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Phytoplankton diversity as a bioindicator of organic pollution in the estuary of Lhokseumawe City, Aceh, Indonesia

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Abstract. *Erlangga, Effendi H, Damar A, Taryono, Nurjaya IW. 2025. Phytoplankton diversity as a bioindicator of organic pollution in the estuary of Lhokseumawe City, Aceh, Indonesia. Biodiversitas 26: 3528-3544.* Phytoplankton biodiversity serves as a crucial bioindicator of organic pollution in estuarine ecosystems. This study aims to assess phytoplankton diversity in the Lhokseumawe Estuary, Aceh Province, Indonesia, to evaluate organic pollution levels. Sampling was conducted at five stations from July to November 2024 using a purposive sampling method. Phytoplankton were identified and analyzed to determine species composition, abundance, and ecological indices. A total of 32 species from five major phytoplankton classes were identified, dominated by Bacillariophyceae (43%) and Mediophyceae, while Cyanophyceae contributed only 3%. The highest species richness was observed in July (25 taxa), decreasing to 20 taxa in September. Phytoplankton abundance declined from 20,525,346 cells/m³ in July to 13,609,643 cells/m³ in November. Spatially, the highest phytoplankton abundance occurred at stations 5 and 3, indicating localized nutrient inputs from surrounding anthropogenic sources. The Mediophyceae class exhibited the highest abundance, while Dinophyceae had the lowest. The Shannon diversity index (H') ranged from 1.79 to 2.30 and evenness from 0.65 to 0.77, indicating moderate community stability with low dominance (0.14-0.24) across stations. The prevalence of Bacillariophyceae and Mediophyceae, particularly eutrophication-tolerant genera like *Nitzschia, Navicula, Skeletonema*, and *Chaetoceros*, suggests nutrient enrichment from anthropogenic sources such as domestic wastewater and agricultural runoff. However, the low Palmer Pollution Index score (6) and Algae Group Index value (3.61) indicate that organic pollution remains minimal, with diatom dominance reflecting relatively good water quality conditions. Seasonal variations in abundance and composition further highlight the influence of environmental changes and pollution on estuarine phytoplankton dynamics. These findings confirm that the Lhokseumawe Estuary is experiencing eutrophication driven by organic pollution, and the phytoplankton biodiversity metrics provide reliable indicators for monitoring such environmental disturbances. This study represents the first assessment of phytoplankton diversity in this region and provides essential baseline data for ongoing environmental monitoring and management strategies.

Keywords: Biodiversity, estuary, organic pollution, phytoplankton

INTRODUCTION

Phytoplankton biodiversity plays a key role in aquatic ecosystems as primary producers and components of food webs, contributing to oxygen production, carbon sequestration, and nutrient cycling (Nurhatika et al. 2018; Tucong et al. 2024). These organisms are highly responsive to environmental changes, making them ideal bioindicators of water quality (Tang et al. 2024). Phytoplankton's sensitivity to pollution, especially in estuaries, allows shifts in their community structure to assess anthropogenic impacts (Febriansyah et al. 2023). In Indonesia, Sulistiono et al. (2022) further support this by showing that changes in Banten Bay's phytoplankton biodiversity reflect organic pollution from nearby industrial and human activities. Given their importance, understanding phytoplankton biodiversity is essential for assessing ecosystem health. Yunandar et al. (2020) also noted that plankton diversity in South Kalimantan's Paminggir peatlands was influenced by factors like salinity and nutrients, emphasizing the need for ongoing monitoring in anthropogenic areas.

Estuaries are highly productive yet vulnerable ecosystems (Hasan et al. 2022a, et al. 2023a). They are frequently subject to pollution from urban, industrial, and agricultural runoff, particularly organic pollutants such as domestic waste, fertilizers, and livestock effluents (Zhang et al. 2015; Hussain 2024). These organic inputs can lead to nutrient enrichment, causing eutrophication—a process that disrupts ecosystem balance by promoting the excessive growth of certain phytoplankton species, often at the expense of biodiversity and water quality (Preisner et al. 2020). Such disturbances are not only ecologically damaging but can also threaten fisheries, tourism, and the overall sustainability of aquatic environments (González

and Roldán 2019). Damar et al. (2021) state that the increase in harmful algal blooms in Jakarta Bay, Indonesia, driven by eutrophication due to human activities, has significant ecological and public health impacts, emphasizing the need for effective phytoplankton monitoring amidst anthropogenic pressures.

Changes in phytoplankton community structure are often the first visible indicators of organic pollution. Tolerant species such as cyanobacteria and certain diatoms may dominate eutrophic waters, while sensitive species decline or disappear (D'Costa et al. 2017; Dos Anjos et al. 2024). These shifts not only reflect the immediate water quality but also have cascading effects on higher trophic levels. Because of their rapid reproduction and short life cycles, phytoplankton respond quickly to environmental disturbances, making them ideal for real-time ecological monitoring (Li et al. 2020). Observations of phytoplankton diversity and abundance, therefore, provide reliable and efficient tools for the early detection of ecological imbalances and pollution levels.

Indonesia, a megadiverse nation, hosts abundant aquatic ecosystems with high endemism (Hasan et al. 2023b; Valen et al. 2024). However, its estuarine and freshwater systems face significant pressure from land-use change, pollution, and poor environmental management (Hasan and Islam 2020; Valen et al. 2020; Arfianti et al. 2022). Despite these challenges, comprehensive assessments of aquatic biodiversity, especially phytoplankton, are limited, hindering effective conservation and management (Fitri et al. 2021). As Vörösmarty et al. (2021) note, integrating biodiversity data into water governance is crucial for sustainable freshwater futures.

The Lhokseumawe Estuary, located in a densely populated and industrialized region of Aceh Province, Indonesia, with over 200,000 inhabitants, represents one of the most anthropogenically impacted estuarine systems in northern Sumatra. This estuary continuously receives untreated domestic sewage and industrial effluents, resulting in elevated nutrient loads and potentially chronic eutrophic conditions. While previous studies in Lhokseumawe Aceh have explored marine fish (Damora et al. 2020), microalgae (Erlangga et al. 2022a), Bivalvia (Erlangga et al. 2022b), Oil spill (Fadilurrahman et al. 2022), assessment of non-metallic pollutant sources (Ezraneti et al. 2021), there remains a significant knowledge gap regarding phytoplankton community structure and its role as a bioindicator of organic pollution in urbanized estuaries. Most prior research has focused on open coastal waters or coral reef habitats, without addressing the synergistic effects of anthropogenic nutrient inputs on estuarine phytoplankton dynamics. To date, no comprehensive study has assessed phytoplankton biodiversity in conjunction with eutrophication processes in the Lhokseumawe Estuary. Therefore, this study offers a novel contribution by integrating phytoplankton-based ecological assessment with eutrophication indicators, providing a scientific foundation for evidence-based management strategies in one of Sumatra's most vulnerable coastal ecosystems.

Based on the background described above, this study is guided by a central research question: How does organic pollution influence the biodiversity and community structure of phytoplankton in the Lhokseumawe Estuary? To address this overarching question, the study focuses on three specific research problems. First, it examines the current status of phytoplankton biodiversity and community composition in the estuary. Second, it investigates the extent to which organic pollution affects phytoplankton diversity and abundance. Third, it explores whether shifts in phytoplankton communities can serve as reliable bioindicators of ecological disturbance caused by nutrient enrichment. These research problems are designed to provide a scientific basis for using phytoplankton as early warning indicators of eutrophication, while also contributing to the development of targeted estuarine management strategies in heavily urbanized coastal areas.

MATERIALS AND METHODS

Study area

The research was conducted in Lhokseumawe Estuary waters, Lhokseumawe City, Aceh Province, Indonesia. To determine the sampling station using purposive sampling method. This method selects stations for sampling purposefully based on the research objectives, namely organic pollution. Based on this method, the research site consists of 5 observation stations that represent the characteristics of coastal waters of Lhokseumawe City that are affected by organic material pollution from land activities. The land area affecting the Lhokseumawe Estuary waters is included in 3 sub-districts, namely Banda Sakti, Muara Satu and Blang Mangat. The research location and sampling coordinates are shown in Table 1 and Figure 1.

Station 1 (Banda Sakti and Muara Satu)

This station is located in the inner estuary area influenced by the Banda Sakti and Muara Satu sub-districts. Banda Sakti covers an area of 11.24 km² with a population of 78,256 people and a population growth rate of 0.35%, characterized by dense settlements and the presence of mangrove ecosystems. Muara Satu spans 55.90 km² with a population of 34,069 people and a growth rate of 0.42%. The main activities in this area include agriculture (approximately 340 hectares of rice fields), residential areas, and small-scale aquaculture. These land uses contribute to organic pollution through domestic waste and agricultural runoff entering the estuary.

Table 1. Coordinate point of observation of phytoplankton

Station	Sub-district	Geographic coordinates
1	Banda sakti dan Muara Satu	$5^0$10'21"N, $97^0$08'10"E
2	Banda sakti dan Muara Satu	$5^0$10'08"N, $97^0$08'19"E
3	Banda sakti dan Blang Mangat	$5^0$09'28"N, $97^0$08'37"E
4	Laut lepas	$5^0$09'37"N, $97^0$09'14"E
5	Blang Mangat	$5^0$09'20"N, $97^0$09'00"E

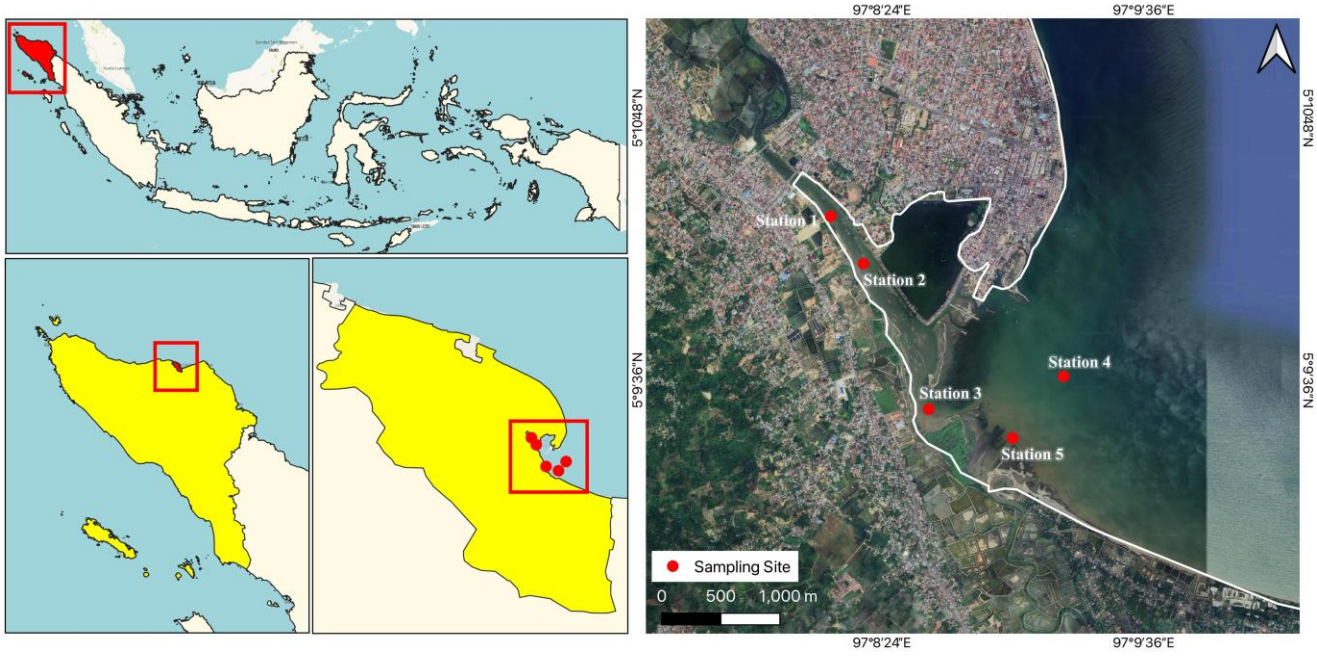

Figure 1. Location and observation stations

Station 2 (Banda Sakti and Muara Satu)

Similar to Station 1, Station 2 is located within the estuarine zone but positioned further downstream. This site continues to receive anthropogenic inputs from Banda Sakti and Muara Satu. The surrounding activities include agriculture, residential areas, and remnants of mangrove ecosystems, which serve as important buffer zones but are under pressure from urban expansion.

Station 3 (Banda Sakti and Blang Mangat)

Station 3 is in a transitional area influenced by the Banda Sakti and Blang Mangat sub-districts. Blang Mangat covers an area of 56.12 km² with a population of 26,992 and a relatively high population growth rate of 1.63%. The land use is dominated by agriculture (approximately 627 hectares of rice fields), settlements, and aquaculture activities. This station reflects the combined influence of urban runoff and agricultural discharge.

Station 4 (Open Sea)

Station 4 is located offshore, representing the outer estuarine environment with limited direct influence from land-based activities. This site serves as a reference area where water circulation is stronger, and anthropogenic input is expected to be lower compared to the inner estuary.

Station 5 (Blang Mangat)

This station is situated in a zone dominated by agricultural land use in Blang Mangat. Runoff from paddy fields and livestock farms contributes nutrients and organic matter to the estuary, making this site important for assessing agricultural impacts.

Procedures

Sampling technique

Phytoplankton sampling was conducted every two months from July to November 2024. At each station, sampling was repeated three times to improve the accuracy and representativeness of the data. All procedures followed standardized ecological monitoring protocols recommended by the BC Ministry of Environment (2016). Phytoplankton samples were collected at depths corresponding to the maximum sunlight penetration, determined using a Secchi disk to measure water transparency in the estuary (Lind 1979; TCEQ 2013). This approach reliably estimates the euphotic zone, the principal habitat for phytoplankton photosynthesis (Preisendorfer 1986; Wernand 2010). Phytoplankton samples were collected using a plankton net and a Van Dorn water sampler. Approximately 4.4 liters of water were collected from the designated depth using the Van Dorn sampler and subsequently filtered to obtain a 100 ml composite sample for laboratory analysis (BC Ministry of Environment 2016; APHA 2017). To preserve the cellular integrity of the phytoplankton and prevent further decomposition, 2 mL of Lugol's iodine solution was added to each 100 ml sample immediately after collection (Lund et al. 1958; TCEQ 2013). Lugol's solution is a standard preservative that stains phytoplankton cells, allowing for their long-term storage and subsequent microscopic examination.

Phytoplankton identification

Identification and counting of phytoplankton were conducted using an Olympus CX 23 microscope light microscope equipped with Sedgwick Rafter Counting (SRC) chamber. Observations were performed at 100× magnification. An ocular micrometer with a range of -100

µm was used to estimate the size and scale of specimens. The census methods were applied, and taxonomic identification was carried out by referring to Yamaji (1984), Tomas (1997), and Guiry and Guiry (2023) to ensure accurate and updated classification of phytoplankton genera.

Data analysis

Phytoplankton biodiversity was calculated from abundance, diversity index (Shannon-Wienner), evenness index and dominance index (Simpson) following the ecological methodology (Krebs 1989). Formulas for calculating abundance using formula (1) (APHA 2017); (2) diversity index (Magurran 2013), (3) evenenes index (Pielou 1966); (4) dominance index (Simpson 1949).

$$N = n\,x\left(\frac{Vr}{Vo}\right)x\left(\frac{1}{Vs}\right) \quad [1]$$

$$H' = -\sum_{i=1}^{n}(pi\ln pi) \quad [2]$$

$$E = \frac{H'}{H\,maks} \quad [3]$$

$$D = \sum_{n=1}^{N}\left(\frac{ni}{N}\right)2 \quad [4]$$

Where, N: Number of cells per liter (Ind/L); n: Number of identified cells (Ind); Vr: Volume of filtered water (mL); V0: Volume of observed water (mL); Vs: Volume of filtered water (L); Pi: Proportion of individuals of species i to the total number of individuals of all species (Pi = ni/N), ni: Number of individuals/species/types; N: Total number of individuals. The assessment of organic pollution in samples in the present study was conducted using the Palmer Algal Pollution Index (Palmer 1969). This index is based on the presence and abundance of algal genera and species known to exhibit high tolerance to organic pollution. Palmer (1969) compiled a list comprising 20 algal genera and 20 algal species, each assigned a specific pollution tolerance score. The cumulative score derived from these taxa provides an indication of organic pollution levels, as categorized in the pollution index scale (Table 2). According to this classification, a score of 0-10 indicates the absence of organic pollution, 11-15 suggests moderate pollution, 16-19 reflects a high likelihood of organic pollution, and a score of ≥20 denotes significant organic pollution.

Table 2. Algal Genus Pollution Index (Palmer 1969)

Genus	Index	Genus	Index
Oscillatoria	5	*Ankistrodesmus*	2
Euglena	5	*Closterium*	1
Scenedesmus	4	*Cyclotella*	1
Chlamydomonas	4	*Gomphonema*	1
Chlorella	3	*Lepocinclis*	1
Nitzschia	3	*Melosira*	1
Navicula	3	*Micractinium*	1
Phacus	2	*Pandorina*	1
Stigeoclonium	2	*Phormidium*	1
Synedra	2	*Anacystis*	1

The Algae Group Index (AGI) was applied in this study to assess the level of organic pollution in the estuarine ecosystem based on the relative abundance of major phytoplankton groups. The index was calculated following the formula proposed by Zalewska-Gałosz et al. (2012), which considers the proportion of pollution-tolerant groups (Cyanophyceae and Euglenophyceae) relative to pollution-sensitive groups (Chlorophyceae and Bacillariophyceae). AGI was computed using the equation:

$$AGI = \frac{(\%Cyanophyceae + \%Euglenophyceae)}{(\%Chlorophyceae + \%Bacillariphyceae)}\ x\ 100$$

A higher Algae Group Index (AGI) value reflects a greater dominance of pollution-tolerant phytoplankton taxa, thereby indicating an increased level of organic pollution in the aquatic environment. However, when applied to estuarine systems, interpretation of AGI should be made cautiously due to the inherent variability in salinity, hydrodynamics, and nutrient inputs typical of transitional waters. Based on the classification by Zalewska-Gałosz et al. (2012), AGI values below 100 suggest good water quality with minimal organic pollution, values between 100 and 200 indicate the onset of organic enrichment, while values exceeding 200 are associated with high levels of organic pollution.

RESULTS AND DISCUSSION

Groups of phytoplankton

The phytoplankton found consisted of 5 major classes, namely Bacillariophyceae, Coscinodiscophyceae, Dinophyceae, Cyanophyceae and Mediophyceae. The percentage of phytoplankton classes found in Lhokseumawe Estuary in July-November 2024 is the highest from Bacillariophyceae class with 43%, while the lowest is from Cyanophyceae class with 3%. The percentage of phytoplankton species can be clearly seen in Figure 2. The species found can be seen in Table 3 and Figures 3-6.

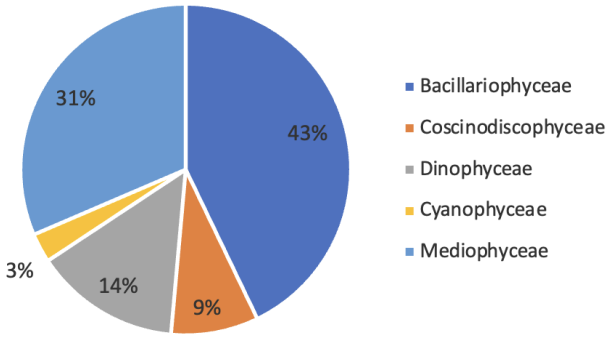

Figure 2. Percentage of phytoplankton classes in the Lhokseumawe Estuary, Lhokseumawe City, Aceh Province, Indonesia

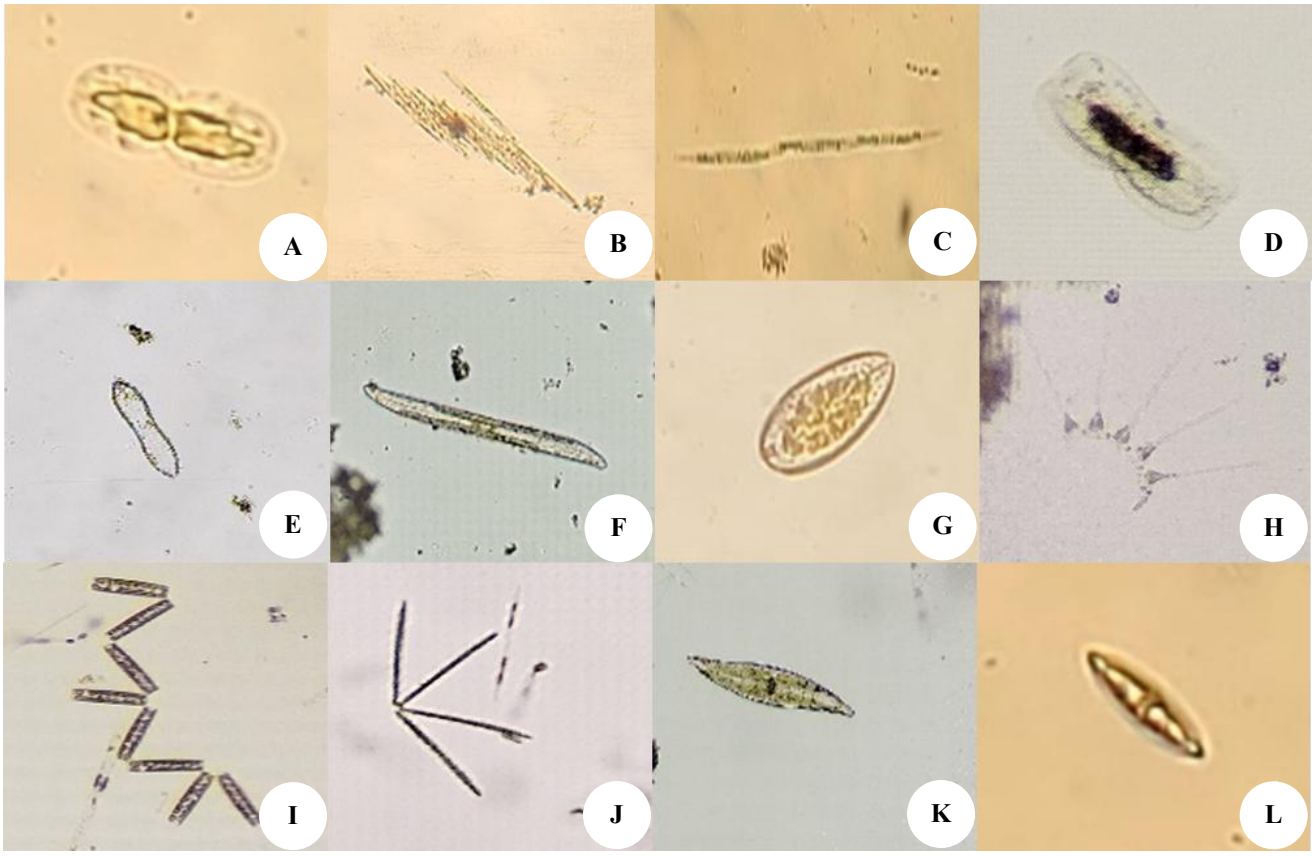

Figure 3. Species from the class of Bacillariophyceae observed under light microscopy (100x). A. *Amphiprora* sp., B. *Bacillaria* sp., C. *Nitzschia* sp., D. *Amphora* sp., E. *Diploneis* sp., F. *Pleurosigma* sp., G. *Surirella* sp., H. *Asterionella* sp., I. *Thalassionema* sp., J. *Thalassiothrix* sp., K. *Gyrosigma* sp., L. *Navicula* sp. Scale estimated using ocular micrometer (0-100 µm)

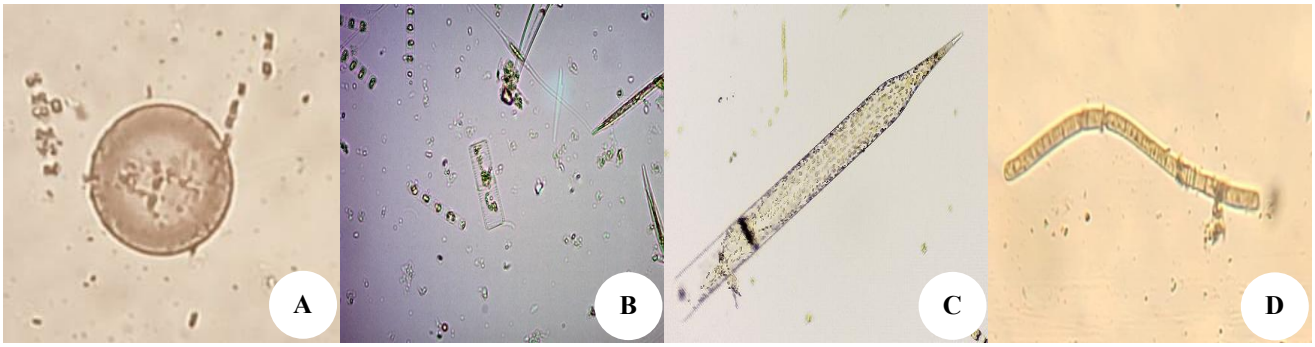

Figure 4. Species from the class of Coscinodiscophyceae and Class of *Cyanophyceae* observed under light microscopy (100x). A. *Coscinodiscus* sp., B. *Guinardia* sp., C. *Rhizosolenia* sp., D. Trichodesmium sp. Scale estimated using ocular micrometer (0-100 µm)

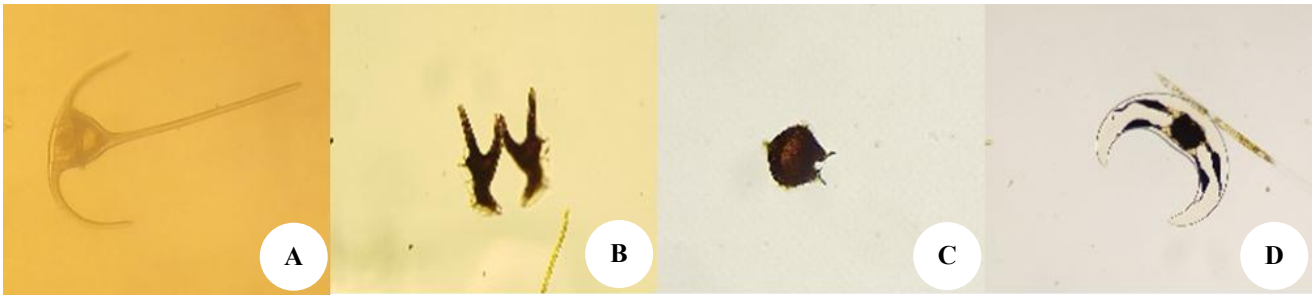

Figure 5. Species from the class of Dinophyceae observed under light microscopy (100x). A. *Ceratium* sp., B. *Dinophysis* sp., C. *Peridinium* sp., D. *Pyrocystis* sp. Scale estimated using ocular micrometer (0-100 µm)

Table 3. Species of phytoplankton in the Lhokseumawe Estuary, Lhokseumawe City, Aceh Province, Indonesia

Class, Family	Genus
Bacillariophyceae	
Fragilariaceae	*Fragilaria* sp.
Amphipleuraceae	*Amphiprora* sp.
Bacillariaceae	*Bacillaria* sp.
	Nitzschia sp.
Catenulaceae	*Amphora* sp.
Cocconeidaceae	*Cocconeis* sp.
Diploneidaceae	*Diploneis* sp.
Pleurosigmataceae	*Pleurosigma* sp.
Striatellaceae	*Striatella* sp.
Surirellaceae	*Surirella* sp.
Tabellariaceae	*Asterionella* sp.
Thalassionemataceae	*Thalassionema* sp.
	Thalassiothrix sp.
Naviculaceae	*Gyrosigma* sp.
	Navicula sp.
Coscinodiscophyceae	
Coscinodiscaceae	*Coscinodiscus* sp.
Rhizosoleniaceae	*Guinardia* sp.
	Rhizosolenia sp.
Dinophyceae	
Ceratiaceae	*Ceratium* sp.
Dinophysaceae	*Dinophysis* sp.
Gonyaulacaceae	*Gonyaulax* sp.
Peridiniaceae	*Peridinium* sp.
Pyrocystaceae	*Pyrocystis* sp.
Cyanophyceae	
Microcoleaceae	*Trichodesmium* sp.
Mediophyceae	
Ardissoneaceae	*Climacosphenia* sp.
Biddulphiaceae	*Biddulphia* sp.
Hemiaulaceae	*Hemiaulus* sp.
Lauderiaceae	*Lauderia* sp.
Leptocylindraceae	*Leptocylindrus* sp.
Lithodesmiaceae	*Streptotheca* sp.
	Ditylum sp.
Skeletonemataceae	*Skeletonema* sp.
Thalassiosiraceae	*Planktoniella* sp.
Chaetocerotaceae	*Bacteriastrum* sp.
	Chaetoceros sp.

Number of taxa and biodiversity

The average number of species found at all stations during July-November 2024 (Figure 7) was lowest in September with a moderate number of 20 taxa and highest in July with 25 taxa. The average abundance of phytoplankton per class shows different percentages, which can be clearly seen in the Figure 8. There is a difference between the Dinophyceae and Cyanophyceae classes. In the Dinophyceae class with a larger number of species than Cyanophyceae but based on the results of the calculation of the abundance of species, it shows that the Dinophyceae class has a very low abundance compared to the Cyanophyceae class. For other classes, the abundance is equal to the number of phyto-species found.

The average abundance at all stations showed a decrease from July to November 2024 with an average value of 20,525,346 cells.m^{-3} to 13,609,643 cells.m^{-3}. This is clearly seen in Figure 9.

To further illustrate the distribution and abundance of dominant phytoplankton genera, Figures 10.A and 10.B present the temporal and spatial abundance of six key genera observed throughout the study period. The phytoplankton community was primarily dominated by Cyanophyceae and Mediophyceae, with three dominant genera (Skeletonema, Chaetoceros, and Trichodesmium) consistently identified throughout the observation period. As illustrated in Figure 10.A, the highest total abundances across all genera were observed spatially at Stations 2 and 3, reaching up to 14×10^6 cells.m^{-3}. Temporally, the highest phytoplankton abundance occurred in July, with a peak value of 77.12×10^6 cells.m^{-3}.

Based on the figure above, it shows that the average abundance of phytoplankton is highest at Station 5 and Station 3 with an average abundance value during July-November 2024 of 20,596,736 cells.m^{-3} and 19,470,194 cells.m^{-3}, respectively. Based on the phytoplankton class during the observation period, it was found that the highest average abundance was in the Mediophyceae class with an abundance value of 7,976,932 cells.m^{-3} and the lowest was in the Dinophyceae class with a value of 217,714 cells.m^{-3}, which can be clearly seen in Figure 11. The value of the diversity index (H'), evenness index (E), and dominance (D) of the research results can be seen in Table 4.

Figure 12 visualizes the spatial and temporal variation of ecological indices, demonstrating the influence of organic pollution on phytoplankton community structure across estuarine gradients. Variations in H′, E, and D indices reflect site-specific ecological responses to environmental stressors.

Spatial analysis of ecological indices revealed distinct patterns across stations. Station 5 consistently exhibited the highest Shannon diversity (H′: 2.31) and the lowest dominance index (D: 0.14), indicating a more balanced and stable phytoplankton community structure. Similarly, Station 4 also demonstrated high diversity and low dominance, reflecting minimal anthropogenic disturbance. In contrast, Station 1 showed the lowest diversity and the highest dominance values, suggesting pronounced ecological stress, likely driven by inputs from nearby urban and domestic runoff sources.

To visualize the spatial heterogeneity of phytoplankton community structure, Figure 13 integrates Shannon diversity (H′) and dominance index (D) across five sampling stations. Symbol size reflects phytoplankton diversity, while color intensity represents the level of dominance, allowing a rapid assessment of ecological stress gradients along the estuary.

Spatial visualization of phytoplankton ecological indices across five stations in the Lhokseumawe Estuary reveals clear spatial gradients in community structure. Symbol size reflects mean Shannon diversity (H′), while color intensity denotes the dominance index (D), enabling simultaneous interpretation of biodiversity and ecological stress levels. Station 5 exhibited the highest phytoplankton diversity and lowest dominance, indicating a more balanced and resilient community likely supported by lower anthropogenic disturbance. Similarly, Station 4 also showed high diversity and low dominance, reinforcing its

status as a relatively stable site. In contrast, Stations 1 and 2—located near urban discharge zones—displayed lower diversity and higher dominance, suggesting increased ecological stress associated with organic pollution and eutrophication. These spatial patterns highlight the value of phytoplankton-based indices in detecting localized environmental degradation and underscore the importance of spatially resolved monitoring in estuarine ecosystems.

Based on the results of the Palmer Algal Pollution Index calculations for the estuarine waters of Lhokseumawe across all sampling stations and observation months (July to November 2024), the pollution scores are presented in Table 5.

Based on the tabulated results and classification thresholds of the Palmer Algal Pollution Index, the estuarine waters of Lhokseumawe, with an index score of 6, fall within the 0-10 category. This score indicates the absence of organic pollution in the studied area.

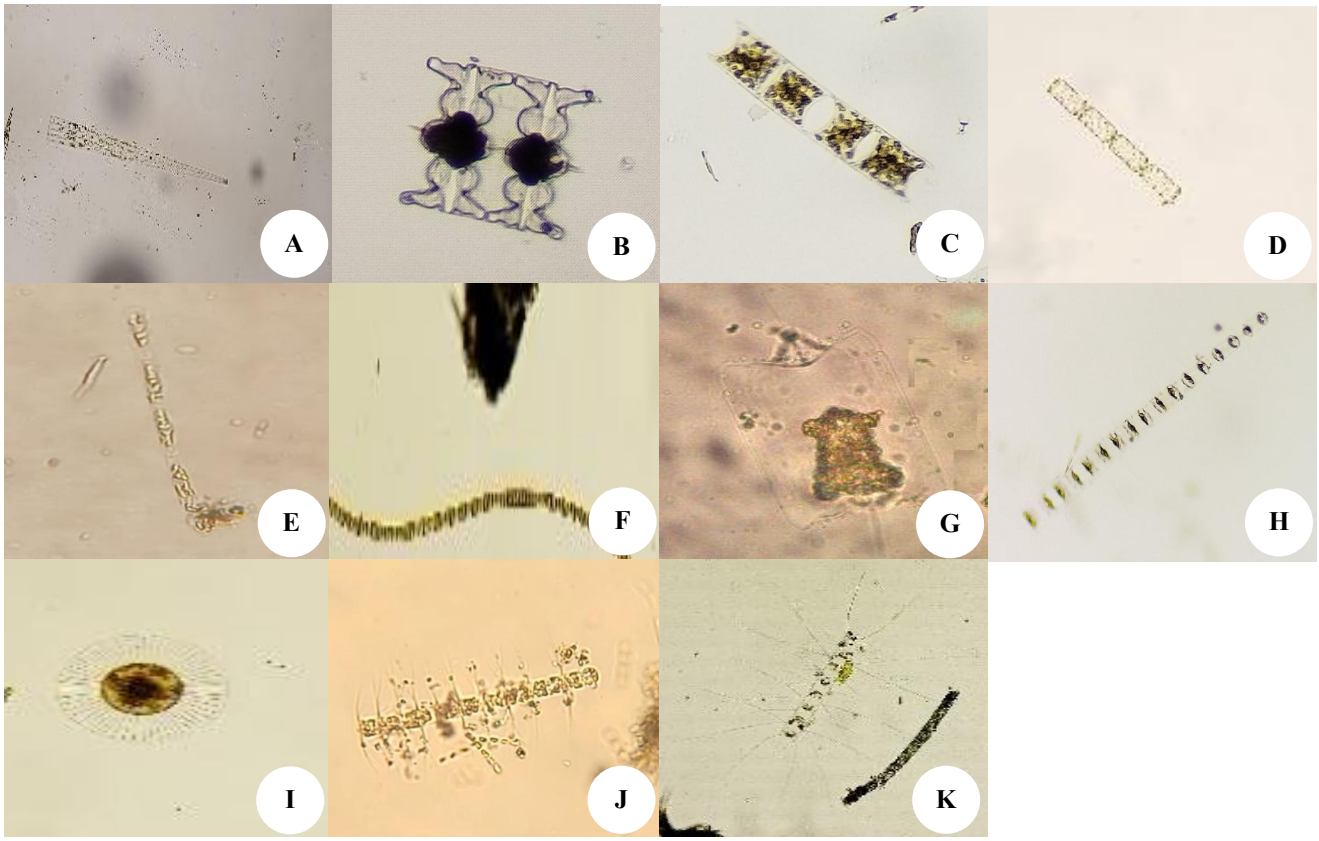

Figure 6. Species from the class of Mediophyceae observed under light microscopy (100x). A. *Climacosphenia* sp., B. *Biddulphia* sp., C. *Hemiaulus* sp., D. *Lauderia* sp., E. *Leptocylindrus* sp., F. *Streptotheca* sp., G. *Ditylum* sp., H. *Skeletonema* sp., I. *Planktoniella* sp., J. *Bacteriastrum* sp., K. *Chaetoceros* sp. Scale estimated using ocular micrometer (0-100 µm)

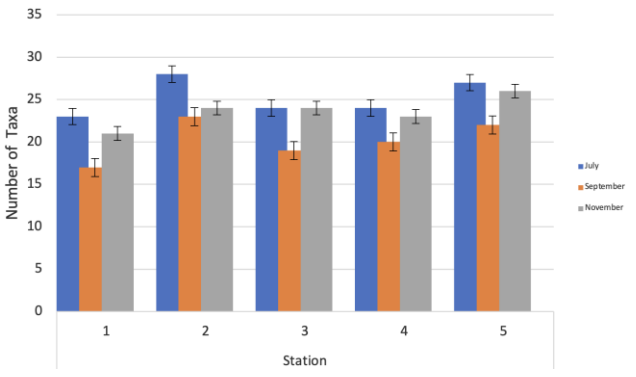

Figure 7. Average number of taxa during July-November 2024 per station

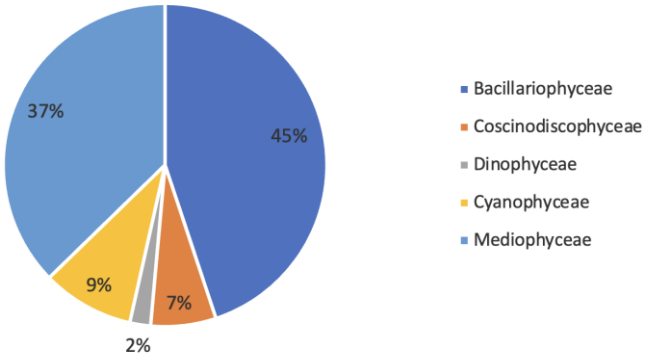

Figure 8. Average abundance percentage per class

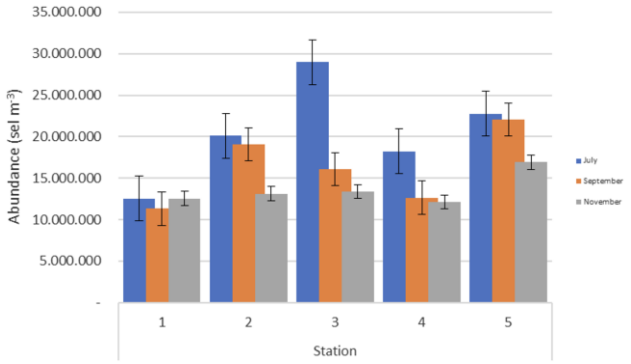

Figure 9. Average abundance of phytoplankton per station

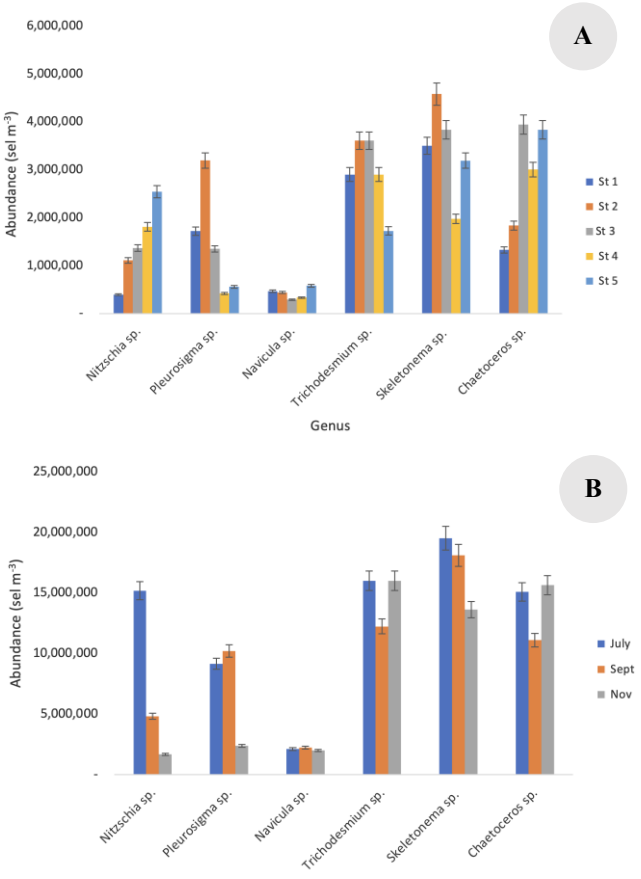

Figure 10. Abundance of six dominant phytoplankton genera in the Lhokseumawe Estuary, Lhokseumawe City, Aceh Province, Indonesia. A. Spatial variation across five stations, B. Temporal variation across three months

To support the assessment of organic pollution levels, the composition of phytoplankton at the class level was analyzed based on the relative abundance of dominant genera observed during the study period (Table 6). In the AGI approach proposed by Zalewska-Gałosz et al. (2012), phytoplankton are classified into two main groups: those tolerant and those sensitive to organic pollution. In the present dataset, the tolerant group is represented solely by Cyanophyceae (3%), with Euglenophyceae not detected. The sensitive group includes Bacillariophyceae (43%), Mediophyceae (31%), and Coscinodiscophyceae (9%), all of which belong to the Bacillariophyta division (Hasle and Syvertsen, 1996). Therefore, the total proportion of sensitive taxa is 83%, and the AGI value was calculated accordingly.

$$AGI = \frac{(3+0)}{(31+43+9)}\ x\ 100 = \frac{3}{83}\ x100 = 3.61$$

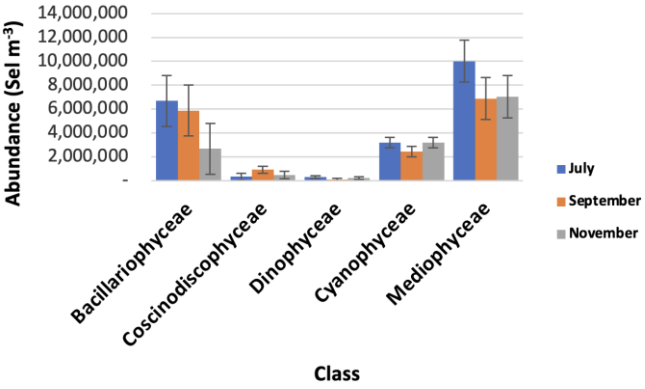

Figure 11. Average abundance per class during the period July-November 2024

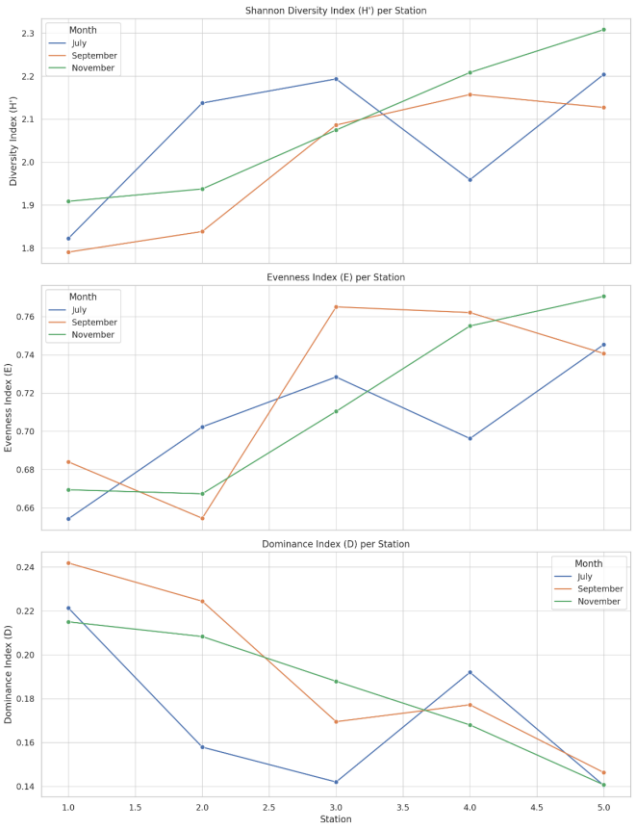

Figure 12. Spatial and temporal variation of phytoplankton diversity, evenness, and dominance indices

Table 4. Diversity, evennes, dominance index by station with temporal

Station	Month	Diversity	Category	Evenness	Category	Dominance	Category
1	July	1.8221	Moderate	0.6542	Moderate	0.2213	Low
	September	1.7903	Moderate	0.6840	Moderate	0.2418	Low
	November	1.9086	Moderate	0.6694	Moderate	0.2150	Low
2	July	2.1375	Moderate	0.7023	Moderate	0.1579	Low
	September	1.8383	Moderate	0.6545	Moderate	0.2244	Low
	November	1.9374	Moderate	0.6673	Moderate	0.2083	Low
3	July	2.1936	Moderate	0.7284	Moderate	0.1420	Low
	September	2.0863	Moderate	0.7651	High	0.1695	Low
	November	2.0746	Moderate	0.7104	Moderate	0.1879	Low
4	July	1.9588	Moderate	0.6962	Moderate	0.1920	Low
	September	2.1573	Moderate	0.7621	High	0.1772	Low
	November	2.2086	Moderate	0.7551	High	0.1680	Low
5	July	2.2043	Moderate	0.7454	Moderate	0.1404	Low
	September	2.1271	Moderate	0.7407	Moderate	0.1463	Low
	November	2.3084	Moderate	0.7706	High	0.1407	Low

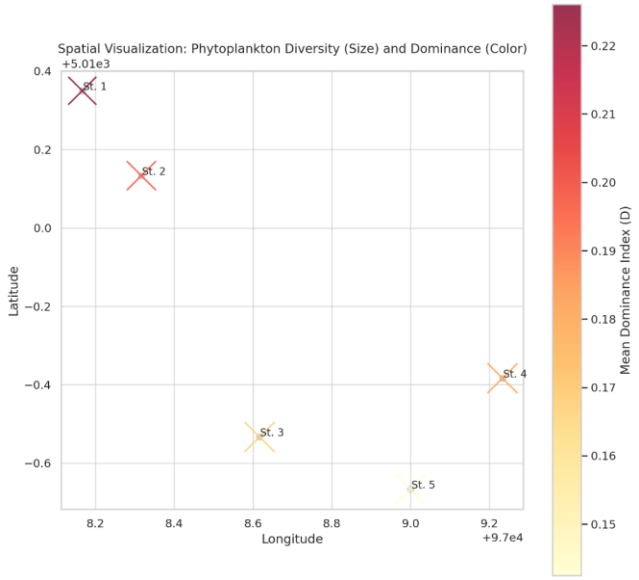

Figure 13. Spatial distribution of phytoplankton diversity and dominance indices

The obtained AGI value of 3.61 indicates very good water quality with minimal to negligible levels of organic pollution in the estuarine system. According to the classification by Zalewska-Gałosz et al. (2012), this value falls well below the threshold of 100, which reflects waters that are not significantly impacted by organic enrichment. Nevertheless, in estuarine environments, this interpretation should be made with caution due to natural variability in salinity and nutrient dynamics that may influence phytoplankton composition.

Discussion

Phytoplankton species composition

The study revealed that Bacillariophyceae dominated the phytoplankton community in the Lhokseumawe Estuary, accounting for 43% of the total population. This result is consistent with Hilaluddin et al. (2020), who reported the ecological adaptability of diatoms in estuarine waters. Similarly, Samawi et al. (2020) found that Bacillariophyceae constituted 75-86% of the phytoplankton community in South Sulawesi estuaries, confirming the frequent dominance of this class in tropical estuarine ecosystems. Additionally, the silica-based cell walls of diatoms confer mechanical strength and adaptability, allowing them to thrive in varying environmental conditions (Pančić et al. 2019). Recent studies have reinforced their role in primary productivity and their sensitivity to nutrient availability (Lefebvre and Dezécache 2020). The abundance of species like *Nitzschia* and *Navicula* is often associated with eutrophic conditions caused by excessive nutrient loading, primarily from organic pollution sources such as domestic wastewater, agricultural runoff, and industrial discharges (Hilaluddin et al. 2020). The dominance of these taxa suggests an environment experiencing nutrient enrichment, likely driven by human activities along the estuarine watershed. Additionally, the presence of *Pleurosigma* sp., a benthic diatom genus responsive to eutrophic and organically enriched estuarine conditions, further supports the indication of nutrient-driven ecological shifts in the sediment environment (Nunes et al. 2021).

Coscinodiscophyceae, represented by species such as *Coscinodiscus* and *Rhizosolenia*, exhibit a low but ecologically significant presence. These centric diatoms contribute to carbon cycling and are highly sensitive to variations in water quality, particularly fluctuations in organic matter (Zhang et al. 2023b). Their occurrence suggests episodic nutrient pulses originating from terrestrial sources, likely associated with stormwater runoff or domestic sewage discharge, which influence the structure of phytoplankton communities (Wang et al. 2022). Dinophyceae, including species such as *Ceratium* sp. and *Peridinium* sp., display relatively low abundance, consistent with their bloom-driven dynamics rather than sustained dominance. However, the detection of *Gonyaulax* sp. species raises concerns regarding the potential for Harmful Algal Blooms (HABs), which are often intensified by nutrient enrichment and organic pollution (Andree et al. 2024).

Table 5. Palmer's Pollution Index in Lhokseumawe Estuary, Lhokseumawe City, Aceh Province, Indonesia

Class	Genus	Juli					Sept					Nov				
		Stations					Stations					Stations				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Fragilariaceae	*Fragilaria* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amphipleuraceae	*Amphiprora* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bacillariaceae	*Bacillaria* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Nitzschia sp.	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Catenulaceae	*Amphora* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cocconeidaceae	*Cocconeis* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diploneidaceae	*Diploneis* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pleurosigmataceae	*Pleurosigma* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Striatellaceae	*Striatella* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Surirellaceae	*Surirella* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tabellariaceae	*Asterionella* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassionemataceae	*Thalassionema* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiothrix sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Naviculaceae	*Gyrosigma* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Navicula sp.	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Coscinodiscaceae	*Coscinodiscus* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhizosoleniaceae	*Guinardia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhizosolenia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratiaceae	*Ceratium* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dinophysaceae	*Dinophysis* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gonyaulacaceae	*Gonyaulax* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peridiniaceae	*Peridinium* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyrocystaceae	*Pyrocystis* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcoleaceae	*Trichodesmium* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ardissoneaceae	*Climacosphenia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biddulphiaceae	*Biddulphia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemiaulaceae	*Hemiaulus* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lauderiaceae	*Lauderia* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptocylindraceae	*Leptocylindrus* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lithodesmiaceae	*Streptotheca* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ditylum sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Skeletonemataceae	*Skeletonema* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosiraceae	*Planktoniella* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chaetocerotaceae	*Bacteriastrum* sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Chaetoceros sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

Table 6. Phytoplankton genus percentages in Lhokseumawe Estuarine, Lhokseumawe City, Aceh Province, Indonesia

Genus	Percentage (%)
Bacillariophyceae	43
Coscinodiscophyceae	9
Dinophyceae	14
Cyanophyceae	3
Mediophyceae	31

The presence of Cyanophyceae, although accounting for only ~3% of the phytoplankton community in the Lhokseumawe Estuary, plays an important role as an indicator of water quality degradation. This finding aligns with Soetignya et al. (2021), who reported a higher proportion (19.3%) of Cyanophyceae in the Kakap River estuary, West Kalimantan, where its abundance was associated with increased nitrogen input from anthropogenic sources. These results collectively support the role of Cyanobacteria, such as *Trichodesmium*, as responsive taxa to nitrogen enrichment caused by sewage discharge or fertilizer runoff. Although their presence is minimal, it indicates localized shifts in nutrient stoichiometry potentially driven by inputs of organic pollution (Rahav and Bar-Zeev 2017). Mediophyceae, including dominant species such as *Skeletonema* and *Chaetoceros*, exhibited the highest abundance, underscoring their role as opportunistic bloom-forming diatoms. These taxa respond rapidly to organic pollution and nutrient enrichment, making them effective bioindicators of estuarine eutrophication. Their dominance suggests episodic nutrient influxes that promote diatom proliferation over other phytoplankton groups (Zhao et al. 2021).

The dominance of Bacillariophyceae, particularly species such as *Nitzschia* and *Navicula*, is frequently associated with eutrophic conditions resulting from organic pollution. These diatoms are widely recognized as effective bioindicators for assessing the ecological status of aquatic ecosystems, as their abundance reflects nutrient enrichment

and anthropogenic influences (Tirado et al. 2021; Zhang et al. 2023a). Studies have shown that shifts in phytoplankton community structure—especially increased dominance of Bacillariophyceae—can serve as indicators of deteriorating water quality related to organic loading (Naik et al. 2020). In Indonesia, the dominance of Bacillariophyceae in phytoplankton communities has been consistently reported across various coastal and estuarine environments. For instance, Damar et al. (2020) observed that diatoms dominated all sampling stations in Jakarta Bay, with abundances ranging from 743,952 cells.L^{-1} in offshore areas to 6,432,016 cells.L^{-1} near river mouths. This finding aligns with Gurning et al. (2020), who reported Bacillariophyceae proportions of 66.00-76.74% in the same bay. Similar patterns have also been recorded in other regions, such as the Barrang Lompo Island in Makassar 97% (Madjid and Priosambodo 2025), and the Selan River estuary in Bangka 90% (Nazar et al. 2024). Therefore, the composition of phytoplankton communities—particularly the prevalence of diatoms—may serve as a reliable indicator of organic pollution levels and overall estuarine health, including in ecosystems such as the Lhokseumawe Estuary. These findings highlight the role of phytoplankton—particularly diatom communities—as effective bioindicators for detecting and monitoring organic pollution in estuarine environments.

Number of taxa and biodiversity

The observed variation in taxa counts, peaking in July with 25 taxa and dropping to 20 taxa in September, aligns with global patterns of phytoplankton seasonality driven by environmental factors such as temperature, light availability, and nutrient concentrations (Xiao et al. 2023). Similar seasonal dynamics were reported by Hasan et al. (2022b) in the Pasur River estuary, Bangladesh, where phytoplankton richness and diversity reached their maximum during the monsoon period, followed by a decline in subsequent seasons. These consistent patterns highlight the strong influence of seasonal environmental changes on phytoplankton diversity in tropical estuarine ecosystems. Recent studies indicate that estuarine ecosystems often exhibit such temporal fluctuations due to changing hydrological regimes and anthropogenic impacts (Kolesar et al. 2022). The biodiversity analysis showed distinct differences in class-level abundance, with Dinophyceae exhibiting greater species richness but lower abundance compared to Cyanophyceae. This inverse relationship is well-documented in phytoplankton ecology, where dinoflagellates often maintain lower population densities despite higher diversity due to their slower growth rates and complex life cycles (Zhao et al. 2024). Meanwhile, the opportunistic and fast-reproducing nature of cyanobacteria often leads to their dominance in terms of cell count (Silva et al. 2021).

The steady decline in average phytoplankton abundance from July (20,525,346 cells.m^{-3}) to November (13,609,643 cells.m^{-3}) reflects seasonal shifts in environmental parameters such as nutrient depletion and temperature variations (Xu et al. 2023). Similar seasonal declines were documented in other estuarine systems; for instance, Narragansett Bay (USA) exhibited a 49% reduction in chlorophyll-a biomass over several decades, with the most significant decrease during winter-spring blooms due to changes in nutrient availability and temperature (Thibodeau et al. 2024). Likewise, in Corpus Christi Bay, USA, phytoplankton biovolume peaked in spring-summer and declined towards fall-winter, driven by seasonal variations in nutrients and water temperature (Tominack and Wetz 2023). These consistent observations confirm that environmental seasonality plays a crucial role in regulating phytoplankton populations in estuarine ecosystems. Spatially, the highest phytoplankton abundance recorded at Stations 5 and 3 indicates localized nutrient inputs or favorable hydrodynamic conditions that enhance phytoplankton growth (Ge et al. 2020). This may be linked to nutrient enrichment from upstream wastewater discharges or urban runoff, emphasizing the direct influence of human activities on phytoplankton communities. These findings reinforce the value of phytoplankton as bioindicators of estuarine pollution. At the taxonomic level, Mediophyceae emerged as the most abundant class (7,976,932 cells.m^{-3}), while Dinophyceae exhibited the lowest abundance (217,714 cells/m^3). A similar pattern was reported by Bhutia et al. (2024) in the Matla-Sundarbans estuary, where Mediophyceae contributed 27% and Dinophyceae only 9% of the total phytoplankton abundance. These comparable proportions indicate that Mediophyceae thrive under nutrient enrichment, while Dinophyceae remain less competitive in such environments. The dominance of Mediophyceae, including fast-growing diatoms such as *Skeletonema* and *Chaetoceros*, aligns with their ecological role in primary production and bloom dynamics (Baek et al. 2023). In contrast, the lower abundance of Dinophyceae reflects their niche specialization and sensitivity to environmental fluctuations (Jiang et al. 2023).

The observed phytoplankton dynamics in the Lhokseumawe Estuary underscore the significant role of organic pollution in shaping aquatic ecosystems. The dominance of Bacillariophyceae, shifts in species abundance, and declining phytoplankton richness suggest ongoing eutrophication processes linked to anthropogenic nutrient inputs. These findings reinforce the need for continuous water quality monitoring and pollution mitigation efforts to maintain estuarine ecological balance. Community diversity remained moderate, with Shannon diversity index (H') values ranging from 1.79 to 2.30, indicating a relatively stable phytoplankton community with a balance between species richness and abundance (Zhang et al. 2022). The evenness index (E) values, fluctuating between 0.65 and 0.77, suggest variations in species distribution, with higher evenness reflecting more balanced community compositions (Zhang et al. 2022). Additionally, the low dominance index (D) values across all stations indicate the absence of a single overwhelmingly dominant species, signifying a well-distributed community structure (Zhang et al. 2022).

However, the moderate diversity index (H': 1.79-2.30) and fluctuating evenness (E: 0.65-0.77) indicate that the phytoplankton community remains under moderate

environmental stress, likely from organic pollution exposure. The low dominance index (D) further supports this, suggesting that although pollution has affected species diversity, no single taxon has completely dominated the assemblage. This pattern is consistent with Idawati et al. (2021), who reported diversity values ranging from H': 1.96 to 2.58, evenness between 0.58 and 0.87, and low dominance indices (D: 0.094-0.283) in the Lemukutan Island coastal waters, Indonesia. Their study concluded that such diversity and evenness ranges reflect moderate environmental stress, where pollution alters species composition without allowing a single species to outcompete others. Nevertheless, prolonged exposure to organic pollution could lead to further ecological imbalances, favoring fewer, more pollution-tolerant species over time (Zhang et al. 2022). The observed decline in phytoplankton abundance and diversity indices may also be indicative of organic pollution within the estuary. Studies have shown that increased organic matter can lead to oxygen depletion, adversely affecting phytoplankton communities and leading to reduced diversity (Li et al. 2023). Additionally, the presence of specific taxa, such as certain diatoms, can serve as bioindicators of organic pollution levels (Méndez-Zambrano et al. 2024). Therefore, the phytoplankton composition in the Lhokseumawe Estuary may reflect the impacts of organic pollution on the aquatic ecosystem, highlighting the need for further research and environmental management strategies. The observed temporal reduction in taxa number and biodiversity indices, combined with fluctuating evenness and low dominance values, reflect ecological stress likely caused by organic pollution inputs into the estuarine system.

Bioindicator-based assessment of organic pollution

The Palmer Algal Pollution Index score of 6, as observed in the estuarine waters of Lhokseumawe, falls within the 0-10 category, which indicates the absence of organic pollution. This result suggests that the phytoplankton community in the study area is composed predominantly of species that are not tolerant to high levels of organic enrichment, and that anthropogenic pressure related to organic waste input remains relatively low. Such a score aligns with findings from similar estuarine systems in tropical regions, where low Palmer Index values were associated with moderate nutrient levels, efficient water circulation, and limited industrial discharge (Hasan et al. 2022b; Bhutia et al. 2024). Furthermore, the absence of pollution-tolerant genera—such as Euglena, Scenedesmus, and Oscillatoria—supports the assessment that eutrophication is not currently a threat in this estuary (Damar et al. 2021; Andree et al. 2024). Numerous studies have demonstrated that increases in these genera are typically correlated with inputs of untreated sewage and agricultural runoff, particularly in densely populated or poorly managed coastal areas (Nhu Y et al. 2019; Ge et al. 2022). The findings in Lhokseumawe are therefore indicative of a relatively balanced estuarine ecosystem in terms of organic pollution, although continuous monitoring is advised in light of ongoing land-use changes and urban expansion.

The use of phytoplankton as primary bioindicators of organic pollution in estuarine systems has been widely supported in tropical studies. Additionally, recent studies highlight the relevance of microprotozooplankton as complementary bioindicators of eutrophication in lagoon and estuarine environments (Rocha et al. 2024). The Algae Group Index (AGI) calculated in this study yielded a value of 3.61, indicating good water quality with minimal signs of organic pollution. This low AGI score reflects the dominance of phytoplankton groups typically found in clean or moderately eutrophic waters, especially diatoms such as Bacillariophyceae and Mediophyceae, which together comprised more than 80% of the total phytoplankton abundance. Such assemblages are widely regarded as sensitive indicators of good water quality (Xiao et al. 2023; Jahan and Singh 2025). The minimal contribution of pollution-tolerant groups, such as Cyanophyceae (only 3%), further reinforces the conclusion that the estuarine waters are not experiencing significant organic loading. Cyanobacteria are commonly associated with elevated nutrient concentrations and often dominate in eutrophic or stagnant waters influenced by human activity (Ge et al. 2022; Hasan et al. 2022b). These results are consistent with previous research in tropical estuaries, where high diatom dominance and low AGI values were linked to effective water exchange, moderate anthropogenic influence, and adequate dissolved oxygen concentrations (Damar et al. 2020; Bhutia et al. 2024). Nevertheless, it is important to emphasize that AGI alone may not fully capture the complexity of estuarine ecosystem dynamics. Therefore, it is recommended to integrate AGI with other biological indices—such as the Palmer Pollution Index and phytoplankton diversity metrics—along with physicochemical parameters (e.g., DO, BOD, nutrient concentrations, salinity) for a more comprehensive assessment of water quality and ecological status.

Phytoplankton play a crucial ecological role as primary producers in aquatic ecosystems, forming the base of the food web. Their abundance and composition directly influence higher trophic levels, including zooplankton and fish. Variations in phytoplankton communities not only reflect environmental conditions but also affect the availability and quality of food resources for aquatic consumers. Thus, understanding phytoplankton dynamics is essential for predicting changes in estuarine productivity and for supporting ecosystem-based management strategies.

Indications of eutrophication based on phytoplankton communities

Based on research conducted in the Lhokseumawe Estuary from July to November 2024, strong indications of eutrophication were observed, as reflected in the structure and abundance of the phytoplankton community. The phytoplankton assemblage was dominated by the class Bacillariophyceae (43%), with genera such as *Nitzschia* and *Navicula*, which are recognized as classical indicators of eutrophic conditions resulting from nutrient enrichment due to organic pollution. Similar patterns were reported in the Taehwa River Estuary, South Korea, where

Bacillariophyceae, including *Navicula*, accounted for approximately 51% of the phytoplankton community under eutrophic conditions driven by organic pollution (Sim et al. 2020). These genera have been reported to dominate in nutrient-rich waters, particularly where phosphate and nitrite concentrations are elevated, reflecting their adaptability to eutrophic conditions (Stenger-Kovács et al. 2019). Additionally, the class Mediophyceae, including *Skeletonema* and *Chaetoceros*, exhibited the highest abundance (7,976,932 cells.m^{-3}), indicating their opportunistic response to nutrient enrichment. This observation is supported by Yoon et al. (2024), who reported rapid proliferation of *Skeletonema* and *Chaetoceros* spp. in both mesocosm and field settings following terrestrial nutrient runoff in Korean coastal waters. Similarly, Sá et al. (2020) documented blooms of *Skeletonema costatum* (up to 1.89×10^6 cells.L^{-1}) in the Bacanga River estuary, Brazil, under elevated nutrient conditions. These findings underscore the opportunistic nature of Mediophyceae in nutrient-rich estuarine environments. *Skeletonema costatum*, for example, has been documented as a dominant species in eutrophic coastal waters, favored by elevated nitrogen and phosphorus levels (Ma et al. 2022). Although comprising only 3% of the total composition, Cyanophyceae showed a relatively high abundance compared to their species count, particularly *Trichodesmium*, which thrives in nitrogen-rich environments. This suggests localized nutrient enrichment likely due to fertilizer runoff or domestic sewage, as supported by findings that *Trichodesmium* blooms are often triggered by anthropogenic nutrient inputs enhancing nitrogen fixation and supporting microbial growth (Beardall et al. 2017).

The total phytoplankton abundance was relatively high, with an average of 20,525,346 cells.m^{-3} in July, decreasing to 13,609,643 cells.m^{-3} in November. The highest abundances were observed at Stations 5 and 3, with 20,596,736 and 19,470,194 cells.m^{-3}, respectively, likely influenced by localized nutrient inputs from anthropogenic sources. This observation is supported by Kumar et al. (2023), who found that anthropogenic nutrient accumulation can lead to fluctuations in phytoplankton abundance and community composition, contributing to environmental stress in estuaries. Spatially, elevated phytoplankton abundances were also observed at Stations 2 and 3, with peak values reaching 14×10^6 cells.m^{-3}, suggesting local nutrient enrichment likely derived from adjacent anthropogenic sources such as market waste, residential discharges, or small-scale aquaculture effluents. Temporally, the maximum abundance (77.12×10^6 cells.m^{-3}) was recorded in July, corresponding to the early rainy season, which may have intensified terrestrial runoff and nutrient loading into the estuary. This pattern aligns with observations by Soondur et al. (2022), who reported that rainfall-driven nutrient loading significantly influenced phytoplankton dynamics in a tropical coastal lagoon, triggering increased algal biomass during the wet season. Similarly, Tran et al. (2022) observed that seasonal shifts in phytoplankton assemblages, including diatoms and cyanobacteria, were closely linked to fluctuations in nutrient concentrations and turbidity during the monsoon period in the Mekong River estuary. The consistent dominance of *Skeletonema, Chaetoceros,* and *Trichodesmium* across both spatial and temporal gradients underscores their opportunistic nature and capacity to rapidly respond to nutrient enrichment, as previously demonstrated in diatom-based nutrient indicator studies (Tsoi et al. 2020). Similarly, Lehtinen et al. (2017) reported that nutrient enrichment in the northern Baltic Sea resulted in alterations in phytoplankton species richness and evenness, reflecting the impact of anthropogenic nutrient inputs on phytoplankton communities. These findings collectively reinforce the conclusion that elevated phytoplankton abundance in the Lhokseumawe Estuary is closely linked to anthropogenic nutrient inputs, underscoring the need for effective nutrient management strategies to mitigate eutrophication and its ecological consequences.

The Shannon-Wiener diversity index (H') ranged from 1.79 to 2.30, indicating moderate diversity, while the evenness index (E) values between 0.65 and 0.77 reflected fluctuating species distribution. These findings are in line with those reported by Kumar et al. (2023), who recorded Shannon-Wiener diversity index values ranging from 0.16 to 2.50 and evenness values between 0.07 and 1.0 along the southeast coast of India. Their study demonstrated that phytoplankton diversity and evenness varied across stations due to differing environmental conditions, supporting the conclusion that similar ecological factors may be influencing species distribution patterns in the Lhokseumawe Estuary.

The low dominance index (D) values across all stations suggest that no single species was overwhelmingly dominant. This finding aligns with observations by Lehtinen et al. (2017), who reported that in the northern Baltic Sea, low species dominance in phytoplankton communities was associated with nutrient imbalances, indicating potential environmental stress due to nutrient overload. While some species, such as *Cylindrospermopsis raciborskii*, are known to dominate in eutrophic conditions, as noted by Futatsugi et al. (2018) in their long-term study of Lake Suwa, Japan, the overall phytoplankton community in the Lhokseumawe Estuary exhibits signs of ecological stress rather than clear dominance by a single taxon. Considering the phytoplankton composition, high cell density, and fluctuating ecological indices (such as Shannon diversity and evenness), it can be concluded that the Lhokseumawe Estuary is undergoing eutrophication, primarily driven by increased nutrient inputs from surrounding human activities. This interpretation is reinforced by findings from Nhu Y et al. (2019), who observed that in the Cau Hai lagoon, Vietnam, shifts in phytoplankton diversity and productivity were strongly influenced by nutrient enrichment and imbalance—conditions that closely parallel those seen in the Lhokseumawe Estuary.

In line with these findings, further ecological signals warrant attention. In addition to the dominance of Bacillariophyceae, the presence of Cyanophyceae—although comprising only 3% of the phytoplankton

community—deserves ecological scrutiny. The genus *Trichodesmium*, identified in this study, is a well-known nitrogen-fixing cyanobacterium frequently associated with nutrient-enriched and organically polluted environments. Its proliferation reflects elevated nitrogen availability from domestic sewage or agricultural runoff, consistent with the observations of Beardall et al. (2017) and Rahav and Bar-Zeev (2017). While *Oscillatoria* and *Euglena* were not recorded in the samples, these genera are widely cited in tropical estuarine studies as indicators of advanced eutrophication and hypoxic conditions (Naik et al. 2020; Silva et al. 2021). Their absence in this study may be attributable to seasonal dynamics or environmental thresholds that have not yet favored their establishment. Nonetheless, continued phytoplankton monitoring is crucial, as the future emergence of these taxa may signal a progression toward more severe ecological degradation.

Similar ecological trends have been documented in other estuarine ecosystems in Indonesia and beyond. In the Kakap River estuary (Soetignya et al. 2021) and Jakarta Bay (Damar et al. 2020), diatoms such as *Nitzschia* and *Navicula* consistently dominated under conditions of high nutrient loading, while cyanobacterial abundance increased with elevated nitrogen concentrations. Studies in the Cau Hai Lagoon, Vietnam (Nhu Y et al. 2019), and the Matla-Sundarbans estuary in India (Bhutia et al. 2024) further confirm that shifts toward eutrophication-tolerant phytoplankton communities serve as robust indicators of organic pollution. The similarity in phytoplankton response across these estuaries and the Lhokseumawe Estuary reinforces the utility of phytoplankton as sensitive and early-warning bioindicators of anthropogenically driven environmental degradation.

The observed phytoplankton metrics—particularly the dominance of Bacillariophyceae and the seasonal decline in diversity and abundance—demonstrate the utility of phytoplankton communities as reliable bioindicators of organic pollution in tropical estuaries. These ecological indices can be integrated into estuarine monitoring frameworks, providing an early-warning system for eutrophication and environmental stress. Incorporating phytoplankton-based assessments into routine environmental monitoring aligns with global practices such as the Water Framework Directive (EU) and coastal management strategies in Southeast Asia. Furthermore, spatial patterns in phytoplankton composition highlight specific hotspots of anthropogenic impact, enabling more targeted pollution mitigation and land-use regulation. The application of phytoplankton indicators in environmental governance thus supports proactive decision-making for coastal resource protection in Lhokseumawe and similar urbanized estuarine systems.

Although this study provides a comprehensive assessment of phytoplankton biodiversity and its role as a bioindicator of organic pollution, several limitations should be acknowledged. Notably, physicochemical water quality parameters such as Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), nitrate, phosphate, and Total Suspended Solids (TSS) were not measured during the sampling campaign. As a result, statistical correlations, or multivariate analyses (e.g., PCA or CCA) between phytoplankton community structure and water quality variables could not be conducted. The absence of such data limits the ability to fully elucidate causal relationships between organic pollution and phytoplankton dynamics. Future studies should incorporate simultaneous measurements of water quality and planktonic communities to enable integrated ecological assessments and to strengthen the use of phytoplankton as diagnostic tools for estuarine pollution management.

In conclusion, this study confirms that phytoplankton biodiversity, particularly the dominance of Bacillariophyceae and the abundance of bloom-forming genera such as *Skeletonema* and *Chaetoceros*, serves as a reliable bioindicator of organic pollution and eutrophication in the Lhokseumawe Estuary. The observed moderate Shannon diversity index (H′: 1.79-2.30), fluctuating evenness (E: 0.65-0.77), and low dominance values collectively suggest environmental stress resulting from anthropogenic nutrient inputs—primarily domestic sewage, agricultural runoff, and industrial discharge. These patterns are consistent with previous findings (e.g., Da Silva et al. 2017; Ge et al. 2022), which link nutrient enrichment to phytoplankton community shifts and ecological degradation in estuarine systems.

Ecologically, such alterations in community composition may reduce habitat suitability for sensitive aquatic organisms, disrupt trophic interactions, and elevate the risk of Harmful Algal Blooms (HABs), with cascading effects on biodiversity and fisheries productivity. If unaddressed, continued eutrophication could lead to hypoxia, fish kills, and long-term loss of estuarine ecosystem functions. Given these implications, phytoplankton-based metrics should be integrated into routine water quality monitoring to enable early detection of ecological disturbances. This study provides essential baseline data to support evidence-based pollution control and estuarine management strategies. Strengthening regulatory enforcement on wastewater discharge and adopting ecosystem-based management are urgently needed to preserve biodiversity, sustain fisheries, and enhance the resilience of the Lhokseumawe Estuary under increasing anthropogenic pressure.

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