HAYATI
Journal of Biosciences
Vol. 33 No. 1, January 2026 114-128
DOI:10.4308/hjb.33.1.114-128
ISSN: 1978-3019
EISSN: 2086-4094

Research Article

Check for updates OPEN ACCESS

The Effect of Tides on Plankton Communities in the Belawan River Estuary, North Sumatra

Rusdi Leidonald[1*], Ahmad Muhtadi[1], Cici Maulidiah Harahap[1], Rizal Mukra[2], Mohd Yusoff Ishak[3], Qadar Hasani[4]

[1]*Department of Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan, 20155 Indonesia*
[2]*Biology Education Study Programme, Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Negeri Medan, Deli Serdang 20221, Indonesia*
[3]*Department of Environment, Faculty of Forestry and Environment, Universiti Putra Malaysia, Persiaran Tulang Daing, Serdang, Selangor 43400, Malaysia*
[4]*Department of Aquatic Resources, Faculty of Agriculture, Universitas Lampung, Bandar Lampung, Lampung 35145, Indonesia*

ARTICLE INFO

Article history:
Received April 23, 2025
Received in revised form August 3, 2025
Accepted September 29, 2025
Available Online October 13, 2025

KEYWORDS:
Estuary,
plankton,
tidal cycles,
Belawan,
Indonesia

ABSTRACT

The Belawan Estuary is a highly important economic and logistics hub in Sumatra, serving as the primary maritime transportation route in western Indonesia. This estuary is also utilized for multiple purposes, including industrial activity, residential areas, and fisheries. These activities inevitably influence water quality, which in turn affects the presence and population dynamics of plankton in the estuary. This study aimed to examine the spatial and temporal distribution of plankton communities in the Belawan Estuary. Observation points were selected from eight locations representing different activities and regions, including areas near the sea, the middle section, and areas close to land. Plankton samples were collected during high and low tides following the tidal cycle (new moon, first quarter, full moon, and last quarter). Principal component analysis was performed to determine the influence of tidal cycles on plankton composition and abundance in the estuary. A total of 64 plankton genera from 16 classes were identified in the estuary. spatially, the highest abundance was recorded in the mouth estuary during low tide. Temporally, the highest plankton abundance across stations was during the first quarter phase at low tide. These findings indicate that tidal cycles significantly influence plankton abundance in the Belawan Estuary. This phenomenon is attributed to the tidal currents that transport nutrients from the lower layers to the surface waters during both high and low tides. Changes in plankton abundance and species composition can serve as indicators of water fertility in this region and reflect the impacts of changes in environmental conditions.

1. Introduction

In tropical regions, estuaries represent unique and distinctive ecosystems, as they not only serve as the confluence of seawater and freshwater but also provide crucial habitats for mangrove growth and thus support coastal ecosystems (Nybakken and Bertness 2005; Rangkuti *et al.* 2017). Estuarine areas serve as important foraging habitats, nursery grounds, and spawning sites for a multitude of aquatic organisms (Abdul and Adekoya 2016; Rangkuti *et al.* 2017; Nugroho *et al.* 2019; Pelage *et al.* 2021; Woodland *et al.* 2022). Particularly, urban estuaries have historically been centres of civilisation, fostering the development of settlements, industries, ports, and trade routes. Additionally, estuaries often function as "receptacles" or "accumulation zones" for various types of waste, either directly or via riverine transport. Consequently, estuarine environments are highly vulnerable to pollution and degradation (Kowalewska-Kalkowska and Marks 2016).

Plankton play a crucial role in aquatic fauna, as they form the primary link in the food chain and serve as key organisms within marine ecosystems (Nybakken and

* Corresponding Author
E-mail Address: rusdi.leidonald@usu.ac.id

Bertness 2005; Buesa 2019). Furthermore, the presence of plankton in water bodies reflects the fertility of the water and can therefore indicate the level of productivity (Gocke *et al.* 2003; Zhao *et al.* 2016). The distribution of plankton in aquatic environments can also be used as an indicator of water quality, and their spatial distribution is highly significant in aquatic ecology (Afonina and Tashlykova 2018; Takarina *et al.* 2019; Muhtadi *et al.* 2020). This is due to the rapid response of plankton communities to environmental changes in aquatic ecosystems (Muhtadi *et al.* 2020; Hasani *et al.* 2022). Environmental changes in estuaries are significantly influenced by tidal rhythms and cycles, which affect the extent of seawater intrusion into rivers or land and influence the mixing of seawater and freshwater. These dynamics result in fluctuating water quality following tidal patterns. Therefore, understanding the impact of tidal cycles on aquatic environments and plankton communities is of great ecological importance.

The Belawan Estuary is an important economic and logistics hub in North Sumatra. As Belawan is located along the northern trade route of Medan, it serves as the primary maritime transportation corridor in western Indonesia. In addition to its role as a major container port and transportation hub, the Belawan Estuary is also an industrial centre as well as an area of dense residential settlements and fisheries (Perda 2019; 2022). The waters of the Belawan Estuary form part of the eastern coastal estuarine system of Sumatra, which is characterised by a distinctive and complex ecosystem with various habitat types (Thoha *et al.* 2022; Pane *et al.* 2023). This complex ecosystem is extensively utilised by both the government and local communities due to its exceptionally high productivity (Widiani *et al.* 2021); in particular, the nutrient-rich water supports a great abundance of plankton. The overall aim of this study was to examine the spatial distribution dynamics of plankton communities in the Belawan Estuary and assess the influence of tidal cycles on these plankton communities.

2. Materials and Methods

2.1. Time and Place of Study

The study was conducted in October 2023 in the Belawan Estuary, North Sumatra Province. Plankton and water quality sampling were carried out at eight sampling stations, and the sampling times coincided with the four lunar phases of the tidal cycle: full moon, first quarter, new moon, and last quarter (Figure 1). Plankton samples were collected during both high and low tides. Plankton identification was performed at the Water Quality Laboratory at Universitas Sumatera Utara.

2.2. Sampling Procedure

Horizontal sampling was conducted from a boat. A plankton net was secured to the stern of the boat, which was then operated for approximately 15 min at very low speed (1-1.5 km/h). After 15 min, the plankton net was retrieved, and the collected samples were transferred

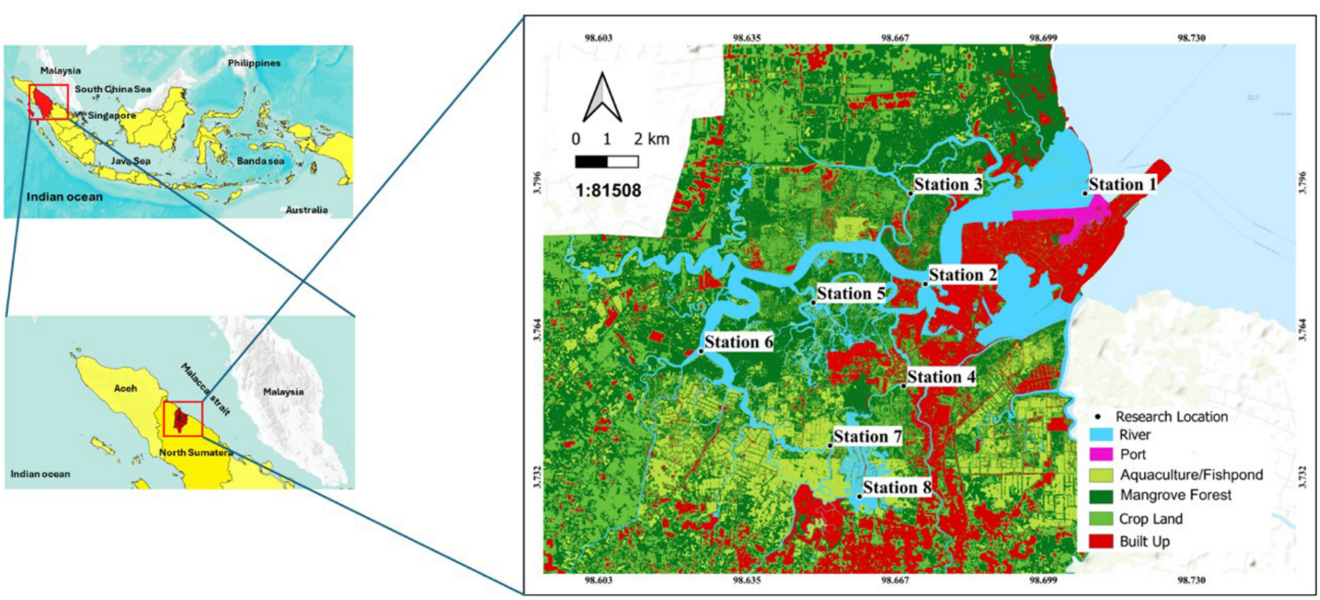

Figure 1. Map of the study location

into a sample bottle. The sample was preserved by adding 3-5 drops of Lugol's solution to maintain the plankton structure and integrity. Plankton samples were then analysed under a microscope and documented in the laboratory. Physical and chemical water quality parameters were measured both *in situ* and *ex-situ*. The in situ parameters included water transparency, current velocity, depth, temperature, pH, dissolved oxygen (DO), and salinity. The ex-situ parameters included the total suspended solids (TSS) and nitrate and phosphate concentrations.

2.3. Data Analysis

Plankton were identified using an Olympus CX33 binocular microscope at 100× magnification. A 50-mL sample was extracted and placed onto a Sedgewick Rafter counting chamber and covered with a cover glass. The plankton were subsequently identified, and their abundance was quantified. Abundance was calculated using the formula provided by APHA (2017):

$$K = n\frac{V_t}{V_{SRC}} \times \frac{A_{SRC}}{A_a} \times \frac{1}{V_d}$$

Where K is phytoplankton and diatoms: cells/L; zooplankton: ind/L; n, the number of observed organisms; V_d, total volume of water filtered through the plankton net (L); Vt, total volume of filtered water (mL); A, area of one microscope field of view (mm^2); V_{SRC}, volume of Sedgewick-Rafter chamber (1 mL); and A_{SRC} is the total area of the Sedgewick-Rafter chamber (1,000 mm^2).

The Shannon-Wiener diversity index (H') was calculated as follows (Krebs 2014):

$$H' = \sum_{n=1}^{i} \left(\frac{n_i}{N}\right) \times \text{Ln}\left(\frac{n_i}{N}\right)$$

Where ni is the number of individuals of species i and N is the total number of individuals of all species.

The evenness index (E) was calculated as follows (Krebs 2014):

$$E = \frac{H'}{\text{Ln}_s}$$

Where H' is the diversity index (calculated as shown above) and S is the total number of species. The evenness index ranges from 0 to 1. If the obtained E value is smaller than or approaches 0, it indicates lower population evenness, meaning that the number of individuals of each species is not equal. Conversely, a larger E value, or one approaching 1, indicates greater population evenness, signifying that the number of individuals in each species was approximately the same.

The dominance index (C) was calculated as follows (Odum and Barrett 2005):

$$C = \sum_{n=1}^{i} \left(\frac{n_i}{N}\right)$$

Where C is the dominance index, ni is the number of individuals of species i, and N is the total number of individuals of all species.

The dominance index ranges from 0 to 1. A value approaching 0 indicates that no individual species dominated the community. Conversely, a value approaching 1 indicates the presence of a dominant species.

The saprobic index (X) was calculated as follows (Mason 1991):

$$K = \frac{C + 3 - B - 3A}{A + B - C - D}$$

Incorporating the number of species of Cyanophyta (A), Euglenophyta (B), Chrysophyta (C), and Chlorophyta (D).

3. Results

3.1. Composition of Plankton Species

Phytoplankton, including algae, diatoms, and protists, found in the Belawan Estuary included 64 species representing 16 classes (Table 1).. Of the 64 species, 60 were identified and grouped into seven classes: Bacillariophyceae, Chlorophyceae, Conjugatophyceae, Coscinodiscophyceae, Cyanophyceae, Dinophyceae, Euglenoidea, Mediophyceae, and Prymnesiophyceae. Three of the classes (Conjugatophyceae, Mediophyceae, and Prymnesiophyceae are represented by a single species. The most abundant species were from the phytoplankton class Bacillariophyceae, which consisted of 23 species. In addition, 14 species of zooplankton were identified and classified into six classes—Chromadorea, Clitellata, Crustacea, Eurotatoria, Oligohymenophorea, and Spirotrichea—and the subphylum Foraminifera (treated here on the same level as a class for comparative purposes).

Table 1. List of plankton found in the Belawan Estuary

Class/genus	Species	Abundance (ind/L)			
		High tide	Low tide	Total	Percentage
Phytoplankton					
Bacillariophyceae					
Asterionella	*Asterionella sp.*	41	68	109	0.24
Aulacoseira	*Aulacoseira granulata*	1	0	1	0.00
Bacillaria	*Bacillaria sp.*	22	13	35	0.08
Bacteriastrum	*Bacteriastrum sp.*	6	9	15	0.03
Biddulphia	*Biddulphia sp.*	6	0	6	0.01
Biddulphia	*Biddulphia sinensis*	0	1	1	0.00
Chaetoceros	*Chaetoceros sp.*	236	692	928	2.06
Cymbella	*Cymbella sp.*	2	3	5	0.01
Eucampia	*Eucampia zodiacus*	1	1	2	0.00
Flagilaria	*Flagilaria sp.*	11	37	48	0.11
Isthmia	*Isthmia sp.*	12	10	22	0.05
Mostogloia	*Mostogloia sp.*	3	6	9	0.02
Navicula	*Navicula sp.*	102	275	377	0.84
Nitzschia	*Nitzschia sp.*	682	492	1174	2.60
Odontella	*Odontella sinensis*	3	0	3	0.01
Paralia	*Paralia sp.*	0	1	1	0.00
Rhizosolen	*Rhizoselenia sp.*	98	204	302	0.67
Skeletonema	*Skeletonema sp.*	11,429	23,425	34,854	77.27
Synedra	*Synedra sp.*	6	5	11	0.02
Thalassionema	*Thalassionema sp.*	2	11	13	0.03
Thalassiosira	*Thalassiosira sp.*	1	1	2	0.00
Thalassiothrix	*Thalassiothrix sp.*	73	40	113	0.25
Triceratium	*Triceratium sp.*	5	4	9	0.02
Chlorophyceae		0	0	0	-
Chlorella	*Chlorella sp.*	19	37	56	0.12
Eudorina	*Eudorina sp.*	1	3	4	0.01
Lepocinclis	*Lepocinclis salina*	103	61	164	0.36
Pediastrum	*Pediastrum boryanum*	2	2	4	0.01
Pediastrum	*Pediastrum sp.*	20	43	63	0.14
Scenedesmus	*Scenedesmus aquadricauda*	27	6	33	0.07
Scenedesmus	*Scenedesmus ocuminatus*	19	9	28	0.06
Scenedesmus	*Scenedesmus sp.*	84	41	125	0.28
Selenastrum	*Selenastrum sp.*	1	3	4	0.01
Conjugatophyceae		0	0	0	-
Cosmarium	*Cosmarium sp.*	1	6	7	0.02
Coscinodiscophyceae		0	0	0	-
Corethron	*Corethron sp.*	2	0	2	0.00
Coscinodiscus	*Coscinodiscus sp.*	298	436	734	1.63
Pleurosigma	*Pleurosigma sp.*	81	107	188	0.42
Cyanophyceae		0	0	0	-
Anabaenopsis	*Anabaenopsis elenkinii*	15	5	20	0.04
Chroococcus	*Chroococcus indicus*	23	30	53	0.12
Chroococcus	*Chroococcus minutes*	1,287	1,544	2,831	6.28
Gomphosphaeria	*Gomphosphaeria sp.*	1	0	1	0.00
Lyngbya	*Lyngbya sp.*	1	1	2	0.00
Oscillatoria	*Oscillatoria sp.*	130	104	234	0.52
Spirulina	*Spirulina sp.*	22	40	62	0.14
Dinophyceae		0	0	0	-
Ceratium	*Ceratium sp.*	289	121	410	0.91
Dinophysis	*Dinophysis sp.*	2	6	8	0.02
Prorocentrum	*Prorocentrum sp.*	0	1	1	0.00
Euglenoidea		0	0	0	-
Euglena	*Euglena oxyuris*	1	1	2	0.00
Phacus	*Phacus obolus*	71	41	112	0.25

Table 1. Continued

Class/genus	Species	Abundance (ind/L)			
		High tide	Low tide	Total	Percentage
Mediophyceae		0	0	0	-
Ditylum	*Ditylum sp.*	78	104	182	0.40
Prymnesiophyceae		0	0	0	-
Phaeocystis	*Phaeocystis globosa*	4	1	5	0.01
Zooplankton		0	0	0	-
Chromadorea		0	0	0	-
Crowcrocaecum	*Crowcrocaecum skrjabini*	0	1	1	0.00
Clitellata		0	0	0	-
Aeolosoma	*Aeolosoma hemprichi*	1	1	2	0.00
Crustacea		0	0	0	-
Dhapnia	*Dhapnia sp.*	2	6	8	0.02
Megacyclops	*Megacyclops viridis*	7	3	10	0.02
	Mucosa sp.	2	0	2	0.00
Nauplius	*Nauplius (stadia)*	248	470	718	1.59
Eurotatoria		0	0	0	-
Brachionus	*Brachionus angularis*	5	4	9	0.02
Brachionus	*Brachionus sp.*	133	101	234	0.52
Filinia	*Filinia longiseta*	18	19	37	0.08
Foraminifera*		0	0	0	-
Foraminifera	*Foraminifera*	0	2	2	0.00
Oligohymenophorea		0	0	0	-
Paramecium	*Paramecium caudatum*	2	0	2	0.00
Spirotrichea		0	0	0	-
Codonella	*Codonella sp.*	354	256	610	1.35
Leprotintinnus	*Leprotintinnus sp.*	12	12	24	0.05
Tintinnopsis	*Tintinnopsis sp.*	34	39	73	0.16
Total		16,142	28,965	45,107	100.00

*Although a sub-phylum, Foraminifera is included in this list of class groupings for comparative purposes

3.2. Plankton Abundance

The sampling stations varied in taxon-specific abundances (Figure 2). Spatially, the highest plankton abundance was found at Station 1 during low tide (10,018 ind/L) and the lowest during high tide at Station 7 (76 ind/L). In other words, the area of the Belawan Estuary nearest to the sea has a higher plankton abundance than the area near land (Stations 1–3). The high plankton abundance was largely influenced by the presence of numerous species of Bacillariophyceae, which dominated the community composition. During high tide, abundance is higher compared to low tide, with an average value of 3,599.09–492.88 ind/L compared to high tide, which ranges from 531.11–1,734.80 ind/L. Temporally, plankton abundance was highest during the first quarter of low tide, at 9,219.8 ind/L (Figure 3), whereas the lowest abundance occurred during the last quarter of low tide, at 80.248 ind/L.

3.3. Diversity Index, Evenness Index, and Dominance Index

The spatial diversity index (H’) of plankton in the Belawan estuary ranged from 0.47 to 2.06 (Table 2). The highest diversity was observed at Station 8 during low tide, whereas the lowest value was observed at Station 1 during low tide. In general, the plankton diversity was higher during low tide than during high tide. Plankton diversity was higher in the upper reaches (near the shore; Stations 6–8) than in the lower reaches (near the open sea; Stations 1–3). This contrasts with plankton abundance, which was higher in the lower reaches (nearest the open sea) than in the upper reaches (nearer to land). The evenness index (E) ranged from 0.17 to 0.60, indicating that the plankton distribution in the Belawan Estuary tends to be uneven. The dominance index (C) was very high, ranging from 0.25 to 0.84, indicating the presence of species that dominate Belawan estuarine waters.

The temporal plankton diversity index (H') during high tide ranged from 0.79 to 1.71 (Table 3). The temporal plankton diversity index (H') during low tide ranged from 0.65 to 1.59. The highest diversity was observed during the First Quarter of the phase at high tide, and the lowest diversity was observed during the Full Moon phase at low tide. The evenness index (E) in the Belawan Estuary was relatively low,

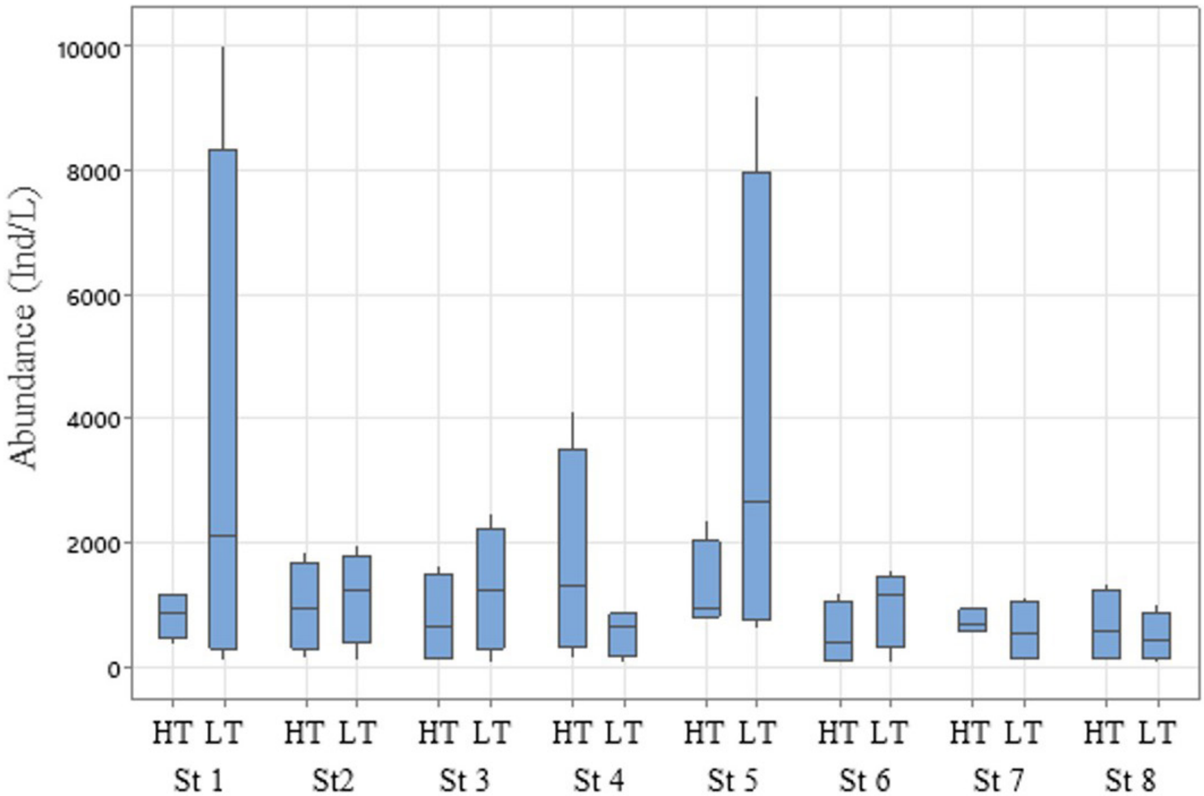

Figure 2. Spatial differences in the abundance of plankton in the Belawan Estuary. “St” denotes sampling station

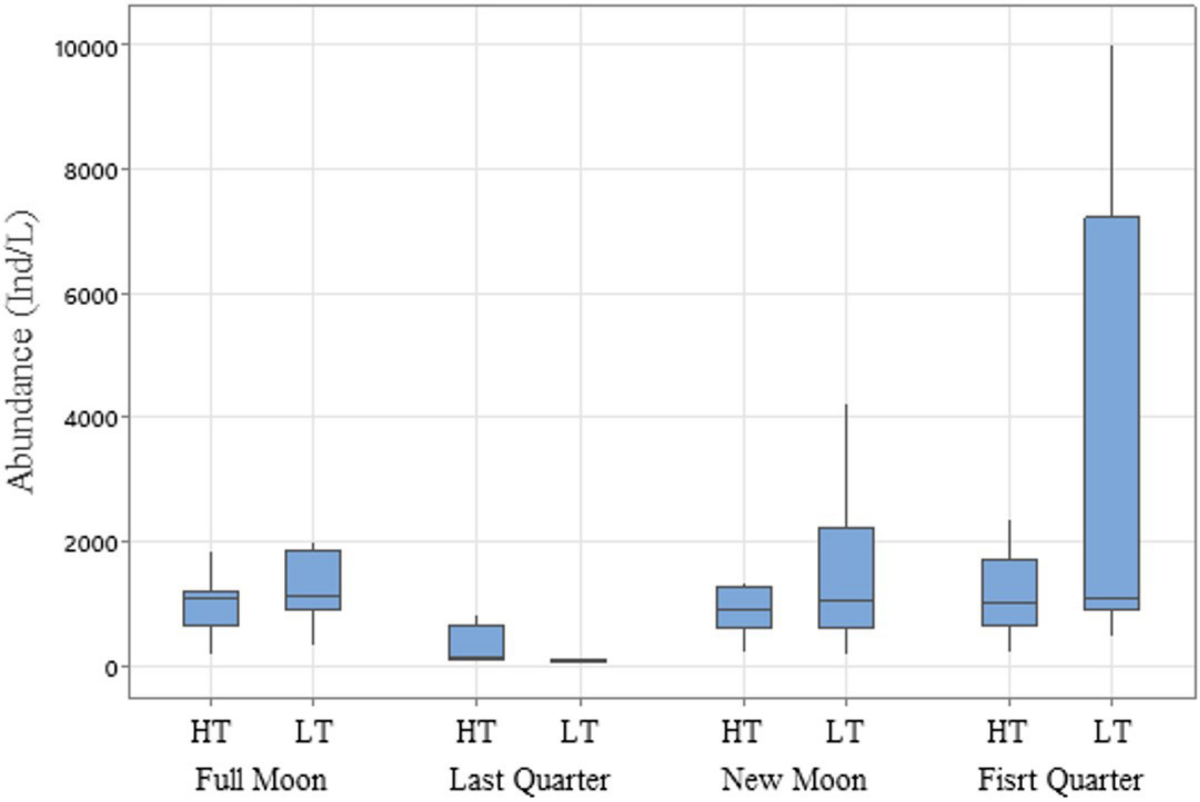

Figure 3. Temporal differences in plankton abundance in the Belawan Estuary

ranging from 0.20 to 0.47. The highest value of E was recorded during the First Quarter phase, with a value of 0.47, whereas the lowest was recorded during the Full Moon phase, with a value of 0.20. The dominance index (C) in the Belawan Estuary was relatively high, ranging from 0.37 to 0.78. The highest dominance was observed during the Full Moon phase, with an E value of 0.78 (high category), and the lowest value (0.37) was recorded during the First Quarter phase.

3.4. Saprobic Index

The spatial saprobic coefficient of plankton in the Belawan Estuary ranged from -1.07 to -3.00 (Figure 4). Based on the criteria for water pollution levels, the Belawan Estuary is classified as being in an α-mesosaprobic-polysaprobic condition (moderately polluted) to polysaprobic (heavily polluted). The temporal saprobic coefficient calculation ranged from -1.19 to -2.74 (Figure 5), indicating that the water pollution level falls within the α-mesosaprobic-polysaprobic condition (moderately polluted) to polysaprobic (heavily polluted).

3.5. Water Quality Characteristics

Spatially and temporally, the temperature and pH of the Belawan Estuary were stable over the study period (Tables 4-6). The temperature ranged between 29–32°C, and the pH ranged between 7.0–7.9. Salinity and Total Dissolved Solids (TDS) fluctuated both spatially and temporally. Spatially, the salinity and TDS values were higher near the sea and lower near the mouth of the river. This is due to the influence of seawater, which has a higher salt content and mixes with freshwater, resulting in lower concentrations near the river where the tidal range decreases. Temporally, the salinity and

Table 3. Temporal biodiversity index of plankton in the Belawan Estuary

Index	Full moon		Last quarter		New moon		First quarter	
	HT	LT	HT	LT	HT	LT	HT	LT
H'	0.79	0.65	1.26	1.59	1.12	0.87	1.71	1.00
E	0.22	0.20	0.37	0.46	0.33	0.26	0.47	0.28
C	0.73	0.78	0.54	0.40	0.56	0.70	0.37	0.64

Observation time (column groups). HT, high tide; LT, low tide; H', diversity index (shannon-wiener); E, evenness index; C, dominance index

Table 2. Spatial biodiversity index of plankton in the Belawan Estuary

Index	I		II		III		IV		V		VI		VII		VIII	
	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT
H'	0.86	0.47	0.60	0.74	0.93	0.66	0.60	1.30	1.34	0.61	1.16	1.28	1.70	1.81	1.97	2.06
E	0.25	0.17	0.23	0.23	0.22	0.20	0.18	0.42	0.46	0.18	0.36	0.38	0.50	0.54	0.60	0.65
C	0.71	0.84	0.78	0.73	0.69	0.78	0.80	0.52	0.41	0.79	0.55	0.50	0.31	0.27	0.28	0.25

Observation station (column groups). HT, high tide; LT, low tide; H', diversity index (shannon-wiener); E, evenness index; C, dominance index

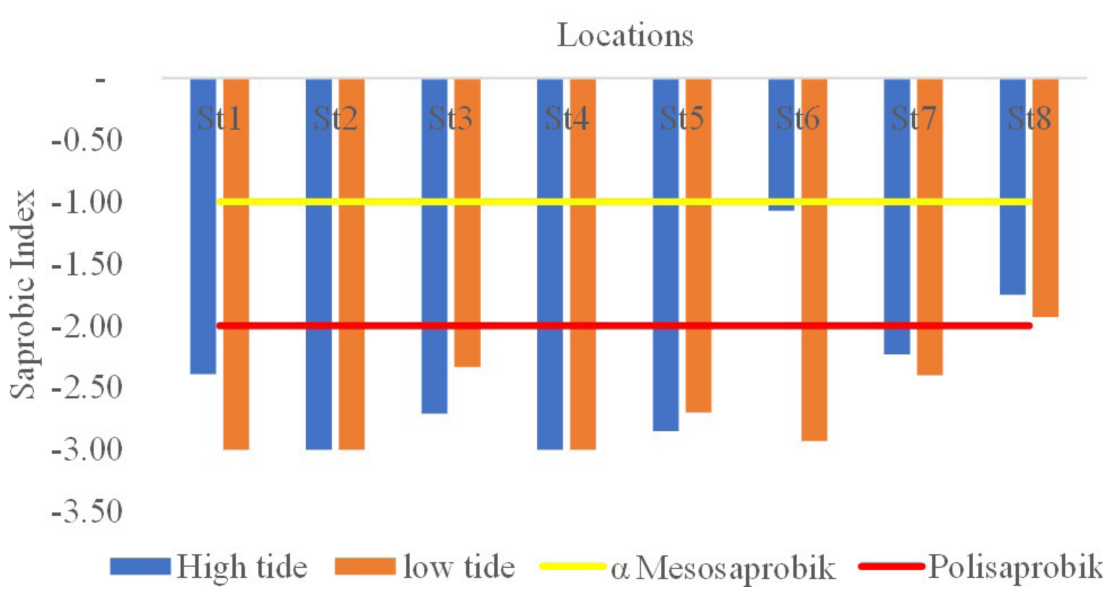

Figure 4. Spatial saprobic index

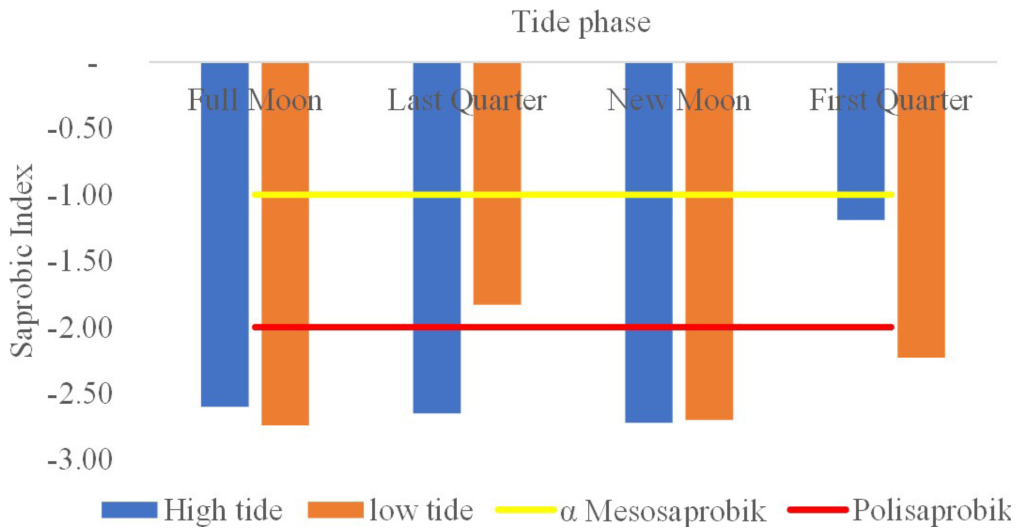

Figure 5. Temporal saprobic index

TDS concentrations were higher during the full moon and new moon periods than during the first and second quarter moons. This was also observed in the water level during the full moon and new moon periods, which were higher than that during the first and last quarters.

Currents in the Belawan Estuary also show spatial and temporal variations. Spatially, the currents at Station 6–Station 8 (St6–St8, near the coast) were higher than the corresponding values at stations nearer the sea. This was mainly because of the narrower channel/river section at St6–St8, resulting in higher currents. Temporally, the currents during the full-moon and new-moon periods were higher than those during the first and last quarters.

The Belawan Estuary is a deposition site for sediments and organic matter transported from the nearby shores and the upper reaches of the Belawan River. As expected, the water samples showed low clarity (<0.5 m) and high turbidity (>10 NTU/ Nephelometric turbidity units). Sediment particles transported from upstream segments of the river and deposited at the river mouth reduce sunlight penetration. Turbidity is caused by suspended and dissolved organic and inorganic materials, such as suspended solids from drainage channels that discharge into the sea. Temporally, the highest turbidity occurred during the full moon phase because of the high-water level, which resulted in significant mixing during high tide and sediment settling during low tide.

Along with sediment, nutrients accumulate in the estuary, being transported from the river system, the surrounding mangrove ecosystem, and marine waters. At the sampling stations, the measured concentration of nitrate and phosphate was much higher than the threshold values set in the national government regulations of Indonesia (more than 0.06 mg/L for nitrate and 0.015 mg/L for phosphate). Based on research conducted in the Belawan Estuary, spatial Biological Oxygen Demand (BOD) test results ranged from 5.7–10.5 mg/L during high tide and 3.3–15.2 mg/L during low tide. Temporally, BOD ranged from 3.3–15.2 mg/L during high tide and 3.3–14.3 mg/L during low tide. Spatially, chemical oxygen demand (COD) ranged from 18.7–25.0 mg/L, and temporal COD ranged from 5.625–10.625 mg/L. The higher concentration of COD compared with BOD was likely due to the oxidation of inorganic compounds. Nearly all organic matter (>95%) can be oxidised by strong oxidants, such as potassium permanganate, in an acidic environment. Spatially, organic matter (BOD and COD) was more prevalent in the estuarine area (St1–5) than in the river section (St6–8). This indicated the accumulation of organic matter at the river mouth. Temporally, organic matter was higher during the last quarter than during the other phases.

4. Discussion

4.1. Spatial and Temporal Distribution

The spatial distribution of plankton varied greatly across the eight sampling stations. The highest abundance was found at Station 1 during low tide (10,018.1 ind/L, dominated by the phytoplankton group Bacillariophyceae, specifically *Skeletonema* sp. Species of *Skeletonema* are marine or estuarine

Table 4. Spatial characteristics of water quality during high tide in Belawan Estuary

Parameter	Unit	Water quality standard*	Sampling station							
			St1	St2	St3	St4	St5	St6	St7	St8
Temperature	°C	±3	30.0	30.3	30.0	30.8	29.5	29.2	31.0	31.7
Salinity	PSU	0-34	17.0	11.8	14.0	15.3	10.8	0.0	3.3	1.0
Turbidity	NTU	5	20.5	19.8	19.4	22.4	19.2	42.7	21.4	11.2
Water transparency	m	-	0.5	0.4	0.4	0.6	0.4	0.3	0.3	0.5
Depth	m	-	2.3	2	1.6	2	2.2	2.1	2.2	2.1
TSS	mg/L	80	23.4	26.3	21.4	27.6	27.0	20.5	21.8	17.4
TDS	mg/L	-	10,746.0	7,815.0	7,992.5	13,677.5	10,792.5	3,831.6	5,574.5	6,113.0
Oil and Grease	mg/L	1	2.2	1.8	2.0	1.9	2.0	1.8	2.5	2.3
Current	cm/s	-	8.9	6.2	13.8	12.5	11.0	14.1	15.1	7.1
DO	mg/L	>5	6.5	7.5	6.6	4.6	5.3	6.3	5.5	5.9
pH	-	78.5	7.6	7.4	7.5	7.0	7.6	7.9	7.5	7.9
BOD	mg/L	20	7.6	7.1	7.4	7.1	7.4	6.1	6.9	5.6
COD	mg/L	-	25.0	23.4	24.3	23.2	24.3	19.9	22.8	18.7
Nitrate	mg/L	0.06	3.7	3.6	4.4	4.2	6.1	7.2	4.6	4.3
Phosphate	mg/L	0.015	1.0	0.7	0.3	0.6	0.5	0.5	1.6	1.7

Sources: Muhtadi *et al.* (2025b) *PP (2021) in Appendix VIII; TSS: total suspended solids, TDS: total dissolved solids, DO: dissolved oxygen, BOD: biological oxygen demand, COD: chemical oxygen demand, PSU: part salinity units, NTU: nephelometric turbidity unit

Table 5. Spatial characteristics of water quality during low tide in the Belawan Estuary

Parameter	Unit	Water quality standard*	Sampling station							
			St1	St2	St3	St4	St5	St6	St7	St8
Temperature	°C	±3	30.1	30.2	29.6	30.6	29.7	29.4	30.6	32.0
Salinity	PSU	0–34	14.8	11.8	9.3	15.3	10.3	1.8	2.0	1.5
Turbidity	NTU	5	20.8	19.2	19.4	22.2	30.4	32.2	18.2	12.8
Water transparency	m	-	0.6	0.4	0.4	0.6	0.4	0.3	0.3	0.4
Depth	m	-	1.1	0.9	0.6	1.1	1	1.4	0.9	0.9
TSS	mg/L	80	17.8	19.9	19.7	18.9	25.5	21.6	30.4	27.0
TDS	mg/L	-	9,992.8	8,630.0	6,949.0	12,147.5	8,620.0	6,060.7	5,870.0	1,907.5
Oil and Grease	mg/L	1	1.4	1.4	1.9	1.7	1.8	1.7	2.6	2.5
Current	cm/s	-	5.9	9.3	5.8	6.8	10.3	10.5	13.2	15.8
DO	mg/L	>5	6.2	7.4	6.7	4.3	6.1	5.5	5.4	5.8
pH	-	7–78.5	7.6	7.6	7.5	7.1	7.2	7.4	7.4	7.8
BOD	mg/L	20	7.1	6.7	7.3	7.2	7.2	5.7	10.6	5.7
COD	mg/L	-	23.6	22.1	24.0	23.6	23.6	18.7	19.0	18.2
Nitrate	mg/L	0.06	4.4	4.3	5.5	6.0	8.3	7.2	6.1	5.1
Phosphate	mg/L	0.015	0.2	0.2	0.7	0.7	0.4	0.4	2.1	1.9

Sources: Muhtadi *et al.* (2025b) *PP (2021) in Appendix VIII; TSS: total suspended solids, TDS: total dissolved solids, DO: dissolved oxygen, BOD: biological oxygen demand, COD: chemical oxygen demand, PSU: part salinity units, NTU: nephelometric turbidity unit

Table 6. Temporal characteristics of water quality of Belawan Estuary

Parameter	Unit	Water quality standard*	Sampling station							
			Full moon		Last quarter		New moon		First quarter	
			HT	LT	HT	LT	HT	LT	HT	LT
Temperature	°C	±3	31.3	31.4	30.2	30.3	30.3	30.2	29.5	29.3
Salinity	PSU	0–34	12.0	12.4	4.4	3.9	11.3	10.0	8.9	7.0
Turbidity	NTU	5	26.4	27.6	19.4	19.7	21.5	21.9	21.0	18.3
Water transparency	m	-	0.3	0.4	0.6	0.5	0.3	0.3	0.4	0.4
Depth	m	-	2.4	0.3	1.6	0.7	2.3	0.2	1.6	0.9
TSS	mg/L	80	16.6	16.6	14.0	15.5	13.3	13.8	48.8	44.5
TDS	mg/L	-	10,198.0	8,967.1	4,824.0	4,883.0	10,298.2	9,051.9	7,951.1	7,186.8
Oil and Grease	mg/L	1	2.6	2.3	2.1	2.0	0.7	0.8	2.8	2.3
Current	cm/s	-	11.7	8.6	6.7	7.8	13.3	11.6	10.7	8.7
DO	mg/L	>5	5.9	5.9	5.2	4.9	6.6	6.6	6.4	6.3
pH	-	7–78.5	7.8	7.7	7.4	7.4	7.4	7.3	7.6	7.4
BOD	mg/L	20	4.5	4.3	4.5	4.3	3.3	3.3	15.2	14.3
COD	mg/L	-	14.8	14.1	14.8	14.1	11.0	11.0	50.2	47.2
Nitrate	mg/L	0.06	7.9	9.1	5.6	6.5	3.8	5.9	1.5	1.8
Phosphate	mg/L	0.015	1.0	0.8	0.9	1.0	0.4	0.6	1.1	0.9

Sources: Muhtadi *et al.* (2025b) *PP (2021) in Appendix VIII; TSS: total suspended solids, TDS: total dissolved solids, DO: dissolved oxygen, BOD: biological oxygen demand, COD: chemical oxygen demand, PSU: part salinity units, NTU: nephelometric turbidity unit diatoms widely distributed worldwide and form non-toxic plankton blooms (Hernández-Becerril *et al.* 2013). Skeletonema is a natural food source for the zooplankton *Artemia* spp. (Firmansyah *et al.* 2013) And serves as an important bioremediator of metal and oil waste (Kurniawan *et al.* 2017; Liwun *et al.* 2020). Diatoms belonging to the class Bacillariophyceae dominate aquatic environments around the globe, particularly in estuarine areas (Ajibare *et al.* 2019; Yang *et al.* 2019). In a previous study conducted at Lake Siombak (Station 8 in this study), the plankton abundance was found to reach 15.09 million cells/m^3 for phytoplankton (81.11%) and 3.51 million individuals/m^3 for zooplankton (18.89%) (Muhtadi *et al.* 2020). The spatial distribution of plankton in the Belawan Estuary showed that plankton abundance in the middle and mouth of the river was higher than that in the upstream areas. This distribution indicates that tidal currents significantly influence local abundance and flow (Cereja *et al.* 2021; Ahmed *et al.* 2022; Baleani *et al.* 2024; Dhanalakshmi *et al.* 2024; Muhtadi *et al.* 2020; 2025a).

The temporal distribution of plankton showed that the highest abundance occurred during the first quarter phase at low tide, also known as the quarter-moon. In a study of plankton communities in the waters of Jepara Beach, the authors reported that plankton abundance was greater during the first and third quarter moons than during the new moon and full moon phases owing to the delayed tidal effects (Aji *et al.* 2014). However, in coastal lakes, where tides have an influence, the highest plankton abundance occurred during the new moon phase compared with the dead tide phase (Muhtadi *et al.* 2025a). Similar results were observed in the Tagus Estuary (Portugal), where the highest plankton abundance/biomass was recorded during the spring tide rather than during the neap tide (Cereja *et al.* 2021). These differences can be attributed to geographical conditions and tidal influences (Cereja *et al.* 2021; Ahmed *et al.* 2022; Baleani *et al.* 2024; Dhanalakshmi *et al.* 2024; Muhtadi *et al.* 2020; 2025a). These results underscore the effect of tidal cycles on the biogeochemical and ecological properties of macrotidal ecosystems (Muhtadi and Leidonald 2024; Cadier *et al.* 2017; Muhtadi *et al.* 2024).

The plankton abundance observed in the Belawan Estuary was relatively lower than that in the Banten Bay Estuary, where the abundance reached 136,971,014 cells/L (Sugiarti *et al.* 2024). In the Perancak Estuary, phytoplankton abundance ranges from 42 million to 3002 million of cells/L (Hastuti *et al.* 2018). Phytoplankton abundance in the coastal waters of South Sulawesi was recorded at 5,094,333 cells/L (Lestari *et al.* 2021), which is still considerably lower compared to previous studies at Lake Siombak (Station 8 in this study), which reached 8610 million cells/L (Muhtadi *et al.* 2020). However, plankton abundance in the Belawan Estuary is still higher than that in the coastal Lake Anak Laut (Aceh), with an average of 2,000 cells/L (Muhtadi *et al.* 2025a).

4.2. Plankton Community Index

The diversity index values in the Belawan Estuary were classified as low, ranging from 0.60 to 1.97. The low H' value indicates generally low community stability (Odum and Baret 2005). This low diversity also suggests that the Belawan Estuary has experienced high ecological pressure. This has also been observed in polluted water (Muhtadi *et al.* 2025b) under highly fluctuating environmental conditions (Muhtadi *et al.* 2020). This condition is consistent with the calculation of the saprobic index (Figure 5), which shows that the Belawan Estuary falls within the α mesosaprobic/polysaprobic (moderately polluted) to polysaprobic (heavily polluted) conditions. Based on the frontier curve (Figure 6), the Belawan Estuary is in Phase 1, representing an ecosystem under high ecological pressure. Similar conditions have also been found in Lake Siombak (part of the Belawan Estuary), which has an unstable plankton community (Muhtadi *et al.* 2020). Tidal currents are the main factors causing ecological pressure on plankton and other biota in estuaries and coastal waters (Muhtadi *et al.* 2020; 2024; 2025a).

The low plankton diversity in the estuary was accompanied by low evenness and high dominance. This indicates an uneven distribution of species and the presence of a dominant plankton species, namely the genus *Skeletonema* (class Bacillariophyceae). Species in this group can rapidly outcompete other phytoplankton because of their rapid adaptation, even under low-light conditions, and their ability to produce and regenerate in higher numbers compared to the species of other classes (Lestari *et al.* 2021; Sugiarti *et al.* 2024; Muhtadi *et al.* 2025a).

4.3. Effect of Tides on Plankton Communities

TDS significantly influenced the spatial abundance of plankton at high tide and DO (Figure 7). During low tide, no single environmental factor predominantly influenced plankton abundance (Figure 8). Plankton

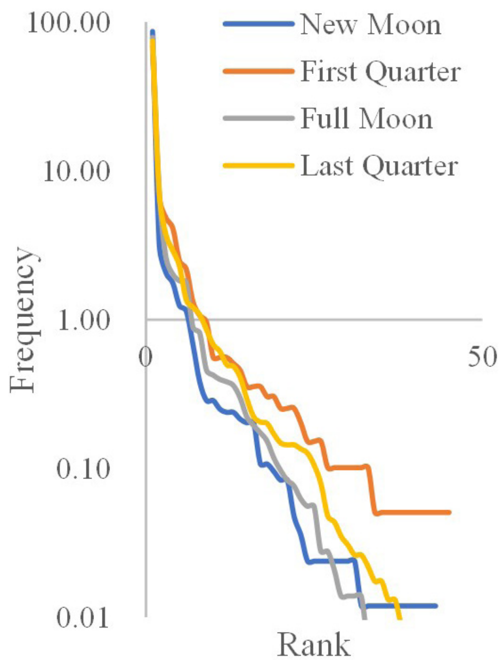

Figure 6. Frontier graph of plankton succession in the Belawan Estuary

diversity, during either high or low tides, is influenced by currents, oil and fats, as well as organic matter and nutrients. In a previous study conducted in Lake Siombak, plankton abundance was found to be influenced by TSS, transparency, and BOD (Muhtadi *et al.* 2020). In contrast, in the coastal Lake Anak Laut, TSS influences plankton abundance and DO (Muhtadi *et al.* 2025a), aligning with the results in the Belawan Estuary. Spatially, during high tide, plankton abundance was associated with Stations 1 and 4, whereas during low tide, greater abundance was seen at Stations 4 and 5. The principal component analysis (PCA) also indicated a spatial division during both high and low tides, forming three groups: Stations 1–3 (front section), Stations 4–5 (middle section), and Stations 6–8 (rear section).

Temporally, during high tide in the Belawan Estuary, DO, current, salinity, transparency, and TDS had a strong influence (correlation value above 0.8) on plankton abundance (Figure 9), as demonstrated in the biplot analysis, with a contribution of all parameters of 77.8% (Figure 10). Analysis during low tide showed that organic matter, nutrients, DO, and temperature strongly influenced plankton abundance (correlation values above 0.7) (Figure 10). Plankton diversity during high tide is influenced by temperature, water level, turbidity, organic matter, and nutrients. During low tide, plankton diversity is influenced by salinity and TDS. Temporally, during the new moon and full moon phases, the water characteristics and plankton community in the Belawan Estuary fell into the same group during high tide. However, during low tide, the four phases exhibit distinct characteristic divisions (Muhtadi and Leidonald 2024; Muhtadi *et al.* 2025a).

Based on the PCA analysis, it can be concluded that tidal fluctuations in the Belawan Estuary significantly influenced the plankton community structure. The tidal cycle, which transports water masses into and out of the estuarine environment, undoubtedly affects water quality while also transporting plankton and other marine organisms to and from the estuary. This, in turn, influences the presence and abundance of aquatic biota within the estuary. In previous studies, researchers have reported that tidal cycles not only alter the dynamics of water quality (Cadier *et al.* 2017; Leidonald *et al.* 2024a; Muhtadi *et al.* 2024; 2025b) but also change the structure of aquatic biota communities (Muhtadi and Leidonald 2024; Muhtadi *et al.* 2025a), particularly plankton (Cereja *et al.* 2021; Ahmed *et al.* 2022; Muhtadi *et al.* 2020; 2025a; Dhanalakshmi *et al.* 2024).

4.4. The Ecological Status of the Belawan Estuary based on Plankton Community Composition

The saprobic index results indicate that Belawan Estuary falls into the category of moderately to heavily polluted, characterised by abundant organic matter in the α-mesosaprobic/polysaprobic and polysaprobic phases. This is likely due to the substantial influx of waste into the estuary, originating from urban activities and the accumulation of agricultural runoff from the upper Belawan watershed. The primary indicators influencing the saprobic level of coastal water are residential activities, urban development, and industrial operations (Nuriasih *et al.* 2018; Tjahjono *et al.* 2018; Nurdin *et al.* 2025).

Previous studies have indicated that the Belawan Estuary has been subjected to moderate-to-heavy pollution (Muhtadi *et al.* 2025b). In addition to organic pollution, the Belawan Estuary has shown indications of plastic pollution, both macro- and microplastics, in the waters of the estuary (Pane *et al.* 2023; Muhtadi *et al.* 2025c), as well as sediments (Leidonald *et al.* 2024b) and aquatic biota (Muhtadi *et al.* 2025d). Heavy metal pollution has also been reported (Pane *et al.* 2023; Sulistyowati *et al.* 2023; Yusfaddillah *et al.* 2023). This indicates that the estuary is affected by pollution from various sources, including organic matter, plastics,

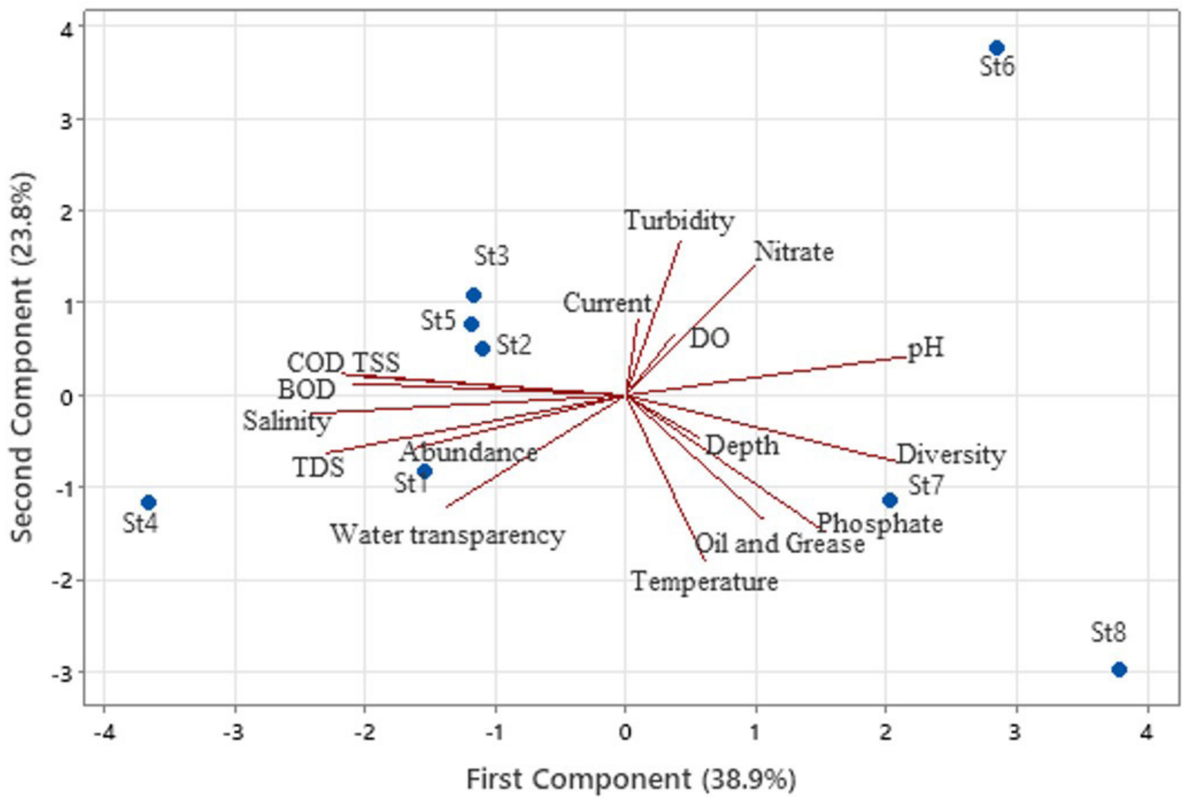

Figure 7. Principal component analysis (PCA) of water quality and spatial abundance and diversity of plankton during high tide in the Belawan Estuary.

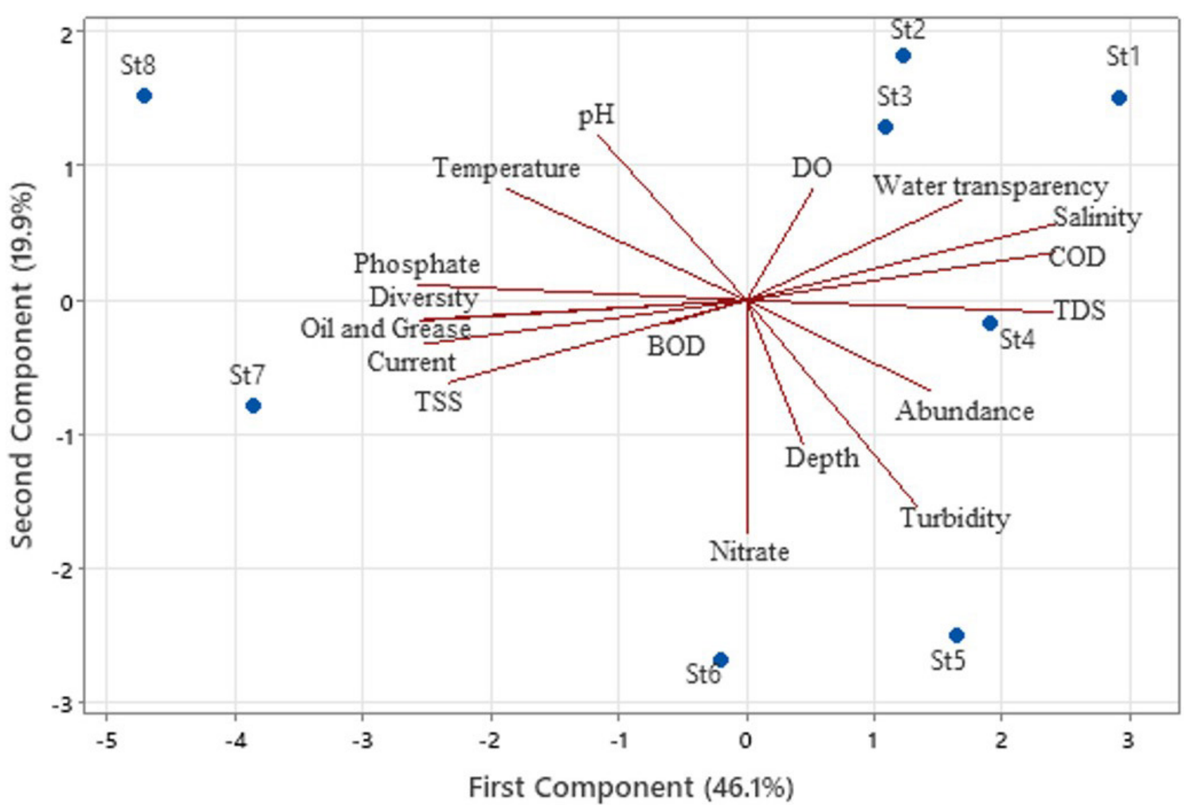

Figure 8. Principal component analysis (PCA) of water quality and spatial abundance and diversity of plankton at low tide in the Belawan Estuary

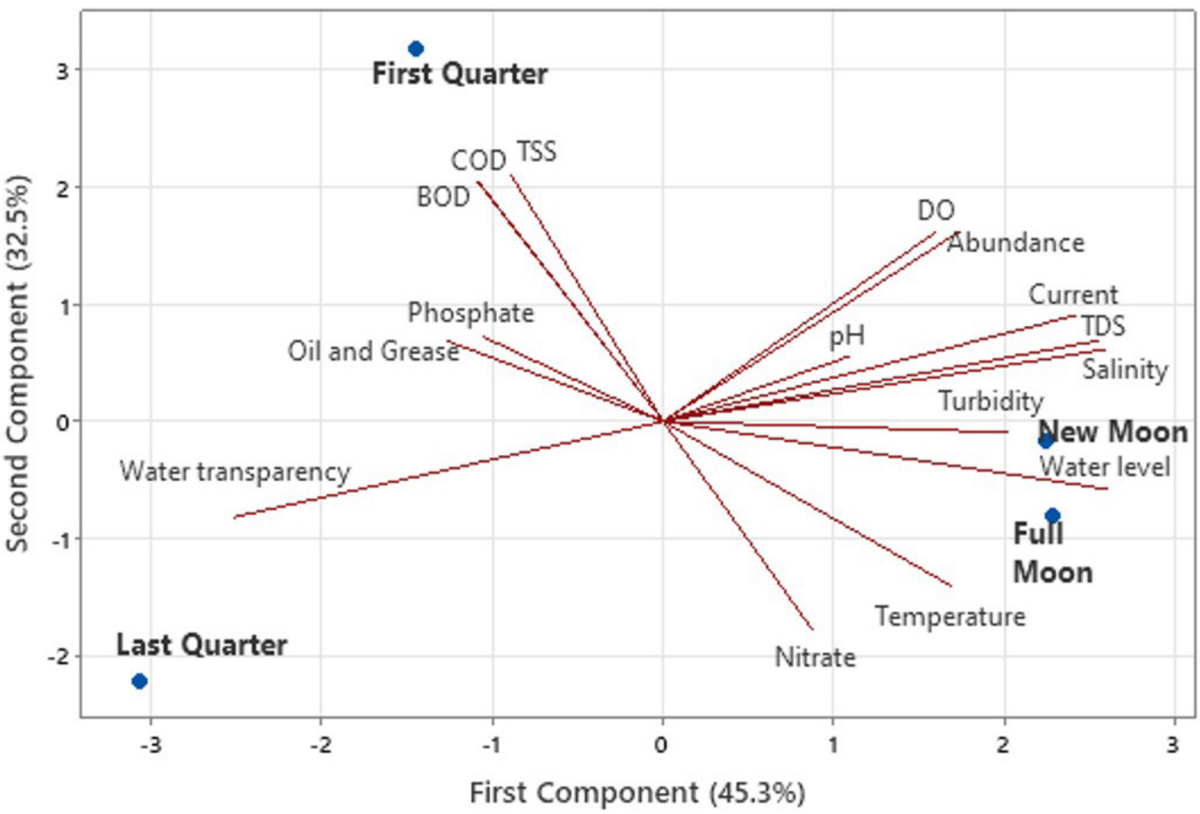

Figure 9. Principal component analysis (PCA) of water quality and temporal abundance and diversity of plankton at high tide in the Belawan Estuary

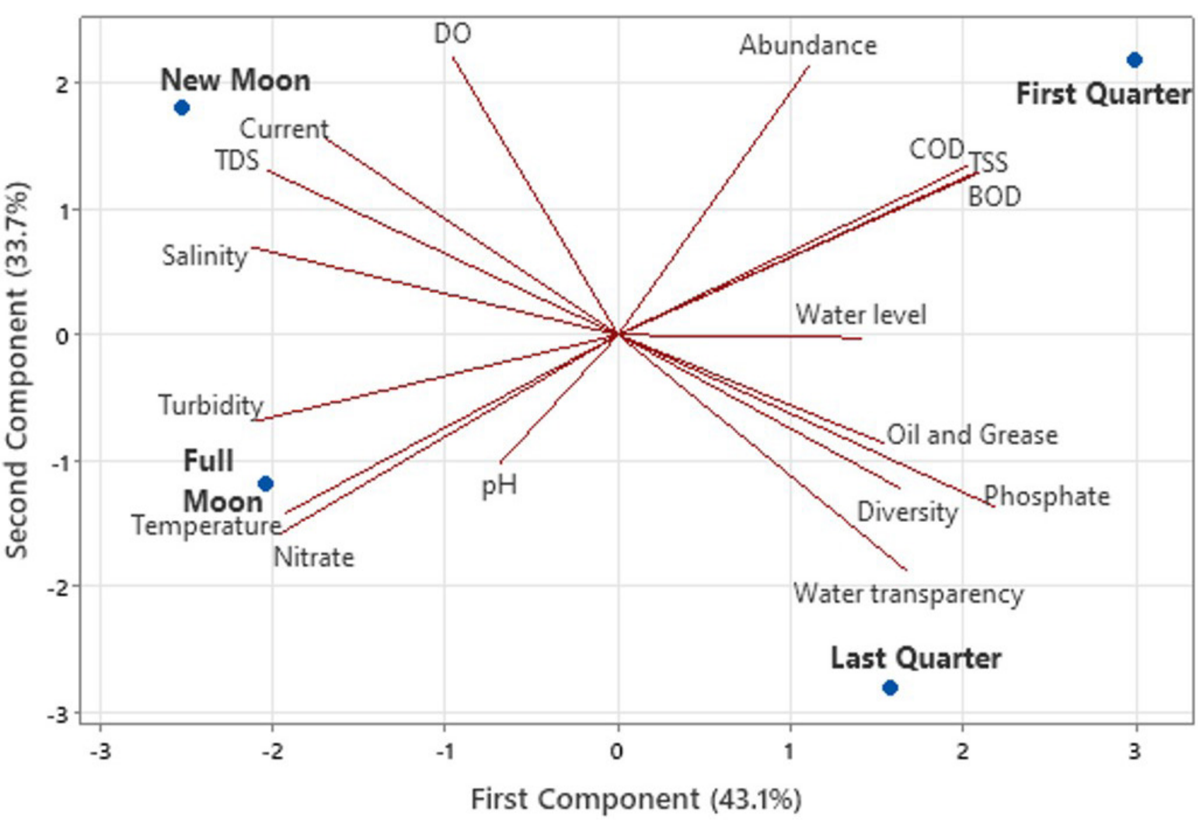

Figure 10. Principal component analysis (PCA) of water quality and temporal abundance and diversity of plankton at low tide in the Belawan Estuary

and metals. Therefore, preventive actions by the government are necessary to mitigate current pollution levels and prevent further deterioration.

Conflict of Interest

All author declares no conflict of interest.

Acknowledgements

We thank the 2020 student team of the Aquatic Resources Management Group of Universitas Sumatera Utara for their kind assistance with the field sampling.

References

Abdul, W.O., Adekoya, E.O., 2016. Preliminary ecopath model of a tropical coastal estuarine ecosystem around the bight of Benin, Nigeria. *Environ Biol Fishes.* 99, 909–923. https://doi.org/10.1007/s10641-016-0532-7

Afonina, E.Y., Tashlykova, N.A., 2018. Plankton community and the relationship with the environment in saline lakes of Onon-Torey plain, Northeastern Mongolia. *Saudi J Biol Sci.* 25, 399–408. https://doi.org/10.1016/j.sjbs.2017.01.003

Ahmed, A., Madhusoodhanan, R., Yamamoto, Y., Fernandes, L., Al-Said, T., Nithyanandan, M., Thuslim, F., Al-Zakri, W., Al-Yamani, F., 2022. Analysis of phytoplankton variations and community structure in Kuwait Bay, Northwestern Arabian Gulf. *J Sea Res.* 180, 102163. https://doi.org/10.1016/j.seares.2022.102163

Aji, W. P., Subiyanto., M., Muskananfola, R., 2014. Kelimpahan zooplankton krustasea berdasarkan fase bulan di Perairan Pantai Jepara, Kabupaten Jepara. *Diponegoro J Maquares.* 3, 188-196. https://doi.org/10.14710/marj.v3i3.6710

Ajibare, A.O., Ayeku, P.O., Akinola, J.O., Adewale, A.H., 2019. Plankton composition in relation to water quality in the coastal waters of Nigeria. *Asian J Fish Aquat Res.* 5, 1-9. https://doi.org/10.9734/ajfar/2019/v5i230070

APHA, 2017. *Standard Methods for the Examination of Water and Wastewater*, twenty-three ed. American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, D.C.

Baleani, C.A., Menéndez, M.C., Vitale A.J., Amodeo, M.R., Perillo, G.M.E., Piccolo, M.C., 2024. Assessing the role of tidal cycle, waves, and wind as drivers of surf zone zooplankton on a temperate sandy beach. *Reg Studies Mar Sci*. 73, 103455, https://doi.org/10.1016/j.rsma.2024.103455

Buesa, R.J., 2019. Plankton-based energy transfer rates in four Cuban coastal lagoons. *Estuar Coast Shelf Sci.* 216, 118–127. https://doi.org/10.1016/j.ecss.2017.10.002

Cadier, M., Gorgues, T., Helguen, S.L., Sourisseau, M., Memery, L., 2017. Tidal cycle control of biogeochemical and ecological properties of a macrotidal ecosystem. *Geophys Res Lett*. 44, 8453-8462. https://doi.org/10.1002/2017GL074173

Cereja, R., Brotas, V., Cruz, J.P.C., Rodrigues, M., Brito, A.C., 2021. Tidal and physicochemical effects on phytoplankton community variability at tagus estuary (Portugal). *Front Mar Sci.* 8, 675699. https://doi.org/10.3389/fmars.2021.675699

Dhanalakshmi, D., Akter, S., Gogoi, P., Deshmukhe, G., Landge, A.T., Bhushan, S., Layana, P., Shivkumar, Wanjari, R.N., Nayak, B.B., 2024. The effect of the tidal cycle on the phytoplankton community assemblage in a mangrove-dominated tropical tidal creek. *Environ Monit Assess.* 196, 795. https://doi.org/10.1007/s10661-024-12954-y

Firmansyah, M.Y., Kusdarwati, R., Cahyoko Y., 2013. Effect of different live feed types (*Skeletonema* sp., *Chaetoceros* sp., *Tetraselmis* sp.) on the growth rate and nutritional content of *Artemia* sp. *Jurnal Ilmiah Perikanan dan Kelautan.* 5, 105-111. https://doi.org/10.20473/jipk.v5i1.11433

Gocke, K., Pineda, J.E.M., Vidal, L.A., Fonseca, D., 2003. Planktonic primary production and community respiration in several coastal lagoons of the Outer Delta of the Rio Magdalena, Colombia. *Boletin de Investigaciones Marinas y Costeras.* 32, 125–144. https://doi.org/10.25268/bimc.invemar.2003.32.0.263

Hasani, Q., Yusup, M.W., Caesario, R., Julian, D., Muhtadi, A., 2022. Autoecology of *Ceratium furca* and *Chaetoceros didymus* as potential harmful algal blooms in tourism and aquaculture sites at Teluk Pandan Bay, Lampung, Indonesia. *Biodiversitas.* 23, 5670-5680. https://doi.org/10.13057/biodiv/d231117

Hastuti, A.W., Pancawati, Y., Surana, I.N., 2018. The abundance and spatial distribution of plankton communities in Perancak Estuary, Bali. *IOP Conf. Ser..: Earth Environ. Sci.* 176, 012042. https://doi.org/10.1088/1755-1315/176/1/012042

Hernández-Becerril, D.U., Barón-Campis, S.A., Salazar-Paredes, J., Alonso-Rodríguez, R., 2013. Species of the planktonic diatom genus *Skeletonema* (Bacillariophyta) from the Mexican Pacific Ocean. *Cryptogamie, Algologie*. 34, 77-87. https://doi.org/10.7872/crya.v34.iss2.2013.77

Kowalewska-Kalkowska, H., Marks, R., 2016. Estuary, estuarine hydrodynamics, in: Harff, J., Meschede, M., Petersen, S., Thiede, J. (Eds.), *Encyclopedia of Marine Geosciences.* Springer, Dordrecht, pp. 235–238. https://doi.org/10.1007/978-94-007-6644-0_164-1

Krebs, C.J., 2014. *Ecological methodology*, third ed. Harper Collins Publisher, New York.

Kurniawan, M.H., Sriati, Agung, M.U.K., Mulyani, Y., 2017. Pemanfaatan *Skeletonema* sp. dalam mereduksi limbah minyak solar di Perairan. *Jurnal Perikanan dan Kelautan.* 8, 68-75.

Leidonald, R., Muhtadi, A., Susetya, I.E., Dewinta, A.F., Hasibuan, J.S., Simamora, L.F.M., Saville, R., 2024a. The dynamics and water quality status of a tropical coastal lake in AnakLaut Lake, Singkil Indonesia. *LMU KELAUTAN: Indonesian Journal of Marine Sciences*. 29, 329-339. https://doi.org/10.14710/ik.ijms.29.3.329-339

Leidonald, R., Muhtadi, A., Fadhilah, A., Susetya, I.E., Panjaitan, E.T., Sihombing, M.A., Qaulya, U., Rohim, N., Firdaus, M., Tampubolon, P.A., 2024b. Spatial distribution and characteristics of microplastic particles in sediments at Belawan Estuary, North Sumatra Province. *IOP Conf. Ser.: Earth Environ. Sci.* 1413, 012009. https://doi.org/10.1088/1755-1315/1413/1/012009

Lestari, H.A., Samawi, M.F., Faizal, A., Moore, A.M., Jompa, J., 2021. Diversity and abundance of phytoplankton in the coastal Waters of South Sulawesi. *HAYATI J Biosci*. 28, 199-211. https://doi.org/10.4308/hjb.28.3.199

Liwun, R.R., Yulianti, L.I., Sidharta, B.R., 2020. Potensi *Skeletonema* costatum (Greville) sebagai fikoremediator logam berat timbal (Pb) limbah batik. *Biota: Jurnal Ilmiah Ilmu-Ilmu Hayati.* 5, 16–24. https://doi.org/10.24002/biota.v5i1.2950

Mason, C. F., 1991. *Biology of Freshwater Pollution*, vol. 2. Longman Scientific & Technical.

Muhtadi, A., Leidonald, R., 2024. The relationship between water quality and aquatic organisms in tidal lakes, Medan-Indonesia. *IOP Conf. Ser.: Earth Environ. Sci.* 1302, 012061. https://doi.org/10.1088/1755-1315/1302/1/012061

Muhtadi, A., Pulungan, A., Nurmaiyah, Fadlhin, A., Melati, P., Sinaga, R.Z., Uliya, R., Rizki, M., Rohim, N., Ifanda, D., Leidonald, R., Wahyuningsih, H., and Hasani, Q., 2020. The dynamics of the plankton community on Lake Siombak, a tropical tidal lake in North Sumatra, Indonesia. *Biodiversitas.* 21, 3707-3719. https://doi.org/10.13057/biodiv/d210838

Muhtadi, A., Leidonald, R., Cordova, M.R., 2024. The effect of tides on the dynamics of water quality in Indonesian tropical tidal lakes. *IOP Conf. Ser.: Earth Environ. Sci.* 1436, 12009. https://doi.org/10.1088/1755-1315/1436/1/012009

Muhtadi, A., Leidonald, R., Rohim, N., Firdaus, M., 2025a. Effect of moon phase during tides on variation of aquatic biodiversity in a tropical coastal lake of Anak Laut Lake, Aceh, Indonesia. *Biodiversitas.* 26, 810-823. https://doi.org/10.13057/biodiv/d260229

Muhtadi, A., Leidonald, R., Fadhilah, A., Mukra, R., 2025b. Water quality dynamics and water pollutions of Belawan Estuary, North Sumatra-Indonesia. Indones. *J. Limnol.* 6, 1-12. https://doi.org/10.51264/inajl.v6i1.80

Muhtadi, A., Leidonald, A., Rahmawati, A., Merdangga, T.D.T., Nurhamiyah, Y., Cordova, M.R., 2025c. Spatial and temporal distribution of microplastics in the Belawan Estuary, Indonesia. *Egypt. J. Aquat. Res.* 15, 163-171. https://doi.org/10.1016/j.ejar.2025.03.004

Muhtadi, A., Leidonald, R., Maiyah, N., Ishak, M.Y. 2025d. Microplastic pollution in the Belawan Estuary, Indonesia: evidence from aquatic biota and polymer characterization. *Biodiversitas.* 26, 2002-2010. https://doi.org/10.13057/biodiv/d260449

Nugroho, H., Anggoro, S., Widowati, I., 2019. Biological hotspot larva ikan diperairan Estuari Desa Timbulsoko, Demak. *Preprints.* 2019, 2019070346. https://doi.org/10.20944/preprints201907.0346.v1

Nurdin, J., Aziz, R., Nur, L., Janra, M.N., 2025. Water quality assessment based on saprobic index of phytoplankton with emphasis on several potentially Harmful Algal Blooms (HABs). *Biodiversitas.* 26, 890-899. https://doi.org/10.13057/biodiv/d260238

Nuriasih, D.M., Anggoro, S., Haeruddin, 2018. Saprobic analysis to marina coastal, Semarang City. *IOP Conf. Ser.: Earth Environ. Sci.* 116, 012096. https://doi.org/10.1088/1755-1315/116/1/012096

Nybakken, J.W., Bertness, M., 2005. *Marine Biology: an Ecological Approach*, sixth ed. San Pearson/Benjamin Cummings, Francisco (US).

Odum, E.P., Barrett, G.W., 2005. Fundamental of Ecology, fifth ed. Brooks/Cole Publishing Co, Belmont, CA.

Pane, Y., Ridwan, F.M., Hassan, Z., Sembiring, D.S.P.S., 2023. Analysis of water pollution problem Belawan waters. *IOP Conf. Ser.: Earth Environ. Sci.* 1135, 012027. https://doi.org/10.1088/1755-1315/1135/1/012027

Pelage, L., Gonzalez, J.G., Le Loc'h, F., Ferreira, V., Munaron, J.M., Lucena-Frédou, F., Frédou, T., 2021. Importance of estuary morphology for ecological connectivity with their adjacent coast: a case study in Brazilian tropical estuaries. *Estuar Coast Shelf Sci.* 251, 107184. https://doi.org/10.1016/j.ecss.2021.107184

Perda, 2019. Peraturan Daerah Provinsi Sumatera Utara tentang Rencana Zonasi Wilayah Pesisir dan Pulau-Pulau Kecil Provinsi Sumatera Utara Tahun 2019-2039. Pemerintahan Provinsi Sumatera Utara, Medan. [Indonesian]

Perda, 2022. Peraturan Daerah Kota Medan Tentang Rencana Tata Ruang Wilayah Kota Medan Tahun 2022-2042. Pemerintahan Daerah Kota Medan, Medan.[Indonesian]

Rangkuti, A.M., Cordova, M.R., Rahmawati, A., Yulma, Adim, H.E. , 2017. *Ekosistem Pesisir dan Laut Indonesia*, first ed. PT.Bumi Aksara, Jakarta.

, Rahmadya, A., Rohaningsih, D., Novianti, R., Waluyo, A., Aisyah, S., Rosidah, 2024. Plankton community structure in the estuaries of Banten Bay, Banten Province, Indonesia. *LIMNOTEK Perairan Darat Tropis di Indonesia*. 30, 69-83. https://doi.org/10.55981/limnotek.2024.5100

Takarina, N.D., Nurliansyah, W., Wardhana, W., 2019. Relationship between environmental parameters and the plankton community of the Batuhideung Fishing Grounds. *Biodiversitas.* 20, 171–180. https://doi.org/10.13057/BIODIV/D200120

Thoha, A.S., Lubis O.O.A., Hulu, D.L.N., Sari, T.Y., Mardiyadi, Z., 2022. Utilization of UAV technology for mapping of mangrove ecosystem at Belawan, Medan City, North Sumatera, Indonesia. *IOP Conf. Ser.: Earth Environ. Sci.* 977, 012102. https://doi.org/10.1088/1755-1315/977/1/012102

Tjahjono, A. Wahyuni, A., Purwantini, S., 2018. The assessment of biological and pollution index of estuaries around port of Tanjung Emas Semarang. *IOP Conf. Ser.: Earth Environ. Sci.* 116, 012087. https://doi.org/10.1088/1755-1315/116/1/012087

Sulistyowati1, L., Yolanda Y, Andareswari, N., 2023. Harbor water pollution by heavy metal concentrations in sediments. *Global J. Environ. Sci. Manage.* 9, 885-898. https://doi.org/10.22034/gjesm.2023.04.15

Widiani, I., Barus, T.A., Wahyuningsih, H., 2021. Population of white shrimp (*Penaeus merguiensis*) in a mangrove ecosystem, Belawan, North Sumatra, Indonesia. *Biodiversitas.* 22, 5367–5374. https://doi.org/10.13057/BIODIV/D221218

Woodland, R.J., Harris, L., Reilly, E., Fireman, A., Schott, E., Heyes, A.,2022. Food web restructuring across an urban estuarine gradient. *Ambio.* 51, 888–900. https://doi.org/10.1007/s13280-021-01610-1

Yang, C., Nan, J., Li, J., 2019. Driving factors and dynamics of phytoplankton community and functional groups in an estuary reservoir in the Yangtze River, China. *Water.* 11, 1184. https://doi.org/10.3390/w11061184

Yusfaddillah, A., Saputri, R.D., Edelwis, T.W., Pardi, H., 2023. Heavy metal pollution in Indonesian waters. *BIO Web of Conferences.* 79, 04001. https://doi.org/10.1051/bioconf/20237904001

Zhao, W., Zhao, Y., Wang, Q., Zheng, M., Wei, J., Wang, S., 2016. The community structure and seasonal dynamics of plankton in Bange Lake, northern Tibet, China. *Chin J Oceanol Limnol.* 34, 1143–1157. https://doi.org/10.1007/s00343-016-5131-0