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Spatiotemporal distribution of benthic communities in Belawan Estuary, Indonesia

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Abstract. *Muhtadi A, Leidonald R, Fadhilah A, Simanjuntak F, Begum S. 2025. Spatiotemporal distribution of benthic communities in Belawan Estuary, Indonesia. Biodiversitas 26: 5556-5566.* The Belawan River predominantly influences the hydrodynamics of the Belawan Estuary, Indonesia, and the tidal currents from the Strait of Malacca are a dynamic ecosystem with high ecological variability. This study examined the spatiotemporal variations in the macro-benthic community structure in the Belawan Estuary in October 2023, North Sumatra Province, Indonesia. Benthic samples were collected from eight points representing the upstream, middle, and downstream areas of the estuary, using an Ekman grab during high and low tides, with three replicates each. Sampling and water quality measurements were conducted four times in accordance with the tidal cycle: during the new moon, first quarter, full moon, and last quarter. Benthic community structure analysis, Principal Component Analysis (PCA) tests correlating water quality with benthic density and diversity, and the Kruskal-Wallis tests with Dunn's post hoc tests were conducted. A total of 36 species were identified, dominated by Mollusks. The polychaete *Nereis virens* was ubiquitous, while the highest densities were of invasive bivalves *Mytilopsis sallei* (average 133 individuals. m^{-2} ±159.76) and *Dreissena polymorpha* (average 199 individuals. m^{-2} ±525.51). Principal component analysis indicated that tidal dynamics explained more than 70% of community variation. These findings demonstrate that tides play a critical role in structuring benthic assemblages in the Belawan Estuary and provide essential baseline data for managing estuarine biodiversity under increasing anthropogenic pressure.

Keywords: Estuary, mollusks, tides, zoobenthos

INTRODUCTION

Estuaries are ecotonal areas that connect freshwater and marine ecosystems, characterized by distinct salinity gradients (Nybakken and Bertness 2005; Odum and Barrett 2005). Estuaries are highly dynamic ecotonal ecosystems due to the combined influences of river discharge, tidal movements, and marine waves (Kowalewska-Kalkowska and Marks 2016; Wolanski and Elliott 2016; Guo 2022). Estuaries are typically rich in organic matter as well as nutrients and among the most productive ecosystems, performing crucial ecological functions in coastal and marine environments (Basset et al. 2013; Pelage et al. 2021; Campbell et al. 2024). However, prolonged anthropogenic disturbances may strongly affect these dynamic and delicate estuarine environments. Many species and ecological systems have evolved in response to such disturbances, forming patches of altered habitats that play key roles in regulating life cycles, food availability, nutrient supply, and habitat accessibility (Kroeker et al. 2020). Consequently, the community structures in such ecosystems, particularly those of benthic communities, spatially and temporally vary (Jia et al. 2022; Zainee and Rozaimi 2022; Zamprogno et al. 2023).

The Belawan Estuary is located in North Sumatra, Indonesia and is strategically important for the northern trade route of Medan City. The Belawan Estuary forms the main maritime transportation corridor in western Indonesia. The estuary functions as an industrial center for Medan, including a harbor (Government of North Sumatra Province 2019; Medan City Government 2022). Furthermore, the estuary supports local fisheries and is heavily used by the surrounding community. The intense human activities in and around the Belawan Estuary have placed considerable ecological pressure and threatened the integrity of the habitats in the area. The water in the area is polluted by organic contaminants (Muhtadi et al. 2025a), heavy metals (Sulistyowati et al. 2023), microplastics (Muhtadi et al. 2025b), sediments (Leidonald et al. 2024a), and aquatic organisms (Muhtadi et al. 2025d). The estuarine hydrodynamics of the Belawan Estuary are primarily governed by the Belawan River and tidal currents from the Strait of Malacca (Tarigan et al. 2017; Muhtadi et al. 2020b), creating a secondary frontal zone (Tarigan et al. 2017). These secondary fronts further impact estuarine and marine ecosystems by increasing the deposition of organic matter and detritus to the benthic layer through the biological pump mechanism, affecting the macrobenthic community (Jia et al. 2022; Siegel et al. 2023).

Macrobenthos are key components of estuarine ecosystems. Macrobenthos play crucial roles in material cycling and energy flow within the food web (Dias et al. 2023) because of their limited mobility, relatively long lifespan, and sensitivity to environmental changes (Jia et al.

2022; Zainee and Rozaimi 2022; Zamprogno et al. 2023). Accordingly, benthic communities must be studied for monitoring environmental changes driven by climatic variability and/or anthropogenic stress (Azovsky and Kokarev 2019; Zainee and Rozaimi 2022). Changes in parameters such as salinity, sediment quality, and turbidity directly affect the macrobenthic community structures in estuaries (Jia et al. 2022).

Extensive research on benthic communities has been undertaken in various Indonesian estuaries, including Porong (Purnomo et al. 2018), Segara Anakan (Rimadiyani et al. 2019), Krueng Cut (Irham et al. 2020), Bulak Setra (Krisnafi et al. 2021), Cimandiri (Ibrahim et al. 2023), Demak (Hartati et al. 2024), Kungkai Baru (Nofridiansyah et al. 2025), and Anak Laut Lake (Muhtadi et al. 2025c), as well as in several Southeast Asian estuaries such as Pahang (Mohammad and Jalal 2018), Merchang, and Pulau Indah in Malaysia (Wan-Hussin and Ab-Lah 2020), and the Kundalika Estuary in India (Dias et al. 2022). Despite this breadth of work, the majority of studies have primarily concentrated on environmental parameters and water quality, with minimal attention to tidal dynamics. Considering that tidal fluctuations play a fundamental role in shaping the distribution, abundance, and population structure of benthic organisms, future estuarine benthos research must integrate both water quality and tidal influences to provide a more comprehensive understanding of benthic community dynamics.

Studies on the benthic communities in the Belawan Estuary are scarce. Only seven benthic species across two sampling sites have been reported in this area (Harahap et al. 2023). Researchers have not examined the spatial distribution of benthic species across the estuarine area or the influence of tidal cycles on the benthic communities. As such, we assessed the spatiotemporal variations in the macrobenthic community structure in the Belawan Estuary. We hypothesized that variations in salinity and sediment influence the composition of macrobenthic communities, whereas tidal cycles affect their distribution. We conducted a benthic survey in 2023 to test this hypothesis, covering representative zones from the estuary mouth as well as middle and upstream areas during four tidal phases: the new moon, first quarter, full moon, and last quarter. Therefore, this study aims to assess spatiotemporal variation in benthic communities and relate variation to environmental factors. The results provide scientific evidence of the influence of tidal phases on estuarine biotic communities, particularly benthic organisms.

MATERIALS AND METHODS

Study area

The sampling was conducted in October 2023 in the Belawan Estuary, North Sumatra Province, Indonesia (Figure 1). The Belawan Estuary serves as the main seaport in western Indonesia and functions as an industrial hub and traditional fishing ground for local communities. The area and its surroundings are polluted with organic matter, heavy metals, and microplastics (Sulistyowati et al. 2023; Leidonald et al. 2024a; Muhtadi et al. 2025a, b, d).

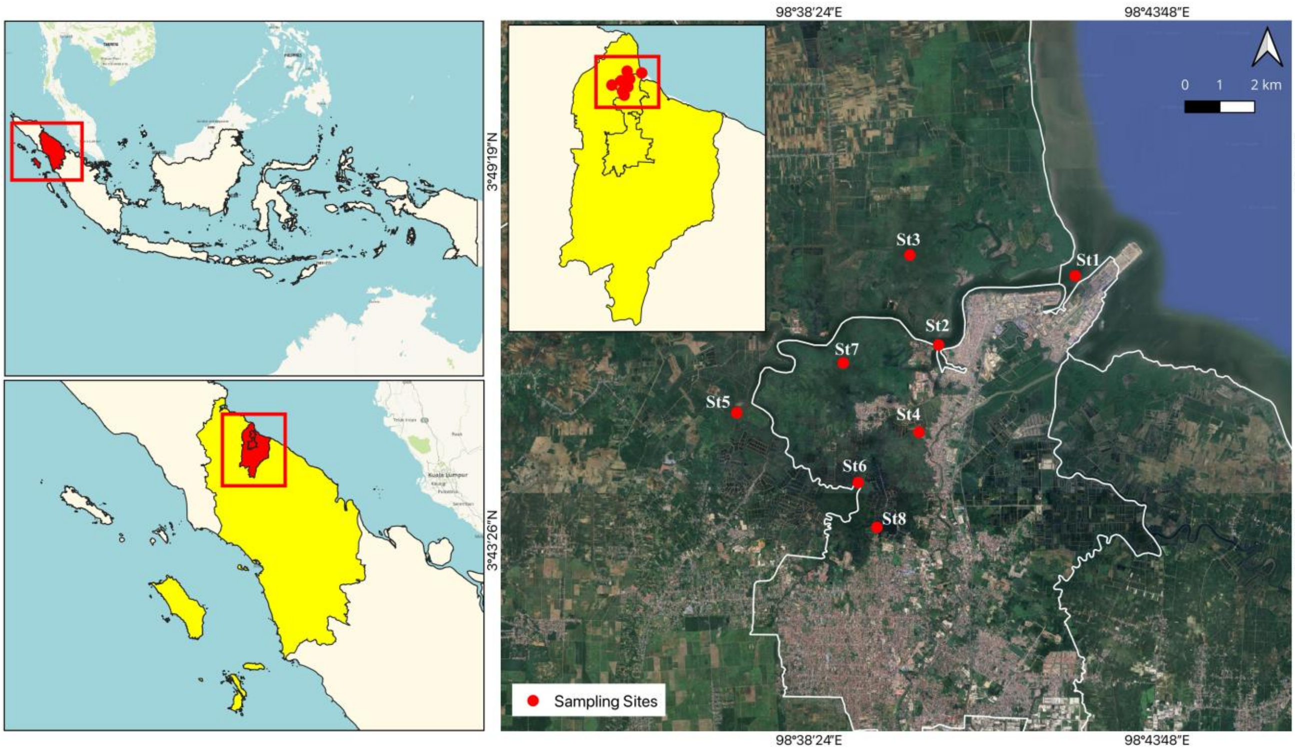

Figure 1. Map of sampling locations: St1 (Station 1: 3°47'33.06"N, 98°42'32.07"E), St2 (Station 2: 3°46'28.74"N, 98°40'24.86"E), St3 (Station 3: 3°47'52.42"N, 98°39'58.10"E), St4 (Station 4: 3°45'7.32"N, 98°40'6.61"E), St5 (Station 5: 3°46'11.82"N, 98°38'56.07"E), St6 (Station 6: 3°45'25.49"N 98°37'17.01"E), St7 (Station 7: 3°44'20.42"N, 98°39'9.98"E); St8 (Station 8: 3°43'38.68"N, 98°39'27.44"E)

Procedures

Sampling of macrozoobenthic

Benthic samples were collected from eight stations representing the upstream, middle, and downstream areas of the estuary using an Ekman grab during high and low tide, with three replicates per tidal condition at each station. The Ekman grab used measured 30x30 cm. Benthic sampling and water quality measurements were performed four times, corresponding to the cyclic tidal phases: new moon, first quarter, full moon, and last quarter. The captured benthic organisms were preserved in 5% formalin until fully submerged. Species were identified following standard taxonomic keys (Carpenter and Niemm 1998; Darma 2009). Invasive specialized mussels such as *Mytilopsis sallei* and *D. polymorpha* were identified by Rosenberg and Ludyanskiy (1994) and Marelli (2021).

Sampling of water quality

The temperature, water transparency, depth, water level, current velocity, salinity, pH, and Dissolved Oxygen (DO) content were measured. Sediment characteristics, including sediment fractions and organic matter content, were also assessed. Water quality measurements and tests were conducted in accordance with the established water quality standards (APHA 2017).

Data analysis

Data analysis was descriptive, with all statistical analyses conducted using PAST version 5.2 (Hammer 2025). Several indices were calculated to assess the benthic community structure, including the Shannon-Wiener diversity index (H'), Pielou's evenness index (J), dominance index (C), and species richness. Principal Component Analysis (PCA) was used to visualize the relationships between the environmental variables with benthic density and diversity. The Kruskal-Wallis tests with Dunn's post hoc tests were employed to compare the macrobenthic abundance and diversity across the sampling locations and tidal phases.

RESULTS AND DISCUSSION

Environmental conditions

The waters of the Belawan Estuary are highly spatiotemporally dynamic. Salinity is a parameter that fluctuates daily and seasonally in estuaries. The salinity was lower at the upstream stations (Stations 6-8) than at the seaward stations (Stations 2-3) (Tables 1-2) owing to the weakening influence of the tidal currents farther inland. Salinity was lower during the spring tide than during the neap tide phase (Table 4). This pattern reflects the larger water mass movement during spring tides, which pushed seawater further into the estuary. Spring tides transport large water masses to the coastal lake at Station 8, intensifying daily and seasonal water dynamics (Muhtadi et al. 2020a). These tidal dynamics influence water quality (Muhtadi et al. 2023, 2025a, b; Leidonald et al. 2024b), as well as aquatic organisms (Muhtadi et al. 2020a; Muhtadi and Leidonald 2024; Muhtadi et al. 2025c).

The results of the substrate texture analysis indicated that the substrate at Stations 1-4 primarily consisted of loam, whereas that at Stations 5 and 8 was characterized as sandy loam; Stations 6 and 7 featured sandy clay loam (Table 3). *Dreissena polymorpha* and *M. sallei* were among the most frequently encountered benthic species and were abundant at Station 6, likely due to the preference of these species for sandy or muddy sand habitats near mangrove areas. Station 8 had the highest sand fraction (76%), resulting in relatively low organic carbon content (Table 3). Although the mussel *D. polymorpha* is known to live in fresh water, it can survive at salinities up to 5 ppt (Karatayev and Burlakova 2022; McGarrity and McMahon 2024), where in the Belawan Estuary it was found at locations with low salinity (Stations 6 and 8) (Table 1-2).

Species composition, abundance, and biodiversity

A total of 36 macrobenthic species were identified in the Belawan Estuary: 14, 16, and 3 species of bivalves, gastropods, and malacostracans, respectively, and 1 species each from the Lingulata, Ophiuroidea, and Polychaeta (Table 5). The polychaete *Nereis virens* was found at all observation stations with a total density of 1215 ind/m^2 (19%) (Table 5). The marine worm (*N. virens*) is a sediment feeder that consumes organic matter. This worm can live in various habitat types, such as sandy and muddy sediments, and is widespread in estuarine waters (Herwati et al. 2021; Windarto et al. 2023). Another species with the widest distribution is *Nassarius reeveanus*, which is a snail species that is widely distributed in the sea and estuaries. Therefore, this marine worm is widespread and found at all observation stations in the Belawan Estuary. However, the highest and most dominant benthos abundances were *M. sallei* and *D. polymorpha*. The total density of the two species reached 2655 ind/m^2 or 41.53% of the total population (Table 5). Mollusks were the dominant macrobenthos in the estuary, accounting for 31 of the 38 species recorded. Mollusks play key ecological roles in aquatic food web dynamics, particularly in detritus decomposition and organic matter mineralization, especially among herbivorous deposit feeders. Mollusks participate in the breakdown of the leaf litter into smaller particles, facilitating further decomposition by microorganisms. Notably, two invasive bivalve species originating from Latin America, *D. polymorpha* and *M. sallei*, were identified. *M. sallei* was previously dominant in Lake Siombak (Station 8) (Muhtadi et al. 2024b). Species richness was the highest and lowest at Stations 1 and 7, respectively (Table 5). Species richness was higher in areas closer to the sea at the stations near the estuary mouth, declining towards the inland zones (Table 5).

The macrobenthic density was highest and lowest at Stations 7 and 8, respectively, average of 151 and 17 individuals per square meter, respectively (Figure 2.A). Much higher densities were previously reported at Lake Siombak (Station 8), ranging from 463 to 5,785 individuals per square meter (Yulianda et al. 2020). The high density observed at Station 7 was due to the mangrove branches retrieved with the Ekman grab, which hosted many *D. polymorpha* individuals. Similar to *M. sallei*, this bivalve species readily adheres to various natural and artificial submerged substrates such as rocks, submerged wood, ship hulls, buoys, piers, intake pipes, and even plastics (Rodrigues et al. 2022; Muhtadi et al. 2024b).

The macrobenthic density significantly differed amongst the stations ($p<0.05$). The macrobenthic densities were generally higher during the neap tide than during the spring tide (Figure 2.B). The mean density was highest during the last quarter, at 123 individuals per square meter. The results of the post hoc Dunn's test revealed that the macrobenthic density only significantly differed between the full moon and last quarter ($p<0.005$).

Table 1. Spatial variations in water quality during high tide in Belawan Estuary, Indonesia

Parameter	Unit	Quality standard*	Sampling location							
			St1	St2	St3	St4	St5	St6	St7	St8
Temperature	(°C)	±3	30	30.3	30	30.8	29.4	29.2	31	31.7
Transparency	(cm)	-	53.5	39.6	39.1	61.4	37.9	26.3	29.1	50
Depth	(m)	-	2.6	2.6	3.5	2	2.2	2.4	2.2	2.1
Current	(cm/s)	-	8.2	6.2	13.8	12.5	11	14.1	15.1	7.1
Salinity	(‰)	Natural	17	11.5	14	15	10.5	0	3	1
pH		6.5-8	7.6	7.4	7.5	6.1	7.6	7.8	7.5	7.9
DO	(mg/L)	4	6.4	7.5	6.6	4.6	5.3	6.3	5.4	5.8

Note: *: Source based on Government of Republic of Indonesia (2021)

Table 2. Spatial variation in water quality during low tide in Belawan Estuary, Indonesia

Parameter	Unit	Quality standard*	Sampling location							
			St1	St2	St3	St4	St5	St6	St7	St8
Temperature	(°C)	±3	30.1	30.6	29.6	30.6	29.7	29.4	30.6	32
Transparency	(cm)	-	55	35.6	40	59.8	35	25.3	26.5	37.5
Depth	(m)	-	1.1	1	1.1	1.1	1	1.8	0.9	0.9
Current	(cm/s)	-	5.9	9.3	5.8	6.7	10.3	10.5	13.2	15.8
Salinity	(‰)	Natural	14.5	11.5	9.5	15	10	1.5	2	1.5
pH		6.5-8	7.55	7.55	7.45	7.125	7.175	7.425	7.425	7.8
DO	(mg/L)	4	6.2	7.3	6.7	4.3	6.1	5.5	5.4	5.8

Note: *: Source based on Government of Republic of Indonesia (2021)

Table 3. Substrate texture and organic C in the Belawan Estuary, Indonesia

Parameter	Satuan	Sampling location							
		St1	St2	St3	St4	St5	St6	St7	St8
Sand	%	46	50	48	48	54	48	60	76
Dust	%	46	40	44	44	28	22	20	6
Clay	%	8	10	8	8	18	30	20	16
Texture	-	Clay	Clay	Clay	Clay	Sandy loam	Sandy clay loam	Sandy clay loam	Sandy loam
C-organic	%	2.44	3.84	4.33	2.86	1.71	2.93	5.30	3.72

Table 4. Temporal variation in water quality in Belawan Estuary, Indonesia

Parameter	Quality standard*	Sampling time							
		Full moon		Last quarter		New moon		First quarter	
		High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide
Temperature (°C)	±3	31.3	31.4	30.2	30.3	30.3	30.2	29.5	29.3
Transparency (cm)	-	27.4	35.2	64.4	49.4	31.4	29.6	41.9	43.1
Water level (m)	-	3.5	1.1	2.0	1.1	2.5	0.9	1.9	1.2
Current (cm/s)	-	6.7	8.6	10.7	7.8	11.7	11.6	13.3	8.6
Salinity (‰)	Natural	12.0	12.4	4.4	3.8	11.0	10.0	8.5	7.0
pH	6.5-8	7.8	7.7	7.4	7.4	7.4	7.3	7. 6	7.3
DO (mg/L)	4	5.9	5.7	5.2	4.7	6.6	6.6	6.3	6.3

Note: *: Source based on Government of Republic of Indonesia (2021)

Table 5. Abundance of macrozoobenthos in the Belawan Estuary (Ind/m^2)

Family	Species	Location								Total	Percentage (%)
		St1	St2	St3	St4	St5	St6	St7	St8		
Tellinidae	*Tellina tenuis*	66	-	-	-	-	-	-	-	66	1.03
	Tellina palatum	-	-	-	-	11	-	-	-	11	0.17
Lucinidae	*Fimbria fimbriata*	22	11	-	-	-	-	-	-	33	0.52
Pharidae	*Phaxas pellucidus*	55	11	11	-	-	-	-	-	77	1.2
Solecurtidae	*Tagelus divisus*	-	-	-	-	11	333	412	11	767	12
Lasaidae	*Tellimya ferruginosa*	111	-	33	-	22	-	-	-	166	2.6
Mactridae	*Spisula solida*	33	-	-	-	-	-	-	-	33	0.52
Solenidae	*Solen lamarckii*	-	33	-	-	-	-	-	-	33	0.52
Cardiidae	*Fragum unedo*	-	11	-	-	-	-	-	-	11	0.17
Arcidae	*Anadara inaequivalvis*	-	-	-	33	-	-	-	-	33	0.52
Cuspidariidae	*Cuspidaria cuspidata*	11	-	-	-	-	-	-	-	11	0.17
Corbulidae	*Corbula faba hinds*	-	-	11	-	11	77	-	-	99	1.55
Dreissenidae	*Dreissena polymorpha*	-	-	-	-	-	1289	211	89	1589	24.9
	Mytilopsis sallei	-	-	-	-	-	433	578	55	1066	16.7
Ampullariidae	*Pomacea canaliculata*	-	-	-	-	-	-	-	11	11	0.17
Naticidae	*Natica tigrine*	-	-	11	-	-	-	-	-	11	0.17
Turritellidae	*Turritella banksii*	11	-	-	-	-	-	-	-	11	0.17
Muricidae	*Murex occa*	-	11	-	-	-	-	-	-	11	0.17
	Chicoreus capucinus	-	-	-	22	-	-	-	-	22	0.34
Fissurellidae	*Scutus unguis*	11	-	-	-	-	-	-	-	11	0.17
Pseudomelatomidae	*Crassispira harpularia*	-	-	-	-	-	22	-	-	22	0.34
Littorinidae	*Littorina scabra*	-	-	-	-	11	33	-	22	66	1.03
Nassariidae	*Nassarius reeveanus*	11	33	11	11	33	-	-	-	99	1.55
Clavatulidae	*Pusionella vulpina*	11	-	-	-	-	-	-	-	11	0.17
Neritidae	*Neritina puligera*	-	-	-	-	-	-	11	-	11	0.17
	Nerita planospira	-	-	11	-	-	-	-	-	11	0.17
	Nerita exuvia	11	11	22	-	-	-	-	-	44	0.69
Dyakiidae	*Asperitas trochus*	-	-	-	11	-	44	-	-	55	0.86
Veronicellidae	*Leidyula floridana*	-	-	-	33	-		-	-	33	0.52
Naticidae	*Notocochlis tigrina*	-	-	11	-	-	-	-	-	11	0.17
Varunidae	*Varuna litterata*	122	89	89	289	33	22	-	-	644	10.1
Decapoda	*Pagurus longicarpus*	-	-	-	11	-	-	-	-	11	0.17
	Clibanarius erythoropus	-	22	11	22	-	-	-	-	55	0.86
Lingulidae	*Lingula anatina*	11	-	-	-	-	-	-	-	11	0.17
Amphiuridae	*Amphipholis squamata*	11	-	-	-	11	-	-	-	22	0.34
Nereidae	*Nereis virens*	222	166	77	256	244	195	44	11	1215	19
Total No. of Species		15	10	11	9	8	10	5	6	74	1.16
Total abundance		719	398	298	688	354	2481	1256	199	6393	100

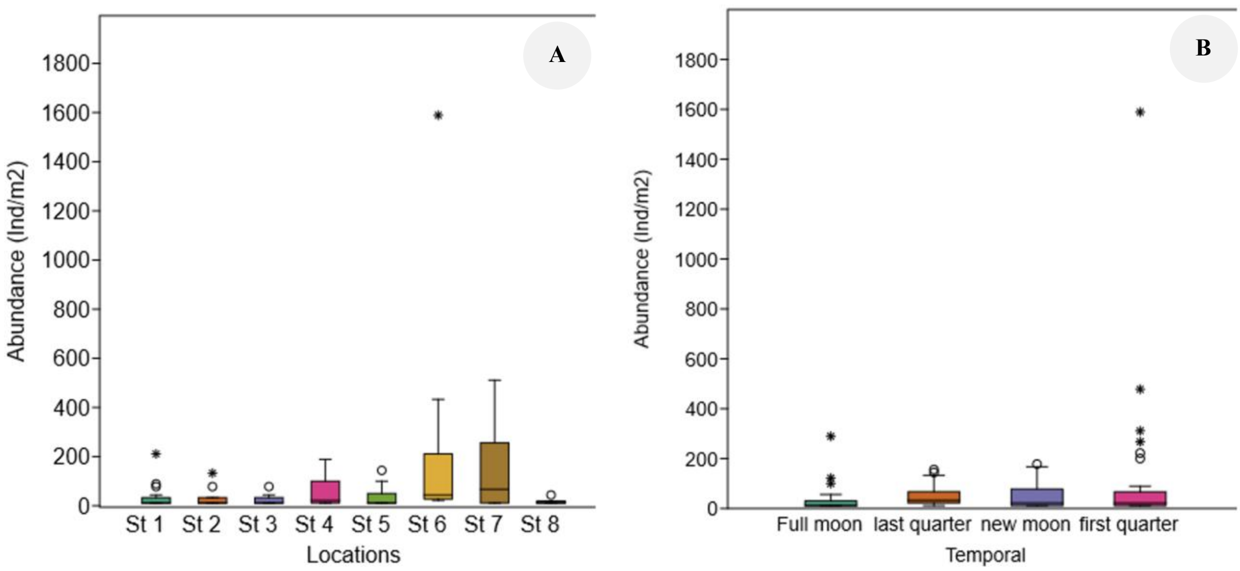

Figure 2. Spatial (A) and temporal (B) variations in macrobenthic density in Belawan Estuary, Indonesia. Ind: individuals

Benthic community structure

The H' of the benthic communities in the Belawan Estuary ranged from 1.18 to 2.14 (Table 6). The highest and lowest diversities were recorded at Stations 1 (H': 2.14) and 7 (H': 1.18), respectively. The benthic diversity was generally higher in the front section of the estuary (Stations 1-3) than in the inland areas (Stations 6-8). In contrast, the benthic abundance was higher inland section than near the estuary mouth. The J value ranged from 0.57 to 0.83, indicating that the benthic organisms in the estuary were relatively evenly distributed, with the exception of Station 6. This was supported by the dominance index, with low values ranging from 0.17 to 0.497, suggesting that no single species strongly dominated the benthic community. The benthic dominance was higher inland (stations 6-8) than at the seaward stations (Stations 1-3).

The H' temporally ranged from 1.63 to 2.19 (Table 7). The H' was higher during the spring tide phases (full and new moon) than during the neap tide phases (first and last quarter). The J values in the Belawan Estuary were relatively high, ranging from 0.541 to 0.86. The J ranged from 0.54 to 0.86, with the highest and lowest values recorded during the last (0.86) and first (0.54) quarters, respectively. The Dominance_D values were low, ranging from 0.18 to 0.32 in the new moon and first quarter, respectively, indicating low dominance. Statistical tests of the community index showed no significant differences either by region or time ($p>0.05$). The benthic diversity in the Belawan Estuary was higher than that reported in many other Indonesian estuaries, despite the presence of these invasive species, with H' values exceeding two. The H' values were generally below two in the Bengawan Solo Estuary (Fu'adah et al. 2025) and in the Segara Anakan Lagoon (Rimadiyani et al. 2019). The H' values in the Krueng Cut Estuary were below one (Irham et al. 2020), as were those in the Musi River Estuary (Rozirwan et al. 2021).

Relationship between tides and benthic communities

The spatial variance in the benthic abundance was significantly influenced during high tide by environmental parameters such as depth, current velocity, salinity, pH, DO, and bottom substrate, which accounted for 60.77% of the total variation (Figure 3). Environmental variables more strongly affected the spatial variation in benthic abundance and diversity during low tide, explaining 70.72% of the total variation (Figure 4). The results of PCA revealed that the association between benthic abundance and high tide was high at Station 6. The ordination plots demonstrated spatial grouping among the stations: Stations 1-3 (seaward section), Stations 4 and 5 (middle section), and Stations 6-8 (inland section), for high and low tides. The results of the statistical tests confirmed that the current velocity, pH, DO, and substrate type were significantly associated with benthic density and diversity in the Belawan Estuary ($p<0.05$).

The tidal phases in the Belawan Estuary exhibited strong temporal relationships with the environmental parameters. Water level, salinity, pH, and DO strongly correlate (>0.8) with benthic abundance, as reflected in the biplot, which explained 94.58% and 74.61% of the temporal variance during high (Figure 5) and low (Figure 6) tide, respectively. The results of statistical analyses confirmed that the water level, salinity, pH, and DO significantly affect benthic density ($p<0.05$), whereas temperature and water transparency significantly influence benthic diversity ($p<0.05$). These results support the hypothesis that tidal fluctuations, particularly changes in water level and salinity, directly affected the structure and distribution of the benthic communities in the Belawan Estuary. The water depth was identified as a critical estuarine parameter, reflecting tidal dynamics and their impact on water quality and biotic components in estuaries. The hydrological characteristics of the estuarine waters temporally differed with the lunar phase and thus the tide (Figures 5 and 6).

Discussion

Seven species of bivalve have been previously reported in the Belawan Estuary (Harahap et al. 2023), but the examination did not include the entire macroinvertebrate community. We identified 15 bivalve species. This difference is likely due to the differences in the study scope and sampling intensity. The prior study solely focused on bivalves at fewer observation sites with only one sampling. In contrast, we covered a larger area and applied a tidal-phase-based sampling regime. Benthic organisms are generally sessile but can slowly move and may shift positions or emerge from sediment layers, especially bivalves that tend to burrow into muddy substrates. Overall, the macrobenthic biodiversity in the Belawan Estuary was higher than that in other Indonesian estuaries. For example, the Segara Anakan Estuary hosted 33 genera, dominated by malacostracans (Rimadiyani et al. 2019), whereas 18 macrobenthic species were found in the Musi River Estuary (Rozirwan et al. 2021). A total of 21 species were recorded in the Bengawan Solo Estuary, with bivalves being dominant (Fu'adah et al. 2025). Seven species were reported in the Krueng Cut Estuary in Banda Aceh (Irham et al. 2020).

We identified two invasive benthic species, *D. polymorpha* and *M. sallei*, originating from Latin America (Muhtadi et al. 2024b) and now widespread across the Indo-Pacific (Tan and Morton 2006; Cai et al. 2014; Tan and Tay 2018; Lutaenko et al. 2019). Invasive species, often introduced through ballast water and hull biofouling, have become increasingly common in aquatic ecosystems due to maritime transport, which has removed geographic and ecological barriers to species dispersal (Fernandes et al. 2018; Neto et al. 2020; Pyšek et al. 2020). These processes have enhanced biological invasions in harbours and estuaries, particularly by species with broad environmental tolerances and rapid growth rates (Wangkulangkul 2017; Queiroz et al. 2020; Klangnurak et al. 2022). Consequently, invasive bivalves such as *M. sallei* and *D. polymorpha* have significantly altered native community structures and ecosystem functioning in coastal systems (Tan and Tay 2018; Magni et al. 2019; Rodrigues et al. 2022).

Table 6. Spatial variation in benthic community indices in Belawan Estuary, Indonesia

Community index	Location							
	St1	St2	St3	St4	St5	St6	St7	St8
Dominance_D	0.17	0.24	0.18	0.32	0.49	0.32	0.34	0.29
Simpson_1-D	0.83	0.75	0.81	0.68	0.50	0.67	0.65	0.70
Shannon_H'	2.14	1.78	2.02	1.45	1.20	1.49	1.18	1.45
Evenness_e^H/S	0.57	0.59	0.68	0.47	0.41	0.44	0.65	0.71
Brillouin	2.03	1.71	1.92	1.41	1.14	1.48	1.172	1.38
Menhinick	0.53	0.50	0.63	0.34	0.42	0.20	0.14	0.42
Margalef	1.98	1.50	1.75	1.22	1.19	1.15	0.56	0.94
Equitability_J	0.78	0.76	0.83	0.65	0.57	0.64	0.73	0.80

Table 7. Temporal variation in benthic community indices in Belawan Estuary, Indonesia

Community index	Lunar phase			
	Full moon	Last quarter	New moon	First quarter
Taxa_S	17	9	17	20
Individuals (total)	742	511	865	3065
Dominance_D	0.22	0.18	0.15	0.32
Simpson_1-D	0.78	0.82	0.84	0.68
Shannon_H'	2.05	1.91	2.19	1.63
Evenness_e^H/S	0.46	0.75	0.53	0.25
Brillouin	1.99	1.86	2.14	1.61
Menhinick	0.62	0.39	0.57	0.36
Margalef	2.42	1.28	2.36	2.36
Equitability_J	0.72	0.86	0.77	0.54

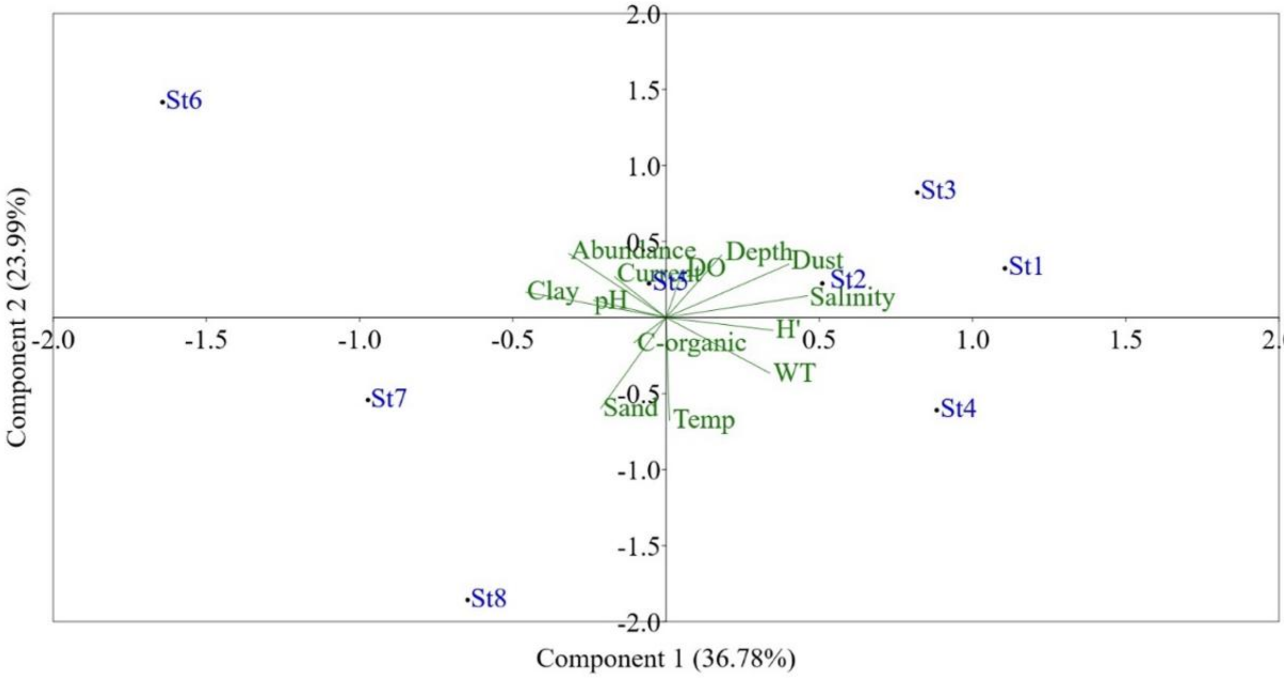

Figure 3. Results of Principal Component Analysis (PCA) of water quality with spatial benthic abundance and diversity in Belawan Estuary during high tide

Spatially, benthic diversity in the Belawan Estuary is higher in the sea (H'>2) and lower inland (H'<2); in this case, benthic diversity shows the opposite pattern to benthic abundance (Figure 2). High benthic abundance does not necessarily equate to high diversity, especially when species distribution is uneven or dominance is high. These species are distributed more evenly in the estuary, resulting in a lower dominance index. In contrast, the inland part has uneven species abundance, dominated by certain species, namely *D. polymorpha* and *M. sallei*. A similar pattern was reported in the Musi River estuary (Fu'adah et al. 2025), where benthic H' is higher in the estuary than upstream. The opposite trend was observed in the Krueng Cut estuary (Irham et al. 2020). Temporally, macrobenthic diversity is highest during the spring tide phase (new moon and full moon) compared to the neap tide phase (first and last quarter). This indicates that tidal strength with more "abundant" water allows benthic organisms to "emerge" more than with less water. This is also in accordance with the results found by Muhtadi et al. (2025c) in coastal lakes of the Anak Laut, which showed a similar pattern where the spring tide phase showed a high diversity of benthic organisms compared to the neap tide. That shows that the influence of tides greatly affects the population of aquatic organisms, including benthos.

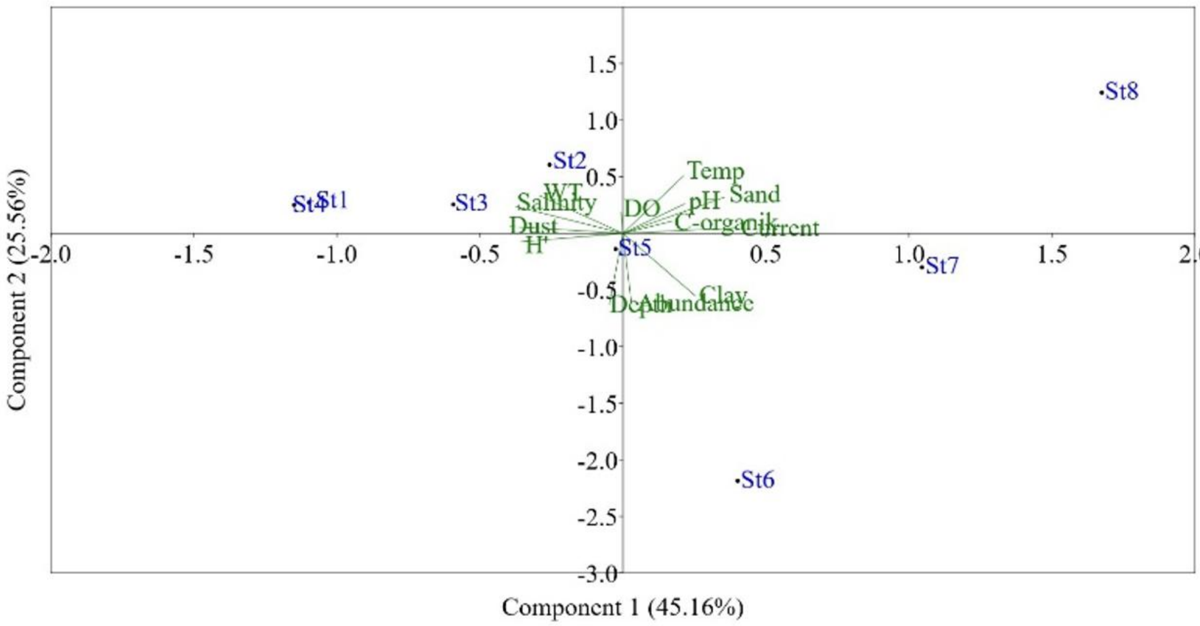

Figure 4. Results of PCA of water quality with spatial benthic abundance and diversity in Belawan Estuary, Indonesia, during low tide

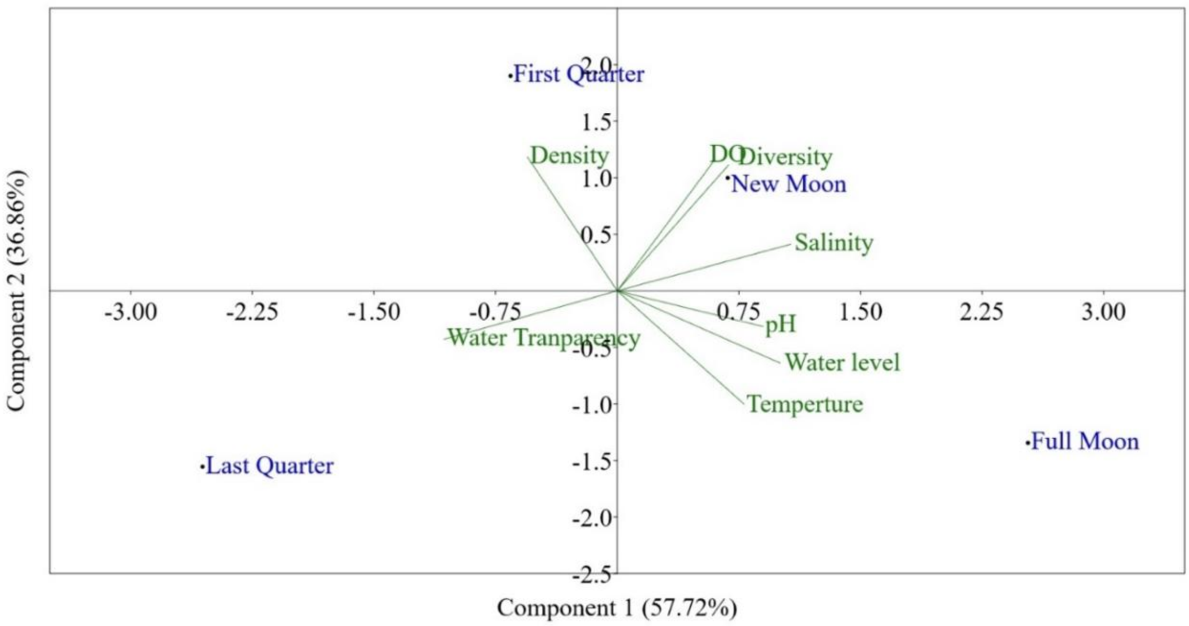

Figure 5. PCA results of temporal variation in water quality with benthic abundance and diversity in Belawan Estuary, Indonesia during high tide

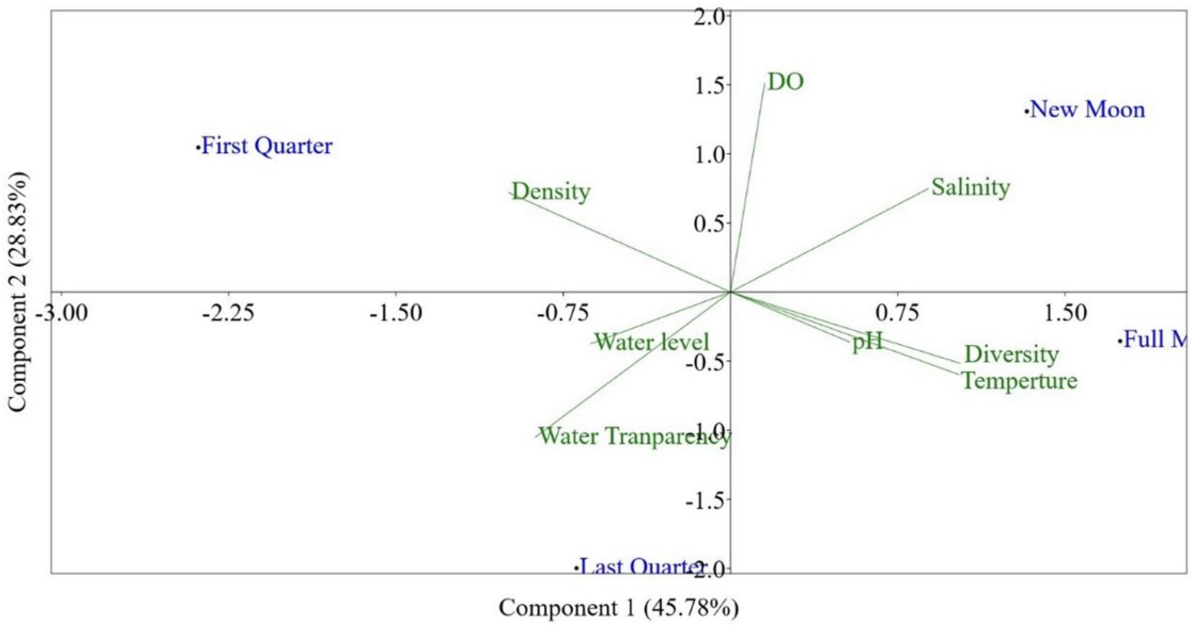

Figure 6. PCA results of temporal variation in water quality in relation to benthic abundance and diversity in Belawan Estuary during low tide

The benthic density in the Belawan Estuary was influenced by environmental parameters such as water depth, salinity, pH, and DO content. The benthic diversity was affected by water temperature and water transparency, with a 94.58% correlation. These environmental factors significantly influenced benthic density and diversity in the Belawan Estuary ($p<0.05$). The water depth and salinity were key indicators of the tidal influence on estuarine conditions (Muhtadi et al. 2020b; Leidonald et al. 2023), which strongly correlated with benthic abundance (r: -0.8) and diversity (r: 0.8) in the Belawan Estuary. Salinity plays a vital role in the distribution and presence of benthic organisms in estuarine environments, affecting the growth and spatial distribution of aquatic biota, being a key determinant of macrobenthic community patterns (Jia et al. 2022; Zainee and Rozaimi 2022; Zamprogno et al. 2023). Temperature was another environmental factor that strongly correlated with the benthic density and diversity. Environmental conditions directly affect the density and spatial distribution of organisms. High organism densities within an ecosystem typically indicate that the environment meets the requirements of the species. This, in turn, affects the availability of organic matter and influences biodiversity metrics, such as diversity, evenness, and dominance (Muhtadi and Leidonald 2024; Muhtadi et al. 2025c).

The results of the PCA indicated that the tidal regime in the Belawan Estuary strongly affected the structure of the benthic communities. Tidal movements transporting water masses into and out of the estuary strongly affected the water quality parameters, which affected the presence and abundance of the aquatic organisms. This observation is consistent with findings from other studies, which reported that tidal cycles altered water quality dynamics (Leidonald et al. 2024b; Muhtadi et al. 2024a; et al. 2025a) and changed the structure of the aquatic biotic communities (Muhtadi and Leidonald 2024; Muhtadi et al. 2025c), including benthic fauna (Jia et al. 2022; Zainee and Rozaimi 2022; Zamprogno et al. 2023; Muhtadi et al. 2025c).

In the future, efforts that need to be made are the need for monitoring, especially regarding the presence of alien species such as *M. sallei* and *D. polymorpha*, and their impact on the benthic community in the Belawan Estuary. Invasive species undermine native species coexistence by outcompeting, preying upon, or altering the habitats of indigenous taxa. The resulting loss in species richness and trait variety diminishes functional diversity, often leading to homogenized, less resilient ecosystems. In aquatic habitats such as those in Estuary Belawan, managing invasive populations and restoring ecological balance is essential to preserving ecosystem function and native biodiversity. This is considering that the population of Dreissenidae is very high compared to other benthic communities. Furthermore, additional studies are required on sedimentation and its effects on the benthic community in the Belawan Estuary. A key measure to maintain the Belawan Estuary ecosystem is re-establishing the protected status of mangrove forests that were downgraded for public and industrial purposes in the revised Medan city regulation on spatial planning.

The study revealed that tidal dynamics significantly influence the structure and distribution of benthic communities in the Belawan Estuary. Spatially, diversity was higher near the estuary mouth and lower inland, while abundance showed the opposite pattern. Temporally, benthic diversity increased during spring tides compared to neap tides. Environmental parameters such as salinity, water depth, pH, and dissolved oxygen were key factors shaping these patterns. However, this study was limited to a single sampling period and a restricted set of physicochemical parameters. Temporal variability across seasons and potential interactions with pollution sources were not fully addressed, which may constrain the generalization of the findings. Further research should focus on long-term monitoring of invasive species such as *M. sallei* and *D. polymorpha* to assess their ecological impact and population dynamics. Future work should also integrate sedimentation processes, nutrient fluxes, and functional diversity to better understand ecosystem resilience under anthropogenic pressures.

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