Sediment classification was therefore qualitative and should be interpreted as descriptive site characteristics rather than quantitative sediment measurements. Future studies should incorporate granulometric laboratory analysis to provide quantitative sediment composition and improve interpretation of ecological relationships.

Quality assurance and quality control (QA/QC) procedures included instrument calibration prior to field deployment, duplicate laboratory measurements where applicable, and acceptance of measurements only when variation among triplicate readings remained within ±5% of the mean value.

Mangrove ecology assessment

Mangrove vegetation was assessed using a plot-based quantitative approach. At each sampling station, three 10 m × 10 m quadrat plots were established to represent the stand structure within sites. Due to logistical constraints and the exploratory nature of this study, the use of three plots per station represents a limited replication and is intended to provide a rapid baseline assessment rather than a statistically robust ecological inference. Within each plot, all mangrove individuals were identified to species level and classified into growth stages based on Diameter at Breast Height (DBH). Identified mangrove species using books from As-Syakur et al. (2023). Individuals with DBH ≥5 cm were categorized as trees, while those with DBH <5 cm were categorized as saplings. Tree and sapling densities were standardized to individuals per hectare (ind ha^{-1}) based on plot area (10 m × 10 m) prior to analysis. For each species and growth stage, structural parameters were calculated, including density (Di), relative frequency (Fi), and dominance (Do). Basal area was derived from DBH measurements to determine species dominance. The Important Value Index (IVI) was calculated as the sum of relative density, relative frequency, and relative dominance for each species at both tree and sapling levels (Dharmawan et al. 2020a). The equation for the mangrove parameter structure can be seen below.

Density was calculated as:

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

Where n_i is the number of individuals of species i and A is the sampled area (ha).

Relative density (RD) was calculated as:

$$RD_i = \frac{D_i}{\sum D_i} \times 100$$

Frequency (Fi) represents the proportion of plots in which species *i* occurred:

$$F_i = \frac{p_i}{P}$$

Where p_i is the number of plots containing species *i* and P is the total number of plots.

Relative frequency (RF) was calculated as:

$$RF_i = \frac{F_i}{\sum F_i} \times 100$$

Dominance was expressed as relative dominance based on basal area:

$$BA_i = \frac{\pi d^2}{4}$$

Where d is the stem diameter at breast height (DBH, cm).

Relative dominance (RDo) was calculated as:

$$RDo_i = \frac{BA_i}{\sum BA_i} \times 100$$

The Importance Value Index (IVI) was obtained as:

$$IVI_i = RD_i + RF_i + RDo_i$$

Mangrove canopy cover was measured using hemispherical photography (Dharmawan 2020b). At each plot, five photographs were taken upward toward the canopy and analyzed digitally using ImageJ software to estimate percentage canopy closure. In addition, mangrove ecological status was assessed using a Mangrove Health Index (MHI), integrating sapling density (in a 10 m x 10 m plot), stand diameter, and canopy cover (Dharmawan and Ulumuddin 2021).

The MHI was calculated as:

$$MHI = \frac{(S_C + S_D + S_{Nsp})}{3} \times 10$$

Where: S_C: Canopy cover score, S_D: Diameter score, S_{Nsp}: Sapling density score

Parameter scores were derived using the following transformation equations:

$$S_C = 0.25C - 13.06$$

$$S_D = 0.45D + 1.42$$

$$S_{Nsp} = 0.13Nsp + 4.1$$

Where: C: Percent canopy cover (%), D: Mean DBH (cm), Nsp: Sapling density (individuals per 10x10 m plot).

Scores were constrained between 0 and 10, such that values <0 were assigned 0 and values >10 were capped at 10. MHI values were calculated at the plot level and then averaged across three plots at each station to obtain mean MHI values, with standard deviation representing variability among plots. Mangrove condition categories were defined as: Poor: MHI < 33.33%, Moderate: 33.33 ≤ MHI < 66.67, and Excellent: MHI ≥ 66.67.

Due to logistical constraints and the exploratory nature of this study, only three 10 m × 10 m plots were established at each station to represent dominant mangrove conditions. Therefore, the sampling design is intended to provide a rapid baseline assessment rather than a statistically replicated ecological inference.

Seagrass ecology assessment

Seagrass ecological condition was evaluated using a multimetric approach based on the Seagrass Ecological Quality Index (SEQI). Seagrass observations were conducted using three transects per station, each 50 m in length. Along each transect, three quadrats (1 m × 1 m) were placed at 0 m, 25 m, and 50 m, resulting in a total of nine quadrats per station to record species found and percentage cover (Figure 2). All seagrass species within each quadrat were identified to species level. Percentage cover of seagrass was visually estimated within each quadrat using a standardized scale ranging from 0-100% (Rigby et al. 2007), and mean cover per station was calculated to represent habitat continuity and structural condition.

In addition to seagrass cover, macroalgae, and epiphyte coverage were recorded to evaluate potential ecological pressure (Rahmawati et al. 2017). Macroalgae cover was measured as the percentage of substrate occupied within each quadrat, while epiphyte cover was estimated as the percentage of seagrass leaf surface covered by attached organisms (Unsworth et al. 2015). Both parameters ranged from 0-100% (Hernawan et al. 2021). Water transparency was assessed in situ and categorized based on visibility conditions of seagrass and bottom substrate, reflecting light availability within the water column.

SEQI was calculated by integrating five parameters: species richness (*S*), seagrass cover (*C*), water transparency (*W*), macroalgae cover (*M*), and epiphyte cover (*E*). Water transparency (*W*) was measured using a Secchi disk and normalized as a continuous variable by dividing measured transparency values by the reference maximum value (Wref), such that W/Wref ranges from 0 to 2 (Hernawan et al. 2021). The index was computed using the formula:

$$SEQI = \left(\frac{S_t}{S_{ref}}\right) \times 0.2 + \left(\frac{C_t}{C_{ref}}\right) \times 0.2 + \left(\frac{W_t}{W_{ref}}\right) \times 0.2 + \left(1 - \frac{M_t}{M_{max}}\right) \times 0.2 + \left(1 - \frac{E_t}{E_{max}}\right) \times 0.2$$

Where Sref represents the maximum expected seagrass richness (9 species), Cref the maximum cover value (100%), Wref the maximum transparency value (2 m), and Mmax and Emax the maximum macroalgae and epiphyte cover values (100%). SEQI scores were classified into five ecological categories: Bad (0-0.36), Poor (0.37-0.52), Moderate (0.53-0.88), Good (0.89-0.94), and Excellent (0.95-1.00) (Hernawan et al. 2021).

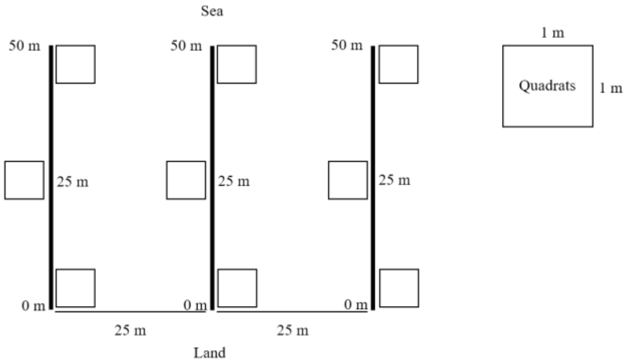

Figure 2. Schematic illustration of seagrass sampling design using transects and quadrats

Plankton community assessment

Plankton sampling was conducted at each station concurrently with water quality measurements. Phytoplankton were identified to the genus level, while zooplankton were identified to major taxonomic or functional groups (e.g., copepods, larval stages), reflecting differences in taxonomic resolution appropriate for baseline ecological assessment. Surface water samples were collected using the pouring method. Plankton sampling was conducted in triplicate at each station, with approximately 150 L of water collected per replicate using a clean bucket and filtered through a plankton net with a mesh size of 25 µm. The concentrated filtrate from each replicate was transferred into 100 mL polyethylene bottles and preserved immediately with Lugol's iodine solution (final concentration approximately 1%) to prevent cell degradation. Samples were stored in cool and dark conditions prior to laboratory analysis.

Phytoplankton identification and enumeration were carried out using a Sedgwick-Rafter counting chamber (50 × 20 × 1 mm) under a binocular light microscope at 10× magnification. Before subsampling, each sample was homogenized to ensure even distribution of organisms. Counts were performed in triplicate across the entire chamber to minimize counting error. Identification was conducted to the genus level following the standard marine plankton reference (Newell and Newell 1963). Phytoplankton were identified to the genus level, while community composition was summarized at the class level (e.g., Bacillariophyceae, Cyanophyceae, Chrysophyceae) to facilitate ecological interpretation. Meanwhile, zooplankton were identified to major taxonomic or functional groups (e.g., copepods, larval stages), and the classification reflects morphological grouping rather than species-level identification. Identification to genus level was considered sufficient for ecological assessment, as genus-level resolution is commonly used in baseline plankton studies and is adequate for describing community structure and environmental response.

Phytoplankton and zooplankton abundance were calculated using the formula:

$$N = \frac{n \times V_t}{V_o \times V_d}$$

Where N is abundance (cells L^{-1} or ind L^{-1}); $n$is the number of individuals counted; V_t is the total volume of the concentrated sample (mL); V_o is the observed chamber volume (mL); and V_d is the volume of water filtered in the field (L).

Community structure was evaluated using multimetric indices, including Shannon-Wiener diversity index (*H'*), Pielou's evenness index (*J*), and Simpson's dominance index (*C*) (Odum 1993; Magurran 2013). The Shannon-Wiener index (H') was calculated as:

$$H' = -\sum p_i \ln p_i$$

Where pi represents the proportion of individuals belonging to genus *i*. $H'<1.0$: Low diversity (unstable/impacted community). $1.0 \leq H' \leq 3.0$: Moderate diversity (moderate diversity, indicating a relatively balanced community structure), $H'>3.0$: High diversity (relatively even distribution of taxa) (Odum 1993; Magurran 2013)

Evenness (J) was calculated as:

$$J = \frac{H'}{\ln S}$$

Where S is the total number of genera. $J<0.4$: Low evenness (domination by few taxa), $0.4 \leq J \leq 0.6$: Moderate evenness, $J>0.6$: High evenness (balanced community structure).

Simpson's dominance index (C) was calculated as:

$$C = \sum p_i^2$$

Where: *Pi* represents the proportion of individuals belonging to the *i*-th genus, and ln is the natural logarithm. A dominance value (*C*) approaching 0 indicates low dominance, meaning no single taxon predominates within the community. A value around 0.5 reflects moderate dominance, whereas a value close to 1 signifies high dominance, indicating that the community is strongly dominated by one or a few taxa.

Statistical analysis

Environmental and biological variables were summarized using descriptive statistics. Mean and standard deviation were calculated for each parameter. Inferential statistical analyses were not applied due to limited independent replication and the non-independent nature of certain measurements. Therefore, comparisons among stations are presented as descriptive interpretations rather than hypothesis testing. All calculations were performed using Microsoft Excel. Because the objective of this study was to establish a baseline ecological characterization, results should be interpreted as site-specific observations rather than statistically generalizable conclusions.

RESULTS AND DISCUSSION

Seawater condition

The measured seawater parameters differed among the three sampling stations. Temperature and pH increased progressively from the first to the third station. Conductivity and salinity showed the same increasing pattern across the stations. Total dissolved solids (TDS) were relatively similar at all locations. In contrast, total suspended solids (TSS) varied more noticeably, with the highest level observed at the first station, decreasing at the second, and increasing again at the third. Redox potential was highest at the second station. Biochemical oxygen demand (BOD) showed only minor differences among stations. Dissolved oxygen (DO) was lowest at the first station and higher at the second and third stations. Sediment type also differed, with muddy sand recorded at the first station, while gravelly sand was found at the second and third stations (Table 2).

Spatial variation in physicochemical parameters was associated with differences in hydrodynamic exposure and substrate composition among stations. Higher suspended solids at S1 were associated with muddy sand substrate and more sheltered conditions, whereas gravelly sand at S2 and S3 may reflect greater water movement. Variations in dissolved oxygen and redox potential may reflect differences in organic matter dynamics and sediment-water interaction. These environmental gradients may influence benthic and pelagic communities differently across stations. These physicochemical conditions form the environmental template upon which mangrove, seagrass, and plankton communities develop (Tarafdar et al. 2021; Röthig et al. 2023). Variations in dissolved oxygen and redox potential further reflect differences in organic matter dynamics and sediment-water interactions, which may indirectly shape community composition in both benthic and pelagic components (Hernández and Tapia 2021).

Mangrove checklist, community structure, and healthiness

The distribution of mangrove species differed among the three stations and growth categories. At S1, five species were recorded, namely *Lumnitzera racemosa*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Ceriops tagal*, and *Avicennia marina*. Most species at this station were found in both tree and sapling stages, except *L. racemosa*, which was only observed at the tree stage, and *C. tagal*, which was only recorded at the sapling stage. At S2, only *Rhizophora stylosa* was present, occurring in both tree and sapling stages, indicating a lower species richness compared to S1. In contrast, S3 showed a slightly higher species composition than S2, with *R. apiculata*, *R. stylosa*, *Bruguiera gymnorrhiza*, and *Sonneratia alba* recorded. At this station, *R. apiculata* and *S. alba* were found in both tree and sapling stages, while *R. stylosa* and *B. gymnorrhiza* were recorded only at the tree stage (Figure 3). Overall, S1 exhibited the highest species richness, S2 the lowest, and S3 showed intermediate composition with dominance of *Rhizophora* species (Table 3).

The importance value index (IVI) analysis indicates differences in species contribution between tree and sapling stages. IVI values were calculated using pooled data across all stations to represent overall species dominance patterns, as the limited number of plots per station constrained robust station-level comparison. Consequently, species dominance derived from pooled IVI values should not be interpreted as station-specific dominance patterns. Therefore, the analysis is intended to provide a general overview of community structure rather than a site-specific statistical comparison.

Table 2. Environmental parameters and sediment characteristics of coastal waters at the three sampling stations

Parameter	**Location**		
	S1	**S2**	**S3**
Temperature (°C)	26.9±0.20	27.4±0.20	28.2±0.15
pH	7.56±0.03	7.63±0.03	7.76±0.02
Conductivity (mS cm^{-1})	49.9±0.20	50.4±0.25	51.1±0.15
Salinity (ppt)	30.6±0.15	30.8±0.20	31.2±0.15
Total dissolved solids (TDS, ppt)	24.9±0.10	25.1±0.20	25.5±0.10
Total suspended solids (TSS, mg L^{-1})	185.7±3.20	123.2±2.40	167.3±3.10
Oxidation-reduction potential (ORP, mV)	52.0±2.00	78.0±2.00	73.7±1.53
BOD (mg L^{-1})	5.40±0.10	5.10±0.10	5.30±0.10
Dissolved oxygen (DO, mg L^{-1})	4.30±0.10	5.20±0.10	4.90±0.10
Sediment type	Muddy sand	Gravelly sand	Gravelly sand

Table 3. Presence of mangrove species at tree and sapling stages across the three sampling stations (+: Present, -: Absent)

Species	**S1**		**S2**		**S3**	
	Tree	**Sapling**	**Tree**	**Sapling**	**Tree**	**Sapling**
Lumnitzera racemosa Willd.	+	-	-	-	-	-
Excoecaria agallocha L.	+	+	-	-	-	-
Rhizophora apiculata Blume	+	+	-	-	+	+
Ceriops tagal (Perr.) C.B.Rob.	-	+	-	-	-	-
Avicennia marina (Forssk.) Vierh.	+	+	-	-	-	-
Rhizophora stylosa Griffith	+	-	+	+	+	-
Bruguiera gymnorrhiza (L.) Lam.	-	-	-	-	+	-
Sonneratia alba Sm.	-	-	-	-	+	+
Total	5	4	1	1	4	2

Figure 3. Documentation for the types of mangroves found in all stations. A. *Lumnitzera racemosa*, B. *Excoecaria agallocha*, C. *Rhizophora stylosa*, D. *Ceriops tagal*, E. *Avicennia marina*, F. *Rhizophora stylosa*, G. *Bruguiera gymnorrhiza*, H. *Sonneratia alba*

At the tree level, *R. stylosa* showed the highest IVI, followed by *R. apiculata*, while *B. gymnorrhiza* and *S. alba* also contributed substantially. In contrast, *L. racemosa* and *A. marina* displayed lower IVI values, and *C. tagal* was not recorded at the tree stage. At the sapling level, *R. stylosa* again exhibited the highest IVI, indicating strong regeneration potential, followed by *R. apiculata*. Several species, such as *E. agallocha*, *A. marina*, *C. tagal*, and *S. alba*, were present with moderate IVI values, whereas *L. racemosa* and *B. gymnorrhiza* were absent at this stage (Table 4).

Overall, species of the genus *Rhizophora* dominated both structural levels, particularly at the sapling stage, reflecting their prominent role in stand structure and regeneration within the study area.The structural characteristics of mangroves differed among the three stations, although all sites fell within the same health category. Tree and sapling density showed variation among stations, with greater within-station variability observed at S1. Stem diameter varied across locations, reflecting differences in stand maturity. Canopy cover remained relatively high across stations, although variability within S1 was greater compared to the other stations. The relatively large standard deviation of canopy cover at S1 reflects natural spatial heterogeneity in canopy structure among plots rather than measurement error, likely associated with uneven stand development and patchy canopy distribution. The mangrove health index (MHI) values were consistently within the Excellent category at all stations (Table 5). Overall, the mangrove ecosystem appears well-developed, with spatial differences in species composition and regeneration patterns indicating localized environmental heterogeneity.

Mangrove structure suggested spatial differentiation, particularly in species composition and regeneration patterns. Although all stations were categorized within the same health class, S1 exhibited the highest species richness, while *R. stylosa* strongly dominated S2 at both tree and sapling stages. Such dominance may reflect adaptive advantage under specific substrate and hydrological conditions (Mulloy et al. 2025). The consistent canopy cover across stations suggests structurally intact forests, yet differences in sapling density indicate varying regeneration trajectories (Sugiana et al. 2022). From a multimetric perspective, the mangrove ecosystem at the sampled stations in Banyuwedang Bay appears structurally stable, but species composition patterns suggest localized environmental filtering rather than uniform ecological conditions within the study area. Given the limited number of plots per station, the results should be interpreted as site-specific observations rather than broadly generalizable patterns.

Seagrass checklist and ecological quality index

The distribution of seagrass species varied among the three sampling stations. *Thalassia hemprichii* was consistently present at all stations, indicating a broad distribution across the study area. At S1, species richness was highest, with *Cymodocea rotundata*, *Halodule uninervis*, and *Halophila ovalis* also recorded. In contrast, S2 showed lower species composition, with only *T. hemprichii* observed. At S3, species composition differed from the other stations, where *Halodule pinifolia* was recorded together with *T. Hemprichii* (Table 6, Figure 4). Overall, S1 exhibited the greatest seagrass species diversity, while S2 had the lowest, and S3 showed a distinct composition characterized by the presence of *H. pinifolia*.

The seagrass ecological parameters showed variation among the three sampling stations (Table 7). Seagrass coverage was highest at S2, followed by S3, while S1 exhibited the lowest coverage, indicating differences in habitat continuity among stations. Water transparency was relatively similar across stations, although slightly lower at S1, suggesting reduced light penetration compared to the other locations. This condition may be associated with the presence of suspended materials in the water column. Macroalgae coverage was highest at S3, whereas S1 showed the lowest values. In contrast, epiphyte coverage was most prominent at S2, followed by S3 and S1. These differences indicate spatial variability in ecological pressure and biological interactions within the seagrass ecosystem.

The Seagrass Ecological Quality Index (SEQI) values ranged from 0.63 to 0.67 across the three sampling stations. S1 recorded a value of 0.63±0.01, while S2 and S3 showed slightly higher values of 0.66±0.01 and 0.67±0.02, respectively. The variation among stations was relatively small, with S3 presenting the highest index value. Based on the established classification criteria, all stations were placed within the Moderate category (Figure 5).

In contrast to mangroves, seagrass meadows displayed moderate ecological quality across all stations, with relatively small differences in SEQI values. The higher seagrass coverage and water transparency at S2 and S3 correspond with lower suspended solids compared to S1, consistent with the observed relationship between light availability and seagrass distribution. However, increased macroalgae and epiphyte coverage at certain stations may indicate competitive interactions and may also be associated with variations in environmental conditions (Prado 2018). The moderate SEQI classification across all sites indicates a pattern associated with seagrass beds that remain functional; they may be experiencing environmental pressures that limit their optimal development (Hernawan et al. 2021). Compared to the excellent mangrove condition, the seagrass ecosystem appears more sensitive to water column variability, highlighting the importance of integrating benthic vegetation with water quality indicators.

Table 4. Relative frequency (Fi), density (Di), dominance (Do), and importance value index (IVI) of mangrove species at tree and sapling levels (value 0 refers to no species found in each category of mangrove growth, and the data is a combination of the three observed stations)

Species	Tree				Sapling			
	Fi	Di	Do	IVI	Fi	Di	Do	IVI
Lumnitzera racemosa Willd.	10	3.3	2.7	16	0	0	0	0
Excoecaria agallocha L.	10	8.7	10.8	29.5	14.3	1.7	0.8	16.9
Rhizophora apiculata Blume	20	16.3	20.2	56.5	28.6	17.2	18.4	64.2
Ceriops tagal (Perr.) C.B.Rob.	0	0	0	0	14.3	1.7	2.7	18.8
Avicennia marina (Forssk.) Vierh.	10	1.1	0.7	11.8	14.3	1.7	2.3	18.3
Rhizophora stylosa Griffith	30	45.7	31.5	107.2	14.3	75.9	73.6	163.7
Bruguiera gymnorrhiza (L.) Lam.	10	10.9	19	39.9	0	0	0	0
Sonneratia alba Sm.	10	14.1	15	39.2	14.3	1.7	2.2	18.2

Table 5. Stand structure parameters and MHI classification at the study stations

Station	Tree (ind ha^{-1})	Sapling (ind ha^{-1})	Diameter (cm)	Canopy (%)	MHI (%)	MHI Category
S1	1,500±624	333±231	29.2±16.9	72.62±28.35	70.53±12.27	Excellent
S2	3,800±200	4,200±200	15.8±5.9	69.95±5.41	75.98±6.12	Excellent
S3	2,633±351	633±153	22.9±11.1	77.35±1.77	67.45±4.96	Excellent

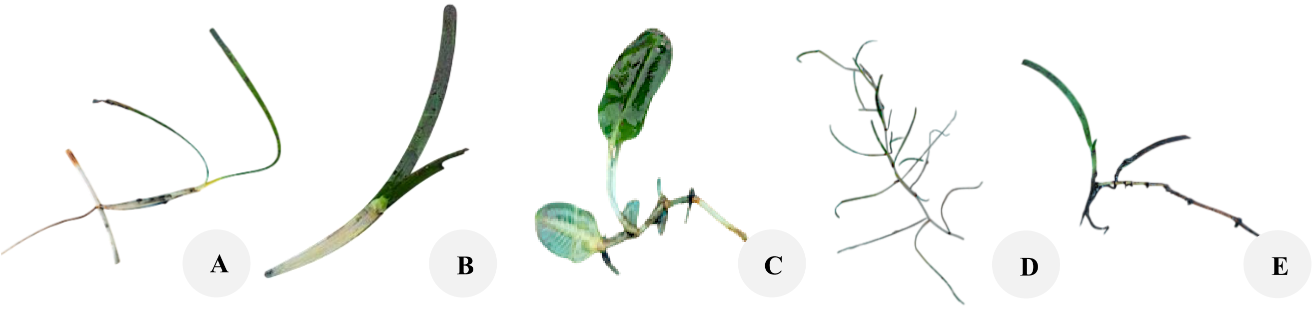

Figure 4. Documentation for the types of seagrasses found in all stations. A. *Cymodocea rotundata*, B. *Thalassia hemprichii*, C. *Halophila ovalis*, D. *Halodule pinifolia*, E. *Halodule uninervis*

A notable pattern emerging from the seagrass analysis was a trade-off between species richness and coverage among stations. S1 exhibited the highest species richness but lower mean cover and greater spatial variability, indicating a patchy and heterogeneous meadow. In contrast, S2 was characterized by a single dominant species with higher overall cover, suggesting a more continuous but less diverse seagrass assemblage. This pattern indicates that seagrass ecological condition cannot be interpreted solely based on coverage or environmental parameters, and instead reflects differences in species dominance, spatial distribution, and local habitat characteristics. Such trade-offs have been reported in heterogeneous coastal habitats where substrate stability and hydrodynamic exposure vary among locations. Given the descriptive design of this study, these patterns should be interpreted as site-specific ecological associations rather than causal responses to environmental gradients.

Plankton checklist and ecological indices

The plankton checklist showed differences in genus composition among the three stations. A total of eight genera were recorded at S1, thirteen at S2, and eight at S3. Several genera, including *Navicula*, *Gyrosigma*, *Nitzschia*, *Rhizosolenia*, *Thalassiothrix*, *Amphora*, and *Fragilaria*, were consistently present across all stations. *Skeletonema* was recorded at S1 and S2 but was absent at S3. In contrast, *Oscillatoria*, *Bacillaria*, *Leptocilindrus*, and *Chromulina* were only observed at S2. *Licmophora* was found at S2 and S3 but was absent at S1 (Table 8, Figure 6). Overall, S2 exhibited the highest number of plankton genera compared to the other stations.

The phytoplankton composition differed among stations at both genus and class levels (Figure 7.A and 7.B). At S1, the assemblage was entirely dominated by Bacillariophyceae (100%), with *Rhizosolenia* contributing the highest proportion (24.6%), followed by *Navicula* and *Nitzschia* (each 17.5%), while genera such as *Fragilaria* showed the lowest contribution (1.7%). In contrast, S2 exhibited a markedly different pattern, where Cyanophyceae accounted for 54.1% of the total abundance, which may be related to the dominance of *Oscillatoria*, making it the most prominent genus at this station, while Bacillariophyceae comprised 45.3% and Chrysophyceae only 0.6%. Within Bacillariophyceae at S2, *Navicula* (16.7%) and *Skeletonema* (5.9%) were among the more abundant genera, whereas several others contributed relatively small proportions. At S3, the community returned to full dominance by Bacillariophyceae (100%), with *Licmophora* showing the highest proportion (30.0%), followed by *Navicula* and *Rhizosolenia* (each 16.8%), while *Amphora* contributed the lowest proportion (3.3%). Overall, S1 and S3 were characterized by complete diatom dominance, whereas S2 was distinguished by a substantial contribution of cyanobacteria associated with *Oscillatoria.*

Table 6. Presence-absence of seagrass species across the sampling stations

Species	**S1**	**S2**	**S3**
Thalassia hemprichii (Ehrenb. ex Solms) Asch.	+	+	+
Cymodocea rotundata Asch. & Schweinf.	+	-	-
Halodule uninervis (Forssk.) Boiss.	+	-	-
Halophila ovalis (R.Br.) Hook.f.	+	-	-
Halodule pinifolia (Miki) Hartog	-	-	+
Total	4	1	2

Table 7. Seagrass ecological parameters of each station

Parameters	**Stations**		
	S1	**S2**	**S3**
Seagrass coverage (%)	31.0±0.9	72.6±2.2	62.3±1.0
Water transparency (m)	1.2±0.1	1.7±0.1	1.7±0.2
Macroalga coverage (%)	5.7±0.4	10.7±1.0	22.3±1.0
Epiphyte coverage (%)	16.6±1.2	30.7±2.0	19.9±0.5

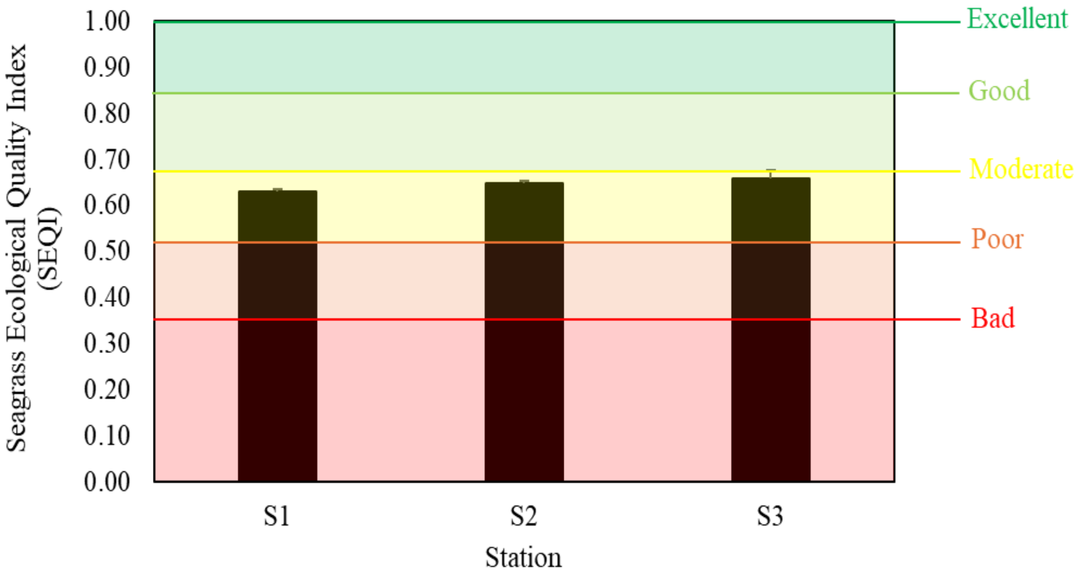

Figure 5. The seagrass ecological quality index value of each station

The zooplankton composition varied among the three sampling stations (Table 9, Figure 8). A total of three groups were recorded at S1, eight at S2, and seven at S3. At S1, the assemblage consisted of crab larvae, mollusk larvae, and copepods. S2 showed the highest diversity, where crab larvae, mollusk larvae, copepods, worm larvae, fish larvae, foraminifera, ostracoda, and Dinophysis were recorded. In contrast, S3 was characterized by the presence of copepods, worm larvae, fish larvae, Foraminifera, nauplii, shellfish larvae, and shrimp larvae. Copepods were the only group consistently present at all stations, while several groups, such as nauplii, shellfish larvae, and shrimp larvae, were restricted to S3. Overall, S2 exhibited the highest zooplankton group richness compared to the other stations.

The zooplankton composition showed differences among stations (Figure 9). At S1, the assemblage consisted of three groups, with mollusk larvae contributing the highest proportion (33.3%), followed by crab larvae (33.3%) and copepods (33.3%), resulting in an evenly distributed composition. In contrast, S2 exhibited a more diverse structure with eight recorded groups. At this station, copepods represented the highest proportion (20.0%), followed by fish larvae and worm larvae (each 16.7%), while crab larvae and mollusk larvae each accounted for 12.5%. Other groups, such as Foraminifera, Ostracoda, and Dinophysis, contributed smaller proportions (each 8.3%). At S3, the composition shifted toward dominance by copepods (42.9%), followed by fish larvae (21.4%) and worm larvae (14.3%). Additional groups, including Foraminifera, Nauplii, Shellfish larvae, and Shrimp larvae, were present in lower proportions (each 7.1%). Overall, S2 and S3 showed greater zooplankton group richness compared to S1, with copepods emerging as the most consistent and dominant group across stations.

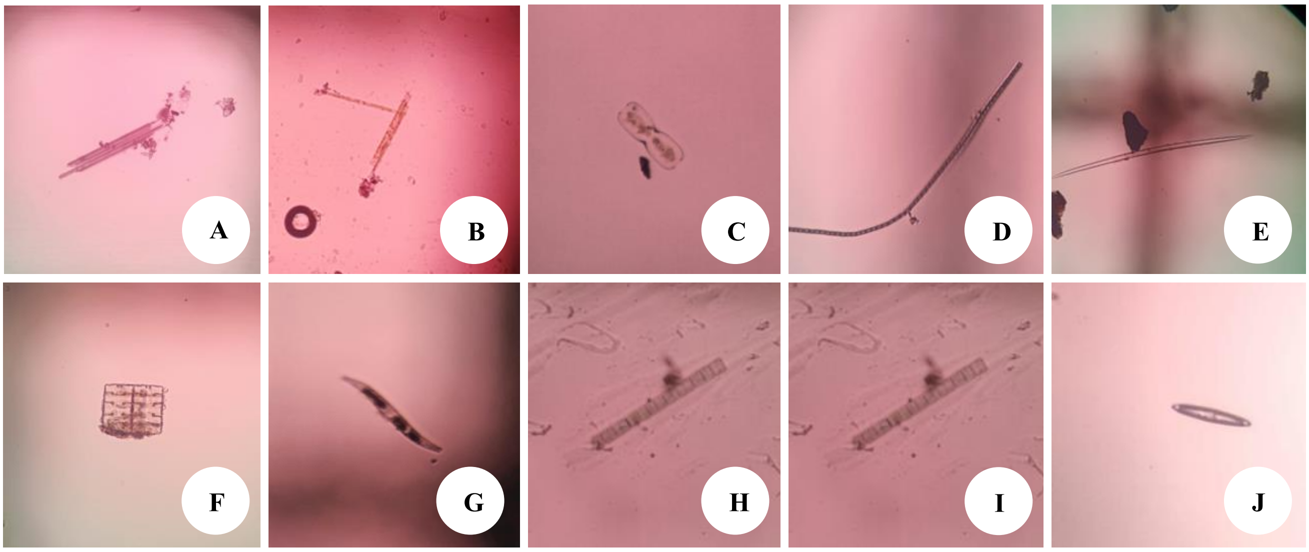

Figure 6. Documentation of several genera of phytoplankton found. A. *Thalassiothrix*, B. *Nitzschia*, C. *Amphora*, D. *Oscillatoria*, E. *Rhizosolenia*, F. *Fragilaria*, G. *Gyrosigma*, H. *Skeletonema*, I. *Navicula*

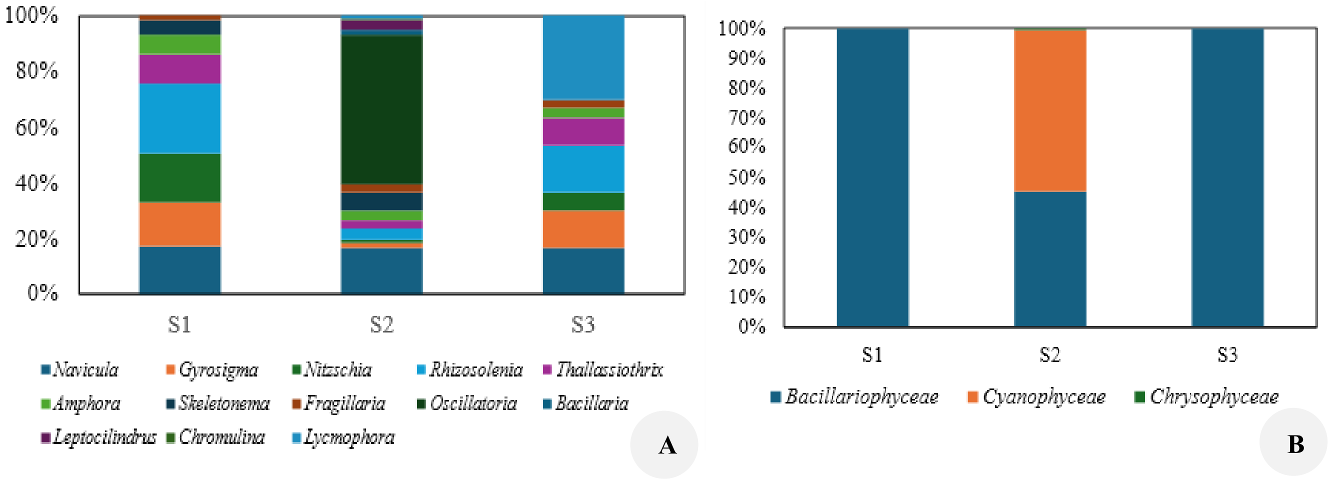

Figure 7. Composition of phytoplankton of each: A. Genus, B. Class

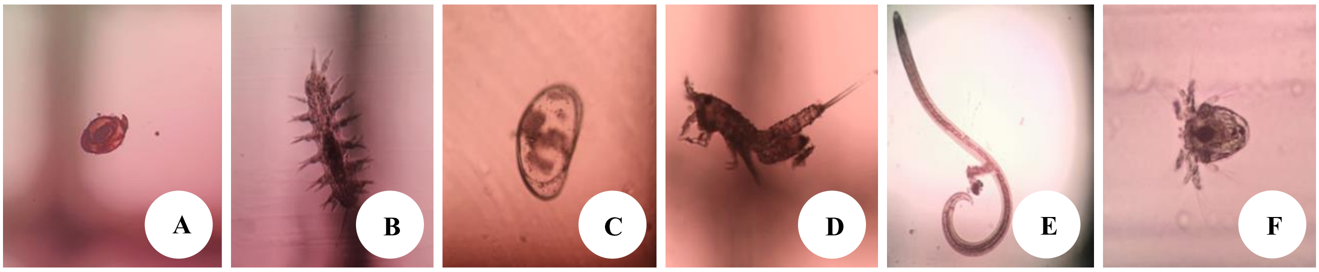

Figure 8. Several types of zooplankton were found at all stations. A. Foraminifera, B. Shrimp larvae, C. Ostracoda, D. Copepod, E. Worm larva, F. Nauplii

Table 8. Presence-absence of plankton genera across the sampling stations

Classes	Genera	S1	S2	S3
Bacillariophyceae	*Navicula* Bory	+	+	+
	Gyrosigma A.H.Hassall, 1845	+	+	+
	Nitzschia Baer, 1826	+	+	+
	Rhizosolenia T.Brightwell, 1858	+	+	+
	Thalassiothrix P.T.Cleve & A.Grunow, 1880	+	+	+
	Amphora C.G.Ehrenberg ex F.T.Kützing, 1844	+	+	+
	Skeletonema R.K.Greville, 1865	+	+	-
	Fragilaria H.C.Lyngbye, 1819	+	+	+
	Bacillaria J.F.Gmelin, 1788	-	+	-
	Leptocilindrus P.T.Cleve, 1889	-	+	-
	Licmophora C.A.Agardh, 1827	-	+	+
Cyanophyceae	*Oscillatoria* Vaucher ex Gomont, 1892	-	+	-
Chrysophyceae	*Chromulina* L.Cienkowsky, 1870	-	+	-
Total		8	13	8

Table 9. Presence-absence of zooplankton groups across the sampling stations

Zooplankton	S1	S2	S3
Crab larvae	+	+	-
Mollusk larva	+	+	-
Copepods	+	+	+
Worm larva	-	+	+
Fish larvae	-	+	+
Foraminifera	-	+	+
Ostracoda	-	+	-
Dhinopisis	-	+	-
Nauplii	-	-	+
Shellfish larva	-	-	+
Shrimp larvae	-	-	+
Total	3	8	7

The plankton community structure showed differences in ecological classification among stations. For phytoplankton, the diversity index (*H'*) at all stations fell within the moderate diversity category, indicating moderately stable community conditions. Evenness values at S1 and S3 were categorized as high evenness, reflecting a relatively balanced distribution of genera, while S2 showed a high dominance tendency, which may be related to its lower evenness classification. The dominance index (*C*) at S1 and S3 indicated low dominance, whereas S2 approached moderate dominance, suggesting stronger control by a few taxa at this station (Table 10).

For zooplankton, diversity at S2 and S3 was categorized as moderate diversity, whereas S1 fell into the low diversity category, indicating comparatively lower structural stability. Evenness values at all stations were classified as high evenness, reflecting a relatively uniform distribution of individuals among groups. The dominance index showed moderate dominance at S1, while S2 and S3 exhibited low dominance (Table 10), indicating that no single zooplankton group overwhelmingly dominated the assemblage at these stations.

Plankton communities illustrated spatial variation in pelagic structure across the three stations, particularly in terms of compositional balance and group richness. Differences in genus composition and proportional distribution indicate that each station supports a distinct plankton assemblage shaped by localized water column conditions. The shift in class-level composition at one station, contrasted with more uniform assemblages at the others, reflects variability in environmental condition and micro-environmental factors (Klais et al. 2017). Zooplankton groups also displayed variation in richness and proportional contribution, suggesting differences in trophic structure and potential energy transfer pathways within the pelagic system (Décima 2022). Overall, the plankton metrics highlight spatial heterogeneity in ecological condition within the coastal waters of North Bali.

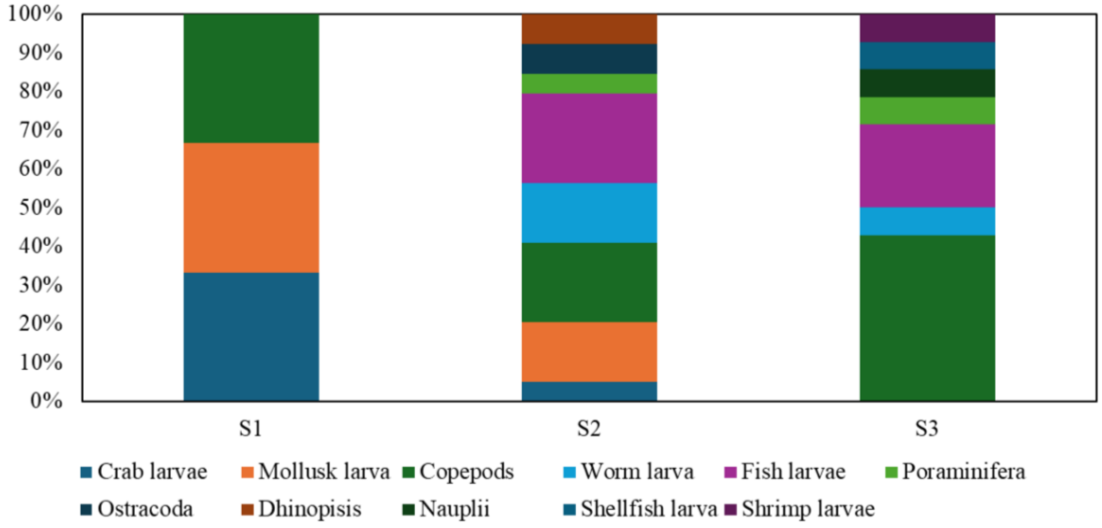

Figure 9. Percentage composition of zooplankton assemblages across sampling stations (data combined from three sampling rounds at each station)

Table 10. Community structure indices of phytoplankton and zooplankton across the sampling stations

Community structure	**Phytoplankton**			**Zooplankton**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**
Density (cell/L for phytoplankton and ind/L for zooplankton)	633±153	1867±1068	333±100	4±2	15±1	6±1
H'	1.75±0.27	1.31±0.80	1.40±0.27	0.83±0.23	1.80±0.20	1.14±0.17
J	0.93±0.03	0.59±0.23	0.92±0.07	0.98±0.03	0.95±0.02	0.95±0.01
C	0.20±0.06	0.47±0.30	0.28±0.09	0.46±0.07	0.18±0.04	0.34±0.05

Integrated multimetric interpretation

When considered together, the mangrove, seagrass, and plankton results indicate an observed spatial pattern across stations in Banyuwedang Bay, where differences in sediment characteristics and suspended materials appear to be related to ecological responses among stations. Areas associated with muddier substrates and higher suspended particles corresponded with reduced water transparency and lower seagrass cover, supporting the established role of sediment dynamics and light limitation in shaping seagrass distribution and performance in shallow coastal waters (Adams et al. 2016; Maxwell et al. 2017). In contrast, mangrove ecosystems maintained consistently high structural condition across stations despite differences in species composition and regeneration patterns, suggesting relatively stable forest structure under varying local environmental settings (Sugiana et al. 2022).

Pelagic communities reflected additional spatial differentiation, with plankton assemblages showing variation in genus composition and dominance patterns among stations. Localized increases in cyanobacterial contribution contrasted with diatom-dominated assemblages elsewhere, indicating sensitivity of plankton communities to small-scale variability in water-column conditions (Klais et al. 2017; Décima 2022). Together, these multimetric indicators suggest that coastal ecosystems in North Bali remain functionally intact while exhibiting spatial heterogeneity across the inner-outer bay gradient.

This study demonstrates the value of an integrated multimetric assessment combining mangrove structure, seagrass ecological quality, and plankton community indicators within a single spatial framework. By evaluating benthic and pelagic components simultaneously, the approach captures ecological variability that may not be detected using single-ecosystem assessments. The results highlight that structurally stable mangrove stands may coexist with moderate seagrass condition and variable plankton communities along the same environmental gradient, providing a baseline ecological reference for monitoring relatively low-disturbance tropical coastal systems. Because this study follows a descriptive, non-inferential design, relationships among environmental parameters and biological responses should be interpreted as associations rather than causal effects, particularly since additional drivers such as nutrient concentrations, chlorophyll-a, and light attenuation were not included.

However, the study is constrained by limited replication and a descriptive analytical framework, with no statistical or multivariate validation of relationships among environmental and biological variables, and the use of pooled data (e.g., IVI) further limits site-specific inference. Future studies should increase spatial and temporal replication, include key drivers such as nutrient concentrations and chlorophyll a, and apply quantitative approaches (correlation analysis, PCA, or regression models) to explicitly link environmental gradients with ecosystem responses, thereby strengthening ecological interpretation and supporting more robust evidence-based coastal management.

In conclusion, this study demonstrates clear spatial heterogeneity in Banyuwedang Bay, with environmental gradients reflected in ecosystem responses. Total suspended solids were highest at the inner bay (S1: 185.7 mg L^{-1}), while temperature (26.9-28.2°C) and salinity (30.6-31.2 ppt) increased toward the outer bay, indicating a transition from terrestrial-influenced to marine-dominated conditions. Mangrove ecosystems remained structurally stable across all stations, with consistently high MHI values (67.45-75.98; Excellent category) despite variation in species composition. In contrast, seagrass meadows showed moderate ecological condition (SEQI: 0.63-0.67), with a trade-off between species richness (up to 4 species at S1) and coverage (up to 72.6% at S2). Plankton communities exhibited moderate diversity (phytoplankton *H'*: 1.31-1.75; zooplankton *H'*: 0.83-1.80) with localized dominance patterns, particularly at S2 (C up to 0.47), indicating spatial variability in pelagic structure. These findings provide a baseline for long-term ecological monitoring and highlight the importance of integrating benthic and pelagic indicators in coastal management, as differences among mangrove, seagrass, and plankton responses indicate that single-ecosystem assessments may overlook spatial ecological variability. Maintaining connectivity between benthic vegetation and pelagic communities is therefore essential for sustaining ecosystem stability and resilience in relatively low-disturbance tropical coastal systems.

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REFERENCES

Adams MP, Hovey RK, Hipsey MR, Bruce LC, Ghisalberti M, Lowe RJ, Gruber RK, Ruiz-Montoya L, Maxwell PS, Callaghan DP, Kendrick GA, O'Brien KR. 2016. Feedback between sediment and light for seagrass: Where is it important? Limnol Oceanogr 61: 1937-1955. https://doi.org/10.1002/lno.10319.

Ambo-Rappe R. 2022. The success of seagrass restoration using *Enhalus acoroides* seeds is correlated with substrate and hydrodynamic conditions. J Environ Manag 310: 114692. https://doi.org/10.1016/j.jenvman.2022.114692.

As-Syakur AR, Wijaya IMS, Andiani AAE, Sugiana IP, Faiqoh E, Wiyanto DB, Rachman HA. 2023. Pedoman Identifikasi Mangrove di Bali. Penerbit AVI, Badung. [Indonesian]

Ayyam V, Palanivel S, Chandrakasan S. 2019. Coastal Ecosystems and Services. In: Coastal ecosystems of the tropics - Adaptive management. Springer, Singapore. https://doi.org/10.1007/978-981-13-8926-9.

Boersma M, Meunier CL. 2020. Zooplankton-Phytoplankton Interactions in A Changing World. In: Teodósio M, Barbosa A (eds). Zooplankton Ecology. CRC Press, Boca Raton. https://doi.org/10.1201/9781351021821-3.

Décima M. 2022. Zooplankton trophic structure and ecosystem productivity. Mar Ecol Prog Ser 692: 23-42. https://doi.org/10.3354/meps14077.

Dewi IGAIP, Faiqoh E, As-Syakur AR, Dharmawan IWE. 2021. Natural regeneration of mangrove seedlings in Benoa Bay, Bali. Jurnal Ilmu dan Teknologi Kelautan Tropis 13 (3): 395-410. https://doi.org/10.29244/jitkt.v13i3.36364. [Indonesian]

Dharmawan IWE, Suyarso, Ulumuddin YI, Prayudha B, Pramudji. 2020a. Panduan Monitoring Struktur Komunitas Mangrove di Indonesia. PT Media Sains Nasional. [Indonesian]

Dharmawan IWE, Ulumuddin YI. 2021. Mangrove Community Structure Data Analysis: A Guidebook for Mangrove Health Index (MHI) Training. Nas Media Pustaka, Makassar.

Dharmawan IWE. 2020b. Hemispherical Photography: Analisis Tutupan Kanopi Komunitas Mangrove. Nas Media Pustaka, Makassar. [Indonesian]

Hernández A, Tapia FJ. 2021. Connecting spatial structure in subtidal benthic communities with temporal variability in bottom temperature and dissolved oxygen along an upwelling coast. Estuar Coast Shelf Sci 250: 107166. https://doi.org/10.1016/j.ecss.2021.107166.

Hernawan UE, Rahmawati S, Ambo-Rappe R, Sjafrie NDM, Hadiyanto H, Yusup DS, Nugraha AH, La Nafie YA, Adi W, Prayudha B, Irawan A, Rahayu YP, Ningsih E, Riniatsih I, Supriyadi IH, McMahon K. 2021. The first nationwide assessment identifies that valuable blue-carbon seagrass habitats in Indonesia are in moderate condition. Sci Total Environ 782: 146818. https://doi.org/10.1016/j.scitotenv.2021.146818.

Hyman AC, Frazer TK, Jacoby CA, Frost JR, Kowalewski M. 2019. Long-term persistence of structured habitats: Seagrass meadows as enduring hotspots of biodiversity and faunal stability. Proc Biol Sci 286 (1912): 20191861. https://doi.org/10.1098/rspb.2019.1861.

Jaffar A, Thamrin NM, Megat Ali MSA, Misnan MF, Mohd Yassin AI. 2020. The influence of physico-chemical parameters to determine water quality: A review. J Electrical Electronic Syst Res 17: 116-121. https://doi.org/10.24191/jeesr.v17i1.016.

Klais R, Norros V, Lehtinen S, Tamminen T, Olli K. 2017. Community assembly and drivers of phytoplankton functional structure. Funct Ecol 31 (3): 760-67. https://doi.org/10.1111/1365-2435.12784.

Ma'ruf MS, Arthana IW, Ernawati NM. 2022. Komposisi Jenis dan Kondisi Mangrove di Teluk Gilimanuk, Taman Nasional Bali Barat. ECOTROPHIC J Environ Sci 16: 153-173. https://doi.org/10.24843/EJES.2022.v16.i02.p04. [Indonesian]

Magurran AE. 2013. Measuring Biological Diversity. John Wiley & Sons, Hoboken.

Maxwell PS, Eklöf JS, van Katwijk MM, O'Brien KR, de la Torre-Castro M, Boström C, Bouma TJ, Krause-Jensen D, Unsworth RKF, van Tussenbroek BI, van der Heide T. 2017. The fundamental role of ecological feedback mechanisms for the adaptive management of seagrass ecosystems - a review. Biol Rev Camb Philos Soc 92 (3): 1521-1538. https://doi.org/10.1111/brv.12294.

Mulloy R, Aiken CM, Dwane G, Ellis M, Jackson EL. 2025. Scalable mangrove rehabilitation: Roots of success for *Rhizophora stylosa* establishment. Ecol Eng 212: 107521. https://doi.org/10.1016/j.ecoleng.2025.107521.

Nagelkerken I. 2009. Ecological Connectivity Among Tropical Coastal Ecosystems. Springer, Dordrecht.

Naik S, Mishra RK, Sahu KC, Lotliker AA, Panda US, Mishra P. 2020. Monsoonal influence and variability of water quality, phytoplankton biomass in tropical coastal waters - a multivariate statistical approach. Front Mar Sci 7: 648. https://doi.org/10.3389/fmars.2020.00648.

Newell GE, Newell RC. 1963. Marine Plankton: A Practical Guide. Hutchinson Educational Ltd, London.

Odum EP. 1993. Fundamentals of Ecology. 5th ed. W.B. Saunders Company, Philadelphia.

Orth RJ, Lefcheck JS, McGlathery KS, Aoki L, Luckenbach MW, Moore KA, Oreska MP, Snyder R, Wilcox DJ, Lusk B. 2020. Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. Sci Adv 6 (41): eabc6434. https://doi.org/10.1126/sciadv.abc6434.

Prado P. 2018. Seagrass epiphytic assemblages are strong indicators of agricultural discharge but weak indicators of host features. Estuar Coast Shelf Sci 204: 140-148. https://doi.org/10.1016/j.ecss.2018.02.026.

Prowe AEF, Su B, Nejstgaard JC, Schartau M. 2022. Food web structure and intraguild predation affect ecosystem functioning in an established plankton model. Limnol Oceanogr 67 (4): 843-855. https://doi.org/10.1002/lno.12039.

Purnomo HK, Yusniawati Y, Putrika A, Handayani W, Yasman. 2017. Seagrass species diversity at various seagrass bed ecosystems in the West Bali National Park Area. Pros Sem Nas Masy Biodiv Indon 3 (2): 236-240. https://doi.org/10.13057/psnmbi/m030213. [Indonesian]

Qur'ani CG, Rizal M, Sugiana IP, Lee B. 2026. Baseline ecological insights of vegetation and carbon stocks assessment in Probolinggo natural mangrove forests. Sustainability 18 (4): 1906. https://doi.org/10.3390/su18041906.

Rahmawati S, Irawan A, Indarto SH, Azkab MA. 2017. Manual of Seagrass Bed Condition Monitoring. P2O LIPI, Jakarta.

Rigby PR, Iken K, Shirayama Y (eds). 2007. Sampling biodiversity in coastal communities: NaGISA protocols for seagrass and macroalgal habitats. NUS Press.

Righetti D, Vogt M, Gruber N, Psomas A, Zimmermann NE. 2019. Global pattern of phytoplankton diversity driven by temperature and environmental variability. Sci Adv 5 (5): eaau6253. https://doi.org/10.1126/sciadv.aau6253.

Röthig T, Trevathan-Tackett SM, Voolstra CR, Ross C, Chaffron S, Durack PJ, Warmuth LM, Sweet M. 2023. Human-induced salinity changes impact marine organisms and ecosystems. Glob Chang Biol 29 (17): 4731-4749. https://doi.org/10.1111/gcb.16859.

Sánchez-Núñez DA, Bernal G, Mancera Pineda JE. 2019. The relative role of mangroves on wave erosion mitigation and sediment properties. Estuaries Coasts 42 (8): 2124-2138. https://doi.org/10.1007/s12237-019-00628-9.

Sugiana IP, Eka Andiani AA, Dewi IGAIP, Karang IWGA, As-Syakur AR, Eka Dharmawan IWE. 2022. Spatial distribution of mangrove health index on three genera-dominated zones in Benoa Bay, Bali, Indonesia. Biodiversitas 23 (7): 3500-3508. https://doi.org/10.13057/biodiv/d230717.

Sugiana IP, Prartono T, Rastina R, Koropitan AF. 2024. Warming effect from soil greenhouse gas emission of each mangrove zone during the dry season in Ngurah Rai Forest Park, Bali, Indonesia. Environ Nat Resour J 22 (5): 449-463. https://doi.org/10.32526/ennrj/22/20240029.

Suryani SAMP, Sudiarta IG, Darmadi NM, Edi DGS, Sudiarta IK, Pratama GAS, Janaguna IMA, Sugiana IP. 2025. Ecological diagnosis of Lake Batur (Bali, Indonesia) post-disturbance using multimetric phytoplankton indices. Biodiversitas 26 (10): 4982-4990. https://doi.org/10.13057/biodiv/d261014.

Tarafdar L, Kim JY, Srichandan S, Mohapatra M, Muduli PR, Kumar A, Mishra DR, Rastogi G. 2021. Responses of phytoplankton community structure and association to variability in environmental drivers in a tropical coastal lagoon. Sci Total Environ 783: 146873. https://doi.org/10.1016/j.scitotenv.2021.146873.

Unsworth RKF, Collier CJ, Waycott M, McKenzie LJ, Cullen-Unsworth LC. 2015. A framework for the resilience of seagrass ecosystems. Mar Pollut Bull 100 (1): 34-46. https://doi.org/10.1016/j.marpolbul.2015.08.016.

Whitfield AK. 2017. The role of seagrass meadows, mangrove forests, salt marshes, and reed beds as nursery areas and food sources for fish in estuaries. Rev Fish Biol Fish 27 (1): 75-110. https://doi.org/10.1007/s11160-016-9454-x.

Wijaya IMS, Sugiana IP, Astarini IA, Ginantra IK, Rahim KAA. 2024. Floristic composition of mangrove community in Ngurah Rai Forest Park and Nusa Lembongan, Bali, Indonesia. Biodiversitas 25 (1): 300-309. https://doi.org/10.13057/biodiv/d250134.