

Diversity and distribution of macrozoobenthos in Bojonegara coastal waters, Banten Bay, Indonesia

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Abstract. Coastal ecosystems, essential for ecological stability, face escalating degradation from pollution and habitat loss. Bojonegara waters in Banten Bay experience anthropogenic pressure that may alter benthic communities. This study examined macrozoobenthos diversity, distribution, and relationships with environmental parameters. Sampling employed a van Veen grab across five periods (January, February, August, and October 2020), with concurrent in-situ and laboratory measurements of physical-chemical parameters. Analyses included genus composition, density, diversity, evenness, and dominance indices, as well as Principal Component Analysis (PCA) and similarity indices. Seventy-seven genera from six phyla and eight classes were recorded, dominated by Gastropoda (37 genera), Bivalvia (18), and Polychaeta (12). The highest macrozoobenthic density occurred at Station 3, the lowest at Station 6. Diversity (0.905–2.640), evenness (0.441–0.772), and dominance (0.260–0.659) indices indicated that the Bojonegara waters were at a low to moderate level of pollution. PCA revealed strong associations between Bivalvia, Gastropoda, and Sipuncula with salinity and water transparency variations. Gastropods and polychaetes predominated in estuarine-freshwater substrates, while bivalves thrived in marine substrates. Findings confirm macrozoobenthos as reliable bioindicators for evaluating ecological status and environmental quality in coastal ecosystems.

Keywords: Biodiversity, bioindicators, environmental parameters, Banten Bay, Bojonegara, macrozoobenthos

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1 Introduction

Banten Bay, located on the northern coast of Java Island, is a dynamic sedimentary basin constantly fed by multiple rivers, which significantly shape its seabed and coastal features. Bojonegara coastal waters, part of this bay, are characterized by high humidity resulting from the strong interaction between seawater and freshwater sources [1]. In recent decades, rapid population growth and industrial development in the surrounding area have increased human pressure on bay ecosystems, causing environmental degradation and alterations in water quality [2, 3]. These impacts have created a need for comprehensive ecological assessments, particularly focusing on bioindicators such as macrozoobenthos, which are sensitive to environmental changes and reflect the overall health of aquatic environments [4, 5]. Macrozoobenthos, defined as benthic invertebrates larger than 1 mm, are essential components of marine ecosystems, play key roles in nutrient cycling, and serve as a food source for higher trophic levels [6, 7].

Macrozoobenthic communities are vital components of aquatic ecosystems and serve as key indicators of ecological balance and environmental health. Their structures and compositions mirror the stability and diversity of aquatic organisms. According to Suminar et al. [8], the physical, chemical, and biological features of aquatic environments primarily determine the spatial distribution of macrozoobenthos. Furthermore, as emphasized by Sulphayrin et al. [9], changes in macrozoobenthic abundance and composition are closely related to the tolerance of each species to environmental stressors. Communities with many taxa of similar abundances are generally regarded as highly diverse. In contrast, those dominated by a few species indicate lower ecological stability and resilience, a pattern often shaped by multiple biological and environmental factors [6]. For instance, marine benthic invertebrates account for 90% of all marine invertebrates in benthic ecosystems and are known to have higher species diversity than pelagic systems [10]. Their sessile or limited mobility, combined with varying sensitivities to pollutants, makes them excellent bioindicators for assessing the impact of human activities on water quality and ecosystem health [11].

Research on macrozoobenthos in Indonesia's coastal and estuarine systems has been conducted at various sites, including the Donan Estuary in Cilacap [12] and the western part of the Segara Anakan Lagoon in Central Java [13]. Similar studies in other Southeast Asian regions, such as Malaysia's rivers [14] and Ly Son Island in Vietnam [15], have shown that macrozoobenthos respond strongly to habitat conditions, making them reliable bioindicators for assessing environmental quality. These organisms play an important role in biogeochemical cycles, including nutrient regeneration and organic matter decomposition, thus affecting the overall ecosystem functioning [16]. Their activities, such as bioturbation and feeding, alter sediment properties and facilitate nutrient exchange, significantly contributing to the productivity and health of benthic environments [10, 17].

In the context of Bojonegara, previous research has mainly focused on the distribution of dissolved heavy metals in coastal waters [2], revealing early signs of industrial contamination. However, to date, no study has specifically examined the diversity and spatial distribution of macrozoobenthos in this area. This knowledge gap limits our understanding of how benthic communities respond to local environmental stressors and the ongoing industrial influence in Banten Bay. This study aimed to fill this critical gap by investigating the diversity, distribution, and community structure of macrozoobenthos in Bojonegara's coastal waters, providing crucial insights into the ecological status and health of this industrially impacted ecosystem [18, 19].

Therefore, this study aimed to analyze the composition, density, diversity, evenness, dominance, and spatial distribution of macrozoobenthos in the coastal waters of Bojonegara, Banten Bay, Indonesia. The results are expected to provide baseline ecological data to

support future monitoring efforts, guide sustainable coastal resource management, and help develop conservation strategies for maintaining ecosystem health in Banten Bay.

2 Materials and methods

2.1 Time and location

Data were collected using a survey method with monthly sampling at six stations from January to October 2020, specifically in the Bojonegara coastal waters and Banten Bay (Fig. 1).

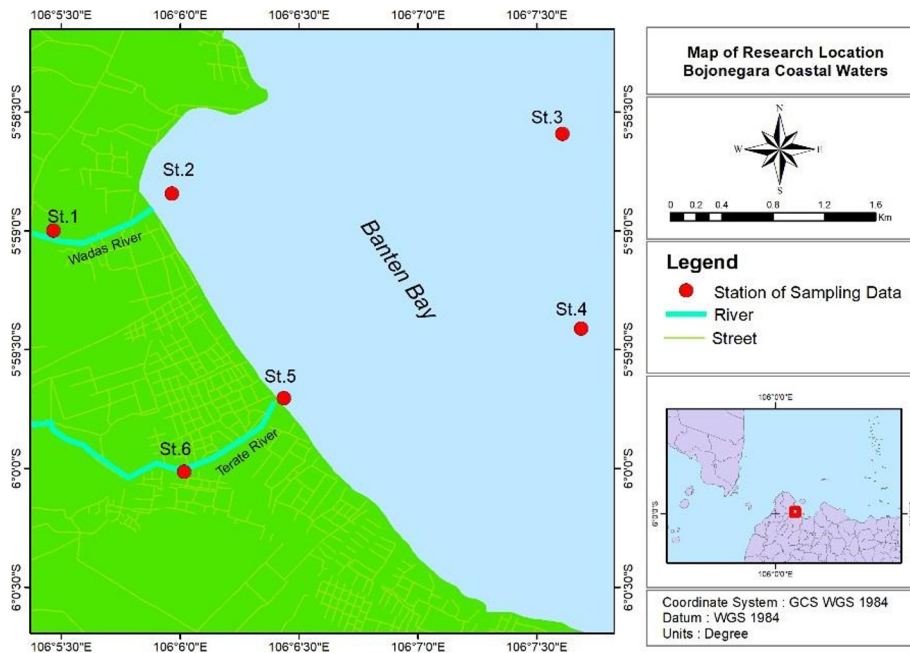


Fig. 1. Location of study with six stations in the Bojonegara coastal waters.

Station 1 is located on the Wadas River near the community settlement, whereas Station 2 is located in the Wadas River estuary close to the industrial zone and shipping route. Stations 3 and 4 were in the open sea to represent the water conditions in marine environments. Station 5 was located in the Terate River estuary near the power plant, and Station 6 was located on the Terate River near a community settlement. The placement of these stations aimed to compare the influence of different water conditions on the macrozoobenthos community.

2.2 Data collecting

2.2.1 Macrozoobenthos sampling

Macrozoobenthos sampling was conducted using a Van Veen Grab (with a mouth opening measuring 13 × 26 cm), repeated three times at each station. Macrozoobenthos samples were placed in jars and preserved in a 10% formalin solution. Macrozoobenthos samples were identified to genus level using WoRMS (World Register of Marine Species) and

MolluscaBase taxonomic databases [20].

2.2.2 Water physical-chemical parameters sampling

In situ sampling was performed once at each station. The observed parameters were temperature, salinity, pH, DO, transparency, and Total Suspended Solids (TSS).

2.3 Data analysis

2.3.1 Substrate type analysis

The substrate type was determined using Millar's Triangle [21] (**Fig. 2**). Substrate type was determined based on the composition of each substrate fraction.

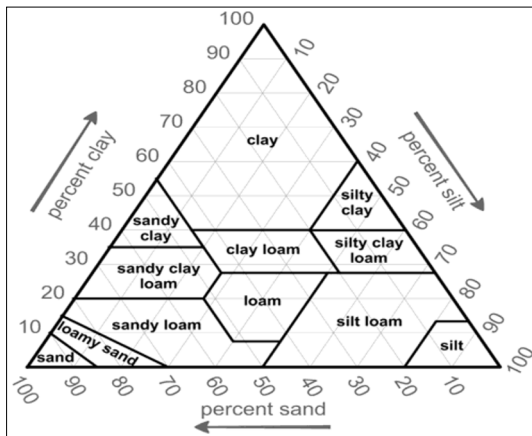


Fig. 2. Types of Substrate based on Millar's Triangle (USDA, [21]).

2.3.2 Density

The density of the population was expressed as individuals per square meter (individuals /m²). Macrozoobenthos density was calculated using the following formula [22]:

$$K = \frac{10000 \times N}{A} \quad (1)$$

Description:

K = macrozoobenthos density (individuals/m²)

N = number of individuals found (individuals)

A = area of the grab opening (cm²)

10000 = conversion of units from cm² to m²

2.3.3 Diversity index (H')

The diversity index can mathematically describe the condition of a macrozoobenthic community, simplifying the analysis of species diversity within the community. Calculations can be performed using the Shannon-Wiener diversity index [23]:

$$H' = - \sum_{i=1}^S (p_i)(\log_2 p_i) ; p_i/N \quad (2)$$

H' = diversity index

p_i = i^{th} species ratio

n_i = number of types of individuals it- i

N = number of individuals of all species

S = number of taxa (species)

Based on the diversity category, the Shannon-Wiener index values can be divided into three categories with the following ranges:

$H' < 1$ = low species diversity

$1 \leq H' \leq 3$ = moderate species diversity

$H' > 3$ = high species diversity

2.3.4 Evenness Index (E)

The Evenness Index is the distribution of individuals across taxonomic levels within a community. Calculations can be performed using the evenness index formula [23].

$$E = \frac{H'}{H'max} \quad (3)$$

Description:

E = evenness index

H' = diversity index

$H'max$ (benthos) = $\text{Log}_2 S$

S = number of taxa (species).

The magnitude of the species evenness index ranged from 0 to 1, with the following categories [23]:

$0 < E \leq 0.5$: Low population evenness

$0.5 < E \leq 0.75$: Medium population evenness

$0.75 < E \leq 1$: High population evenness

2.3.5 Domination Index (C)

A dominance index was used to determine the dominant species in the community. The dominance index was calculated using the Simpson dominance index formula [23].

$$C = \sum_{i=1}^S \left(\frac{n_i}{N}\right)^2 \quad (4)$$

Description:

C = dominance index

n_i = number of genera of individuals it- i

N = total number of individuals

The dominance index values ranged from 0 to 1. If the C value approaches 0, no individual dominates, whereas if the C value approaches 1, some individuals dominate in a community [23]. With a range:

$0 < C \leq 0,5$: low dominance

$0,5 < C \leq 0,75$: moderate dominance

$0,75 < C \leq 1$: high dominance

2.3.6 Similarity Index

The similarity index was used to assess grouping based on the physicochemical properties of the water and the abundance of macrozoobenthos, as determined by the Bray-Curtis Index. A formula can be used to determine the Bray-Curtis Index Similarity index [24]:

$$I_{BC} = \left[1 - \frac{\sum_{i=1}^n |x_{ij} - x_{ik}|}{\sum_{i=1}^n (x_{ij} + x_{ik})} \right] \quad (5)$$

Description:

I_{BC} = Bray-Curtis similarity index

x_{ij} and x_{ik} = the number of individuals of genus i in each k th example

n = number of genera compared

The function of subtracting 1 is to determine the similarity index value in the range of 0–1. The similarity index value was supported by the Paleontological Statistics (Past3) software for displaying the similarity index dendrogram (Bray-Curtis).

2.3.7 Principal Component Analysis (PCA)

The relationship between macrozoobenthos community structure and environmental characteristics was analyzed using Principal Component Analysis (PCA). PCA presents data graphically, where the data matrix shows research stations as rows (samples) and environmental factors as columns (variables) [25]. This method aims to describe the connection between macrozoobenthos and their environment and to identify the correlation between these two components. The analysis was performed using the XLSTAT 2021 software.

3 Results

3.1 Aquatic environmental conditions

The physicochemical parameters of the water support the survival of macrozoobenthos. The results of water quality parameter measurements are presented in **Table 1**. Based on water quality parameter measurements, the coastal waters of Bojonegara range from 28 to 37 °C. The site with the lowest average temperature was Station 6 (31.32 °C), but this still falls within the quality standards outlined in the Decree of the Ministry of Environment No. 51 (2004), which states that the suitable temperature range for marine life and organism survival is from 28 °C to 32 °C.

The transparency value ranged from 0.05 to 4.7 meters, with the highest average at Station 3. The variation in transparency at each station was influenced by depth, light penetration, and turbidity levels. Turbidity ranged from 0.7 to 380 NTU, with the highest average at Stations 1 and 6. TSS ranged from 3.5 to 415 mg/L, indicating that the coastal waters of Bojonegara have a high suspended solids content. According to the Decree of the Ministry

of Environment No. 51 of 2004 concerning the seawater quality standard for biota, the acceptable limit is 80 mg/L.

The pH levels at the six stations ranged from 6.63 to 8.20, which is suitable for macrozoobenthos. Salinity measurements ranged from 0 to 38, with the lowest values recorded at Stations 1 and 6, both of which are located on the river. The highest salinity levels were observed at Stations 3 and 4, both of which are situated in the open sea. Dissolved oxygen (DO) levels varied from 3.3 to 7.5 mg/L, with the highest average at Station 6, which had a river flow of 5.68 mg/L.

Table 1. Physicochemical parameters (temperature, salinity, pH, dissolved oxygen, transparency, and total suspended solids) measured at six stations in Bojonegara coastal waters. Values are presented as means ± standard deviations from five observation periods in 2020.

Parameters	Unit	Stations					
		1	2	3	4	5	6
Physic							
Temperature	°C	31.46±2.31	31.36±1.00	31.48±0.82	31.98±2.10	35.28±1.82	31.32 ±2.04
Transparency	m	0.22±0.13	1.95±1.21	2.96±1.34	2.55±1.07	1.53±0.73	0.60±0.93
Turbidity	NTU	98.60 ±47.78	11.12±11.83	5.31±4.51	4.06±3.00	13.66±17.30	130.60±146.78
TSS	mg/L	181.48±117.82	22.55±29.57	27.28±34.84	11.53±6.50	24.65±18.41	99.75±65.69
Chemical							
pH		7.71±0.50	7.52±0.48	7.51±0.46	7.46±0.19	6.90±0.19	7.30±0.41
Salinity	‰	17.40±13.63	29.00±4.18	30.00±5.51	29.20±9.17	25.90±9.17	3.60±2.51
DO	mg/L	6.04±1.07	5.56±1.26	5.04±1.22	5.24±1.44	4.10±0.40	5.68±0.61

3.2 Substrate characteristics

The distribution of sediments is mainly influenced by tides, waves, and water discharge, along with the interaction of other marine biophysical factors [23]. Substrate characteristics were analyzed to identify the substrate composition at each station. The substrate composition of the Bojonegara coastal waters is shown in **Table 2**.

Based on the substrate texture triangle (**Fig. 2**), a comparison of sand, silt, and clay compositions at all stations showed that the substrate was dominated by clay. This clay-rich substrate provides favorable conditions for macrozoobenthic colonization due to its high organic matter retention capacity [26].

Table 2. Substrate composition at six sampling stations in Bojonegara coastal waters. The composition was derived from laboratory particle-size analysis of sediment samples collected during five observation periods in 2020.

Station	Sand (%)	Silt (%)	Clay (%)	Substrate
1	49.11	19.60	31.30	Sandy clay loam
2	18.94	36.69	44.38	Clay
3	7.18	37.13	55.66	Clay
4	7.67	38.83	53.50	Clay
5	2.55	36.99	60.47	Clay
6	25.37	39.56	35.08	Clay loam

3.3 Macrozoobenthos community structure

Macrozoobenthos composition recorded across six stations in the Bojonegara coastal waters (Banten Bay) over five months included six phyla: Mollusca, Annelida, Arthropoda, Echinodermata, Nematoda, and Sipuncula. These were grouped into eight classes and 77 genera: Bivalvia (18 genera), Gastropoda (37 genera), Polychaeta (12 genera), Malacostraca (four genera), Echinoidea (two genera), Chromadorea (one genus), Scapopoda (one genus), and Sipunculidea (one genus). The overall composition is shown in **Fig. 3**, indicating that gastropods (48%) and bivalves (43%) were the dominant groups, followed by Polychaeta (5%), Malacostraca (1%), Scapopoda (0.8%), Echinoidea (0.5%), Chromadorea (0.01%), and Sipunculidea (0.006%). Bivalves and Gastropods appeared consistently during all sampling periods. During the rainy season (January–February), bivalves dominated at Station 5 (100%), whereas gastropods were most abundant at Station 1 (71%), with polychaetes observed only at Stations 1 and 3.

Six to seven macrozoobenthic classes were recorded at each station during the dry season (August–October). In August, six classes were found, mainly Bivalvia, Gastropoda, Polychaeta, Malacostraca, Echinoidea, and Scapopoda, with the highest polychaete proportion at Station 5 (22.22%), whereas Malacostraca was limited to Station 4 (0.76%). In September, seven classes, including Chironomidae, were identified. Bivalves reached their peak abundance at Station 4 (73.68%), whereas gastropods were distributed across all stations, with the lowest abundance at Station 1 (1.73%). Polychaetes was concentrated at Station 1 (56.36%), and Malacostraca was mainly observed at Stations 1–3. In October, seven classes were again recorded, with bivalves highest at Station 3 (69.74%) and gastropods dominating at Station 5 (75.11%). Polychaeta and Malacostraca appeared at multiple stations and Sipunculidea (*Sipunculus* sp.) was recorded exclusively at Station 3.

Macrozoobenthos density varied across the locations (**Fig. 4b**). The highest density was recorded at Station 3 (2057.8 ind/m²), followed by Station 2 (1600.6 ind/m²), Station 5 (1240.6 ind/m²), Station 4 (997.8 ind/m²), and Station 1 (990.8 ind/m²). The lowest density was observed at Station 6 (38.25 ind/m²), situated on the Terate River, an area affected by effluents from an electric power plant and degraded water quality. The dominance of Bivalves and Gastropods at most stations indicated suitable substrates and stable physicochemical conditions. In contrast, the low density at Station 6 reflects stress from human activities and unfavorable environmental conditions.

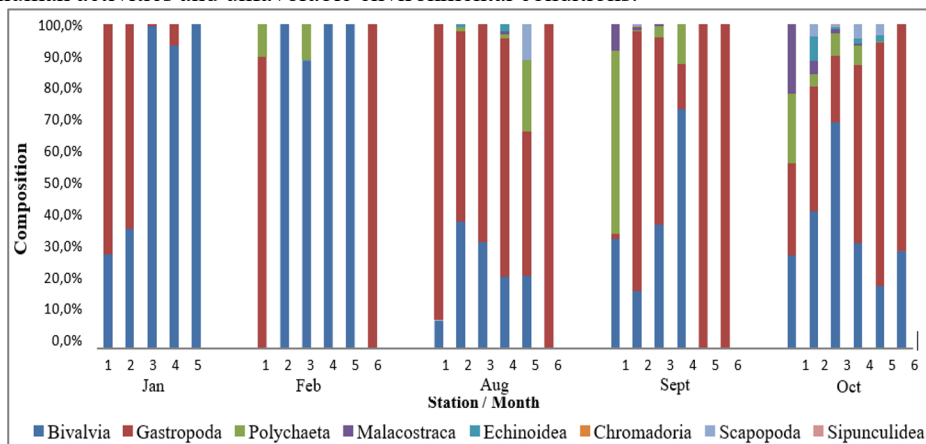


Fig. 3. Monthly and spatial variation in macrozoobenthos community composition across six stations in Bojonegara coastal waters.

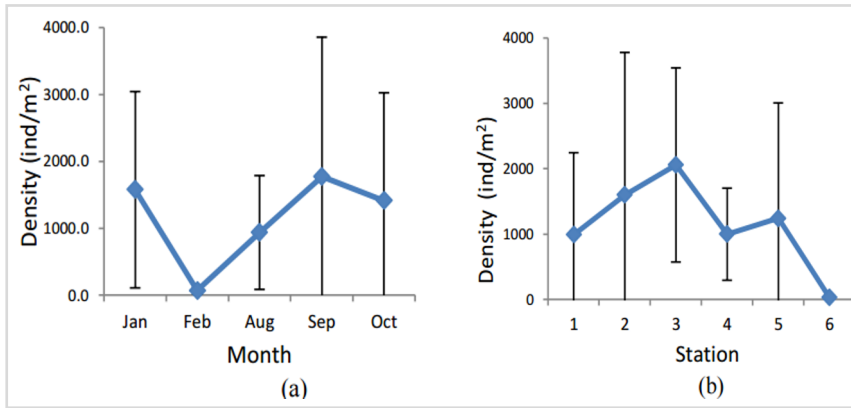


Fig. 4. Temporal (January–October 2020) (a) and spatial (b) density variation of macrozoobenthos (ind/m²) across six stations in Bojonegara coastal waters.

3.4 Diversity Index (H')

The diversity index of macrozoobenthos in the coastal waters of Bojonegara ranged from 0.621 to 2.712 depending on the time of data collection (**Fig. 5a**). The highest diversity index value was recorded in October (2.712). According to Meisaroh et al. [22], a high diversity index can be attributed to greater biotic diversity, which leads to the absence of dominant species. A high diversity index might also be associated with a low dominance index. In September, the diversity index was 1.588, in August, it was 2.309, in February, it was 0.621, and the lowest value recorded was 1.237 in January.

Based on the data collection station (**Fig. 5b**), the diversity index ranged from 0.905 to 2.640, with the highest value at Station 4 (2.640). For the other stations, the values were 1.259 (Station 5), 0.906 (Station 6), 1.386 (Station 3), 2.222 (Station 2), and 1.681 (Station 1). The differences in values between the stations can be attributed to variations in substrate types and monthly fluctuations driven by seasons and currents.

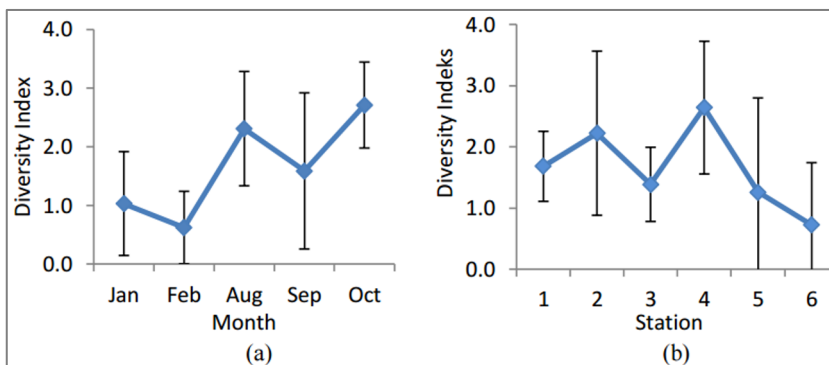


Fig. 5. Monthly (a) and spatial (b) variation in macrozoobenthos diversity index (H') across six stations in Bojonegara coastal waters.

3.5 Evenness Index (E)

The Evenness index based on data collection time in the Bojonegara coastal waters ranged from 0.410 to 0.789 (**Fig. 6a**), with the highest value of 0.789 recorded in October, followed

by August (0.724), January (0.512), September (0.414), and February (0.441). Based on the data collection stations, the evenness index ranged from 0.441 to 0.772 (**Fig. 6b**). The highest value was recorded at Station 4 (0.772), followed by Stations 1 (0.652), 2 (0.624), 6 (0.465), and 3 (0.458). The lowest value was observed at Station 5 (0.441). The evenness index values at Stations 1, 2, and 4 were close to 1. Therefore, it can be categorized as high, ensuring that the macrozoobenthos were evenly distributed at these stations. The low dominance index value at this station influenced this result. However, Stations 3, 5, and 6 had lower values than the other stations, which can be categorized as moderate, indicating that the distribution of macrozoobenthic species in the area was less even. A low diversity index value and high dominance index value can influence this result.

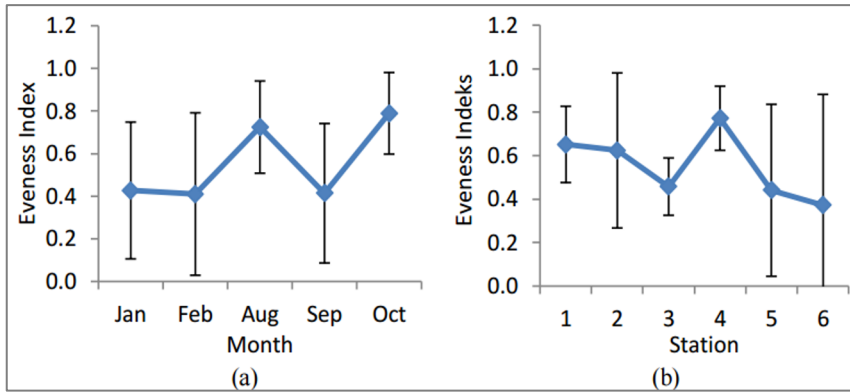


Fig. 6. Monthly (a) and spatial (b) variation in macrozoobenthos evenness index (E) across six stations in Bojonegara coastal waters.

3.6 Dominance index (C)

Based on the time of data collection, the dominance index in Bojonegara coastal waters ranged from 0.229 to 0.758 (**Fig. 7a**). The highest dominance index value was recorded in February (0.758), followed by January (0.584), September (0.530), August (0.316), and October (0.229). February had a significantly higher dominance index than January and September, indicating that it was a month when macrozoobenthos species dominated. Meanwhile, January and September were categorized as moderate, whereas August and October had low dominance index values, indicating that no genus dominated the data collection in those months.

Based on the data collected from the stations, the obtained dominance index values ranged from 0.260 to 0.659 (**Fig. 7b**). Station 6 had the highest dominance index (0.659), followed by Stations 5 (0.636), 3 (0.552), 1 (0.447), 2 (0.363), and 4 (0.260). Stations 6, 5, and 3 had high values; therefore, they were included in the high dominance index, indicating the presence of dominant genera, as the abundance of one genus was high and tended to dominate.

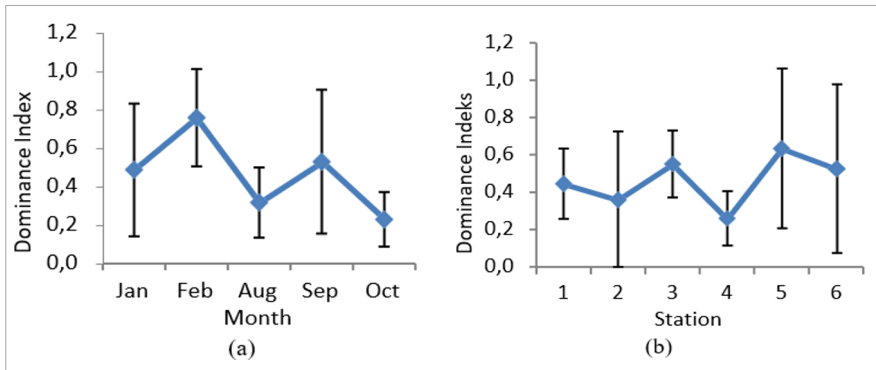


Fig. 7. Monthly (a) and spatial (b) variation in macrozoobenthos dominance index (C) across six stations in Bojonegara coastal waters.

3.7 Macrozoobenthos and water quality relationship

Principal Component Analysis (PCA) was used to determine the relationships between macrozoobenthos and physicochemical parameters of the water at the observation locations (**Fig. 8**). Based on principal component analysis (PCA), which identified two components, the biplot accounted for 73.35% of the total F1 presentation, with 49.58% attributed to F1 and 23.77% to F2.

The results of the principal component analysis indicated that the angle formed by the variable types of macrozoobenthos, Bivalves, Gastropods, and Sipunculidea, regarding transparency and salinity, showed a positive correlation (**Fig. 8**). Thus, these two components influence each other. The graph illustrates a stronger correlation between Sipunculidea and lower water quality than between Bivalves and Gastropods. Additionally, the components showing a positive correlation in the graph were between Echinoidea and Scapopoda and temperature, all of which had a positive influence on each other. Polychaeta, Malacostraca, and Chromadorea positively correlated with pH.

3.8 Macrozoobenthos with substrate relationship

Principal component analysis was also conducted to investigate the relationship between macrozoobenthic density and substrate type. The substrate is the primary medium for macrozoobenthic survival. The substrate characteristics of water affect the functional morphology and behavior of benthic animals. Benthic animals adapt according to the type of substrate [31]. Based on the results of the principal component analysis (two components), the biplot accounted for 71.39% of the total F1 (46.32%) and F2 (25.07%).

The results of the analysis showed a positive correlation between the type of clay substrate and gastropods, bivalves, sipunculidea, echinoidea, and spapopods, which were found near Stations 3 and 5 (**Fig. 9**).

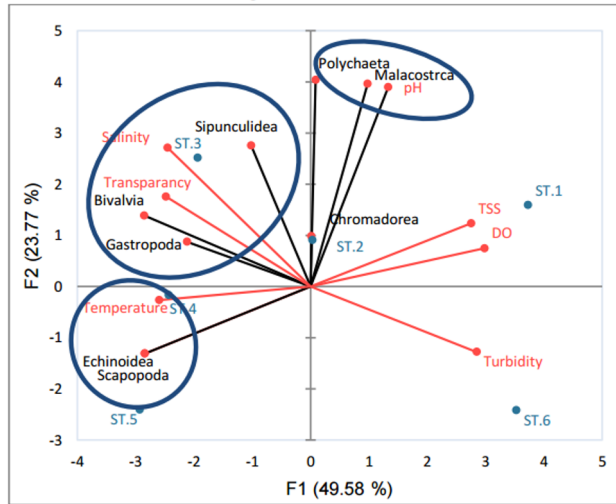


Fig. 8. PCA biplot of macrozoobenthos taxa and environmental parameters across six stations in Bojonegara coastal waters. Data integrate taxonomic composition and physicochemical variables from five sampling periods in 2020.

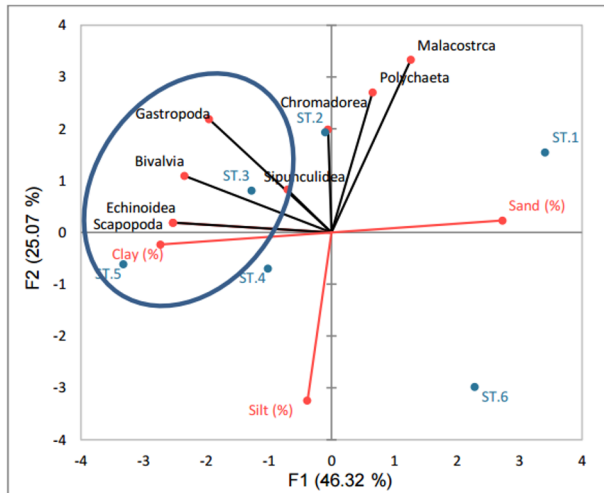


Fig. 9. PCA biplot of macrozoobenthos taxa and sediment composition across six stations in Bojonegara coastal waters. Data integrate taxonomic composition and substrate characteristics from five sampling periods in 2020.

3.9 Similarity between stations

Macrozoobenthos grouping analysis used the Similarity Index (Bray-Curtis) to determine the similarity between stations based on the acquisition of macrozoobenthos and water quality. Macrozoobenthos habitat grouping patterns were analyzed using cluster analysis based on the Bray-Curtis similarity index with biological parameters (macrozoobenthos density) and water quality. The Bray-Curtis similarity index ranged from 0 to 1. An S value close to 0 indicates a low level of similarity, whereas an S value close to 1 indicates a high level of similarity. The similarity dendrogram based on macrozoobenthos density (**Fig. 10a**) shows the highest similarity between Stations 1 and 2, while Station 6 shows no similarity with the other

stations. Stations 3 and 4 had something in common, while Station 5 was in between.

The similarity based on water quality (Fig. 10b) shows the highest similarity between Stations 1 and 6, as these stations are located within the same river body. Thus, the similarity in water quality was very high. The similarity in water quality between the estuary and sea areas was due to the influence of a mixture of freshwater and seawater.

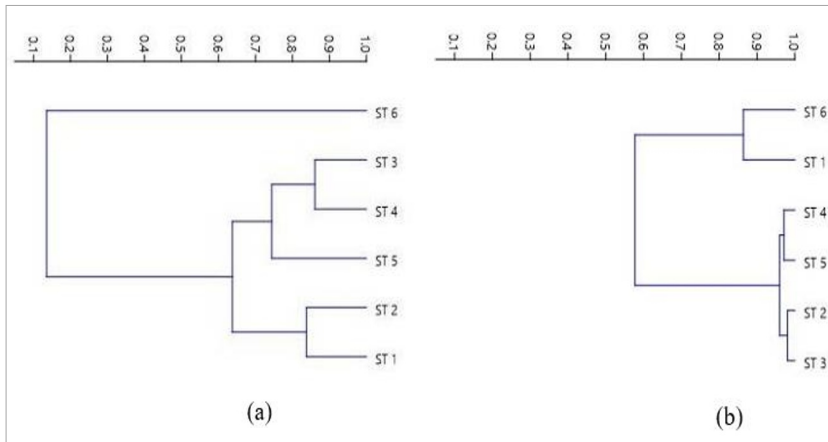


Fig. 10. Similarity dendrograms of (a) macrozoobenthos density and (b) water quality parameters across six stations in Bojonegara coastal waters. Data aggregated from five sampling periods in 2020.

3.10 Macrozoobenthos distribution

The physical, chemical, and biological features of the coastal waters of Bojonegara greatly affect the distribution of macrozoobenthos. Observations showed that the spatial distribution patterns varied between stations, and the species composition was uneven. Eight macrozoobenthos classes were identified, mainly Bivalvia, Gastropoda, Polychaeta, Malacostraca, Echinoidea, Scapopoda, Chironomidae, and Sipunculidea. Gastropods and bivalves were the most common groups. Gastropods were more abundant in river areas, whereas bivalves increased toward marine stations. Station 1, located in the Wadas River basin with sandy clay soil, hosted by Bivalvia, Gastropoda, Polychaeta, and Malacostraca, including *Pila* sp., *Perna* sp., *Clea* sp., *Pomacea* sp., and *Nephtys* sp. At Station 2, near the Wadas River mouth with a clay substrate, macrozoobenthos diversity was high, featuring *Anadara* sp., *Tellina* sp., *Semicassis* sp., *Turritella* sp., and *Leptolaimus* sp. (Chromadorea) uniquely found there.

Stations 3 and 4, located offshore, showed the highest macrozoobenthos composition and diversity, mainly consisting of Bivalvia and Gastropoda, along with other classes, such as Polychaeta, Malacostraca, Echinoidea, and Scapopoda. Station 3 was notable for the presence of *Sipunculus* sp. (Sipunculidea), indicating good water quality, supported by clay substrates at both stations. Station 5, situated in the Terate River estuary and affected by nearby industrial activities, also exhibited high macrozoobenthic abundance with a clay substrate similar to Stations 2–4, dominated by *Anadara* sp., *Nassarius* sp., and *Aliculastrum* sp. Conversely, Station 6 had only a small number of Bivalvia and Gastropoda, reflecting poorer water quality, likely impacted by domestic waste and power plant discharge. Species such as *Tarebia* sp., *Pomacea* sp., and *Opalia* sp. remained, indicating some resilience. Stations 1 and 6, both within the river systems, mainly contained macrozoobenthos originating from freshwater inflows.

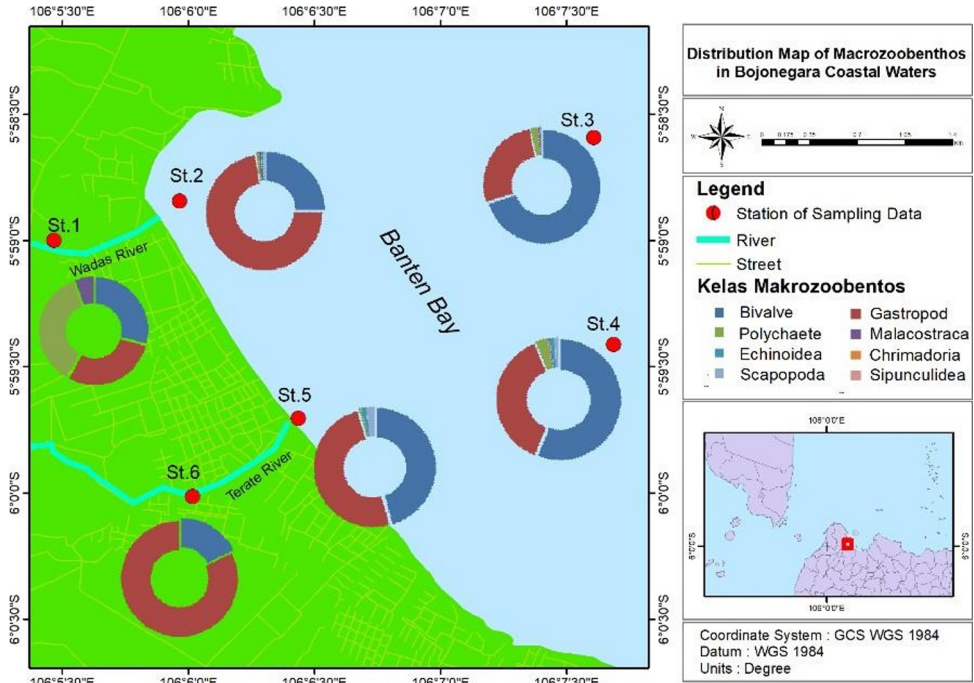


Fig. 11. Spatial distribution of macrozoobenthos community composition across six stations in Bojonegara coastal waters, shown as proportional abundance of eight taxonomic classes. Data aggregated from five sampling periods in 2020.

4 Discussion

4.1 Water quality factors and their relationship with macrozoobenthos

Banten Bay waters experience substantial environmental pressure from rapid population growth and industrial expansion, particularly in Bojonegara, a coastal zone hosting large- and medium-scale industries in basic metals, chemicals, and maritime sectors [19]. Despite this anthropogenic pressure, temperature measurements across six stations remained within the optimal 25–35 °C range for macrozoobenthos survival [27]. Elevated turbidity (0.7–380 NTU) and high total suspended solids (3.5–415 mg/L), driven by seasonal river discharge and tidal dynamics, may suppress primary productivity yet favor benthic and demersal species adapted to turbid conditions [28]. Dissolved oxygen levels consistently fell within the favorable 4–6 mg/L range for macrozoobenthic communities, reflecting generally suitable habitat conditions [29].

Spatial variations in salinity (0–38 ppt) strongly influenced species distribution patterns. Stations 1 and 6, located in riverine zones, recorded near-freshwater salinity (<5 ppt), whereas marine stations (3 and 4) exhibited oceanic salinity (>30 ppt). This gradient shaped community composition: gastropods dominated low-salinity estuarine zones, while bivalves thrived in higher-salinity marine environments. Although localized inputs such as power plant effluents and river-borne heavy metals can negatively impact nearshore diversity, metal concentrations tend to decrease toward the open sea [2]. This spatial gradient demonstrates the macrozoobenthos' adaptive capacity to heterogeneous environmental conditions while underscoring the need for continuous monitoring of industrial impacts on coastal ecosystems [30].

4.2 The effect of substrate on macrozoobenthos life and distribution

Spatial variations in salinity (0–38 ppt) strongly influenced species distribution patterns. Stations 1 and 6, located in riverine zones, recorded near-freshwater salinity (<5 ppt), whereas marine stations (3 and 4) exhibited oceanic salinity (>30 ppt). This gradient shaped community composition: gastropods dominated low-salinity estuarine zones, while bivalves thrived in higher-salinity marine environments. Although localized inputs such as power plant effluents and river-borne heavy metals can negatively impact nearshore diversity, metal concentrations tend to decrease toward the open sea [2]. This spatial gradient demonstrates the macrozoobenthos' adaptive capacity to heterogeneous environmental conditions while underscoring the need for continuous monitoring of industrial impacts on coastal ecosystems [30].

Gastropods show broad adaptability and high tolerance to various environmental and seasonal conditions [6]. Similarly, Bivalves display strong resilience to environmental fluctuations, which explains their widespread distribution across all stations and sampling periods. As demonstrated in global meta-analyses of estuarine benthos [17], molluscs such as Bivalves, Gastropods, and Polychaetes are characteristic of estuarine benthic communities because of their ability to withstand dynamic and variable water conditions. Therefore, substrate type is a key factor in determining the life and distribution of macrozoobenthos. Polychaetes, bivalves, and gastropods prefer clay substrates rich in organic matter, and changes in substrate composition can significantly alter the overall structure of macrozoobenthic communities.

4.3 Macrozoobenthos community, abundance, and adaptation

Environmental stressors, including habitat modification, pollution, and seasonal hydrological changes, directly influence macrozoobenthic abundance, diversity, and dominance patterns. During the rainy season (January–February), increased river discharge transported large sediment loads to estuarine zones, elevating turbidity and TSS while reducing salinity. This period coincided with the lowest diversity index ($H' = 0.621$ in February) and highest dominance ($C = 0.758$), indicating community stress and the proliferation of tolerant taxa such as *Pomacea* sp. and *Tarebia* sp. in freshwater-influenced stations.

Conversely, the dry season (August–October) exhibited improved water clarity, stabilized salinity gradients, and enhanced organic matter accumulation from prior runoff. These conditions supported higher species richness and evenness, culminating in the peak diversity index ($H' = 2.712$) and lowest dominance ($C = 0.229$) recorded in October. Station 4 achieved the highest spatial diversity ($H' = 2.640$), attributed to its marine location, clay substrate, and minimal anthropogenic disturbance. The appearance of sensitive taxa such as *Sipunculus* sp. (*Sipunculidea*) exclusively at Station 3 further corroborates favorable environmental conditions in offshore zones. These seasonal dynamics align with patterns observed in tropical estuaries globally, where dry-season stability promotes benthic community recovery and diversification [17, 21].

4.4 Diversity and evenness indices

Diversity ($H' = 0.905$ – 2.640) and evenness ($E = 0.441$ – 0.772) indices collectively indicate that Bojonegara waters range from low to moderate pollution levels. Stations 1, 2, and 4 exhibited relatively high evenness values (>0.62), suggesting balanced community structures with no single taxon dominating—characteristic of healthy ecosystems [24]. In contrast, Stations 3, 5, and 6 showed moderate evenness (<0.46) coupled with elevated dominance indices ($C > 0.55$), reflecting environmental stressors such as industrial effluents (Station 5)

and power plant discharges (Station 6).

The inverse relationship between diversity and dominance indices reinforces their utility as complementary bioindicators. High diversity coincided with low dominance during stable dry-season months (August–October), whereas the rainy season (January–February) exhibited low diversity and high dominance—consistent with pollution-induced community simplification [11]. Gastropods and bivalves dominated across stations, underscoring their role as pollution-tolerant indicator groups in tropical estuaries [6]. Notably, the absence of sensitive taxa (e.g., certain polychaetes and crustaceans) at Stations 1 and 6 further corroborates localized degradation from freshwater pollutants and thermal discharge. These patterns validate macrozoobenthos as reliable, cost-effective bioindicators for rapid assessment of coastal ecosystem health in industrially impacted regions.

4.5 Macrozoobenthic community structuring across riverine, estuarine, and marine environments

Bray-Curtis cluster analysis revealed three distinct groupings corresponding to the riverine-estuarine-marine continuum (**Fig. 10a**). Riverine stations (1 and 6) exhibited low density (<1000 ind/m²) and dominance by pollution-tolerant gastropods (*Pomacea* sp., *Tarebia* sp., *Opalio* sp.), with Station 6 showing extreme dominance ($C = 0.659$) due to power plant effluents. Estuarine stations (2 and 5) displayed intermediate diversity ($H' = 1.386$ – 2.222) with euryhaline assemblages of Gastropoda, Bivalvia, and Polychaeta adapted to fluctuating salinity (5–25 ppt). Marine stations (3 and 4) formed a tight cluster (>65% similarity) with highest richness (77 genera), peak density (2057.8 ind/m² at Station 3), and sensitive taxa (*Sipunculus* sp.), reflecting stable oceanic conditions.

Critically, water quality parameters showed high similarity between riverine stations 1 and 6 (>80%; **Fig. 10b**), despite stark biotic dissimilarity. This decoupling underscores macrozoobenthos' superior sensitivity as bioindicators: they integrate cumulative stressors invisible to snapshot physicochemical measurements [13]. Clay-rich substrates positively correlated with taxonomic richness across all zones [26], a pattern consistent with Indonesian estuarine studies [32]. These findings affirm macrozoobenthos as essential sentinels for detecting chronic pollution in tropical coastal ecosystems.

5 Conclusion

Macrozoobenthic communities in Bojonegara coastal waters exhibit distinct structuring along a riverine-estuarine-marine continuum. Seventy-seven genera from six phyla were recorded, dominated by Gastropoda (37 genera), Bivalvia (18), and Polychaeta (12). Riverine stations displayed low diversity and dominance by pollution-tolerant taxa under chronic anthropogenic stress; estuarine stations showed intermediate richness with euryhaline assemblages adapted to fluctuating salinity; and marine stations harbored the highest taxonomic diversity, including sensitive indicators such as *Sipunculus* sp. Clay-rich substrates emerged as a fundamental driver of distribution across all zones, while seasonal dynamics modulated community composition—rainy season conditions induced community simplification (low H' , high C), whereas dry season stability promoted recovery. Critically, the decoupling between physicochemical similarity and biotic dissimilarity at riverine stations underscores the superior sensitivity of macrozoobenthos as bioindicators: they integrate cumulative environmental stressors more effectively than snapshot physicochemical measurements. These findings affirm macrozoobenthos as indispensable tools for robust ecological assessment of tropical coastal ecosystems under industrial pressure.

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