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Phytoplankton Diversity as a Water Quality Bioindicator of Mangrove Ecosystems in the Mangrove Rehabilitation and Mangrove Ecotourism Area of Merdeka Beach Serdang Bedagai

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Abstract

This study investigates the diversity and composition of phytoplankton as a bioindicator of water quality in the mangrove ecosystems of Merdeka Beach, Bagan Kuala Village, Serdang Bedagai. Sampling was conducted at three sites representing long-term rehabilitation (2010–2025), recent rehabilitation (2024–2025), and mangrove ecotourism areas. Phytoplankton abundance and diversity were analyzed using ecological indices, including Shannon-Wiener Diversity Index (H'), Trophic Diatom Index (TDI), and Percentage Pollution Tolerance Value (%PTV), alongside physicochemical water parameters. Results indicate spatial variation in water quality and phytoplankton communities. Station 1 showed moderate abundance and high diversity, indicating ecological stability. Station 2 exhibited increased abundance but lower diversity, reflecting transitional conditions. Station 3 demonstrated the highest abundance and pollution-tolerant taxa, consistent with elevated nutrient levels due to human activities. TDI and %PTV values corroborated these findings, identifying Station 3 as hypertrophic and heavily polluted. These results highlight the utility of phytoplankton as sensitive indicators of environmental quality and the effectiveness of rehabilitation efforts. The integration of biotic indices and water parameters provides a robust framework for ongoing ecological monitoring and coastal management strategies, particularly in mangrove ecosystems undergoing anthropogenic pressure and restoration.

Keywords: Phytoplankton; Mangrove Rehabilitation; Ecotourism; Bioindicator; Water Quality.

INTRODUCTION

Mangrove ecosystems represent one of the most productive and biologically important environments along tropical and subtropical coastlines (Alongi, 2002; Kathiresan & Bingham, 2001). These habitats support a wide range of ecological functions such as carbon sequestration, nutrient cycling, coastal protection, and nursery grounds for marine biota (Duke et al., 2007; Donato et al., 2011). In Indonesia, mangrove degradation remains a critical environmental concern due to anthropogenic pressures including deforestation, aquaculture, and urban expansion (Setyawan et al., 2018; Giri et al., 2008).Rehabilitation and restoration efforts are increasingly being implemented in areas such as Bagan Kuala Village, Serdang Bedagai, where the Merdeka Beach mangrove ecosystem is undergoing both rehabilitation and ecotourism development (Adame et al., 2015; Rudianto et al., 2020). Such initiatives are crucial for reinstating lost ecological functions and providing sustainable economic alternatives to coastal communities (Bosire et al., 2008; Primavera & Esteban, 2008). However, monitoring the ecological effectiveness of these efforts requires comprehensive and cost-effective bioassessment tools (Barbier et al., 2011; López-Portillo et al., 2017).

Phytoplankton diversity has been widely used as a sensitive and informative bioindicator of aquatic ecosystem health (Suthers & Rissik, 2009; Chalar, 2009). These microscopic autotrophs respond rapidly to changes in nutrient concentrations, salinity, turbidity, and pollution, making them ideal for detecting early signs of eutrophication and organic contamination (Caroppo et al., 2006; Domingues et al., 2014). Several studies have demonstrated that changes in phytoplankton composition can reflect anthropogenic impacts in mangrove-fringed estuaries (Yuliana et al., 2012; Inyang & Wang, 2020).Indices such as the Shannon-Wiener Diversity Index (H'), Trophic Diatom Index (TDI), and Percentage Pollution Tolerant Value (%PTV) are useful for quantifying phytoplankton community structure and determining water quality status (Kelly & Whitton, 1995; Wu et al., 2014). A high TDI or %PTV value often correlates with elevated concentrations of nitrogen and phosphorus, which are common in areas adjacent to aquaculture ponds or domestic discharge (Gupta &

Rastogi, 2008; Salmaso et al., 2006). Conversely, lower index values typically reflect pristine or minimally disturbed sites (Silva et al., 2014).

Water quality parameters such as dissolved oxygen (DO), pH, temperature, turbidity, nitrate, and orthophosphate have been also critical for phytoplankton growth and community dynamics (Effendi et al., 2016; Onyema, 2013). In mangrove environments, these parameters are influenced by tidal flushing, organic matter decomposition, and freshwater inflows (Hossain et al., 2016; Rahmania et al., 2019). Evaluating the interplay between these abiotic factors and phytoplankton indicators can reveal spatial and temporal trends in ecosystem health (Dalu et al., 2017; Elliott & Quintino, 2007). In the context of mangrove ecotourism and rehabilitation, understanding phytoplankton dynamics become even more important. Tourism-related development, if not well-managed, can introduce additional nutrient loads and disrupt sediment dynamics (Pourafrasyabi & Ramezanpour, 2012; Çulha et al., 2022). Similarly, replanting efforts may temporarily alter hydrological patterns, affecting water clarity and nutrient distribution (Friess et al., 2019; Amalia et al., 2018). Thus, phytoplankton data provide a functional lens through which to assess both degradation and recovery.

Merdeka Beach offers a unique opportunity to investigate these ecological interactions, as it represents a transitional area between degraded, rehabilitated, and conserved mangrove zones (Hakim et al., 2017; Saputra et al., 2020). The juxtaposition of tourism activities and ongoing restoration provides a valuable natural laboratory for assessing the relative impact of human intervention on water quality and plankton diversity (Nichols et al., 2019; Bao et al., 2020). This study also seeks to contribute baseline data for coastal management in North Sumatra. Previous research in similar tropical settings has shown that bioindicators based on phytoplankton can effectively detect nutrient enrichment, organic loading, and habitat alteration (Hilmi et al., 2020; Ferreira-Marinho et al., 2014).

Such indicators are particularly valuable in resource-limited regions where conventional water quality monitoring may be infrequent or logistically challenging (Junaidi & Azhar, 2018; Lobo et al., 2002). Furthermore, integrating biological indices with physicochemical parameters enhances the predictive power of environmental assessments (Zhang et al., 2021; Gao & Zheng, 2010). Therefore, this research aims to assess the diversity and community composition of phytoplankton in the mangrove ecosystems of Merdeka Beach, particularly in the context of ongoing rehabilitation and ecotourism development. By correlating phytoplankton indices with water quality parameters, this study seeks to evaluate the ecological status of the site and inform future conservation and management strategies (Reynolds, 2006; Gell et al., 1999). It is hoped that this integrative approach will strengthen local efforts to safeguard mangrove ecosystems in North Sumatra and contribute to broader coastal resilience initiatives (Barbier et al., 2011; Donato et al., 2011).

MATERIALS AND METHODS

Study area

The research was carried out in May 2025. The location of water and phytoplankton sampling was carried out in the mangrove ecosystem at Mangrove Rehabilitation and Ecotourism Areas at Merdeka Beach, Bagan Kuala Village, Serdang Bedagai.

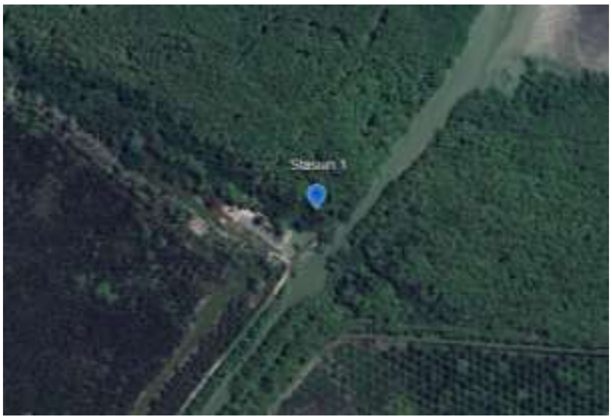

Figure 1. Mangrove Rehabilitation Area 2010-2025.

Figure 2. Mangrove Rehabilitation Area 2024-2025

Figure 3. Ecotourism Mangrove

Procedures

Sampling Design

Sampling was conducted at three stations. Station 1 represents a mangrove rehabilitation area that has undergone restoration from 2010 to 2025, located at coordinates 3°29′24″N, 99°15′34″E. Station 2 is a mangrove rehabilitation site restored during the 2024–2025 period, located at coordinates 3°30′35″N, 99°13′56″E. Station 3 is situated in the Merdeka Beach mangrove ecotourism area, Bagan Kuala Village, Tanjung Beringin Subdistrict, Serdang Bedagai Regency. Water and phytoplankton sampling were conducted in triplicate at each station to ensure data reliability and representativeness.

Phytoplankton Sampling, Identification, and Enumeration

Phytoplankton samples were obtained by filtering 5 liters of surface water ±15 cm below the surface using a plankton net. The collected samples were preserved in sampling bottles with the addition of 1 mL of 4% formalin. For microscopic examination, 1 mL of each sample was pipetted into a Sedgwick-Rafter counting chamber and observed under a light microscope at 200× magnification. Phytoplankton identification was performed by comparing the observed species with taxonomic references (Gell et al., 1999; Du Buf & Bayer, 2002; Van Vuuren et al., 2006; Bellinger & Sigee, 2010). Phytoplankton abundance was calculated using the formula provided by Effendi et al. (2016).

Water Physicochemical Parameter Measurements

A total of 100 milliliters of water was collected at each station from a depth of approximately 15 cm below the surface using a water sampler and stored in clean sampling bottles. The measured physicochemical parameters included water temperature, air temperature, pH, conductivity, dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrate concentration, and orthophosphate concentration. The parameters and their respective units and analytical method are follows:

Tabel 1. Physicochemical parameters of water with its measurement method

Parameter	Unit	Tool/Method
Salinity	%	Refaktometer
Water temperature	°C	Thermometer
Air temperature	°C	Thermometer
pH	-	pH meter
Conductivity	Siemens/meter	IK III/09/2020 (Elektrometri)
DO	mg/L	SNI 06-6989.14-2004
BOD	mg/L	SNI 6989.72-2009
Nitrate	mg/L	Colorimetric
Orthophosphate	mg/L	SNI 06-6989.31: 2005

Data analysis

Phytoplankton community structure and diversity were analyzed using several ecological indices, including the Importance Value Index (IVI), Shannon-Wiener Diversity Index (H'), Simpson Dominance Index (Id), and Evenness Index (E), following the formulas proposed by Wu et al. (2014). Descriptive statistical analysis was employed to summarize the minimum and maximum values of the measured water quality parameters. Furthermore, biplot analysis using PAST 16.0 software was conducted to assess the correlation between physicochemical parameters and biotic indices. To evaluate the trophic status and organic pollution level of the waters, phytoplankton biotic indices were applied: the Trophic Diatom Index (TDI) and the Percentage Pollution Tolerance Value (%PTV**).** TDI was calculated based on diatom species only, as suggested by Kelly & Whitton (1995). The %PTV was determined by calculating the proportion of tolerant diatom taxa (e.g., *Gomphonema sp.*, *Navicula spp.*, *Sellaphora spp.*, and *Nitzschia spp.*) relative to the total diatom assemblage.

The equation used to determine the TDI value index (Wu et al. 2014):

$$TDI = (WMS \times 25) - 25$$

Where, WMS is the weighted average sensitivity and can be obtained from the following formula:

$$WMS = \sum_{i-1}^{n}(ai \times si \times vi) / \sum_{i-1}^{n}(ai \times vi)$$

Notes:

WMS : weighted mean sensitivity
ai : proportion of all individuals in a sample that belong to species i
si : pollution sensitivity (1-5) of species i
vi : indicator values (1-3) of species i
n : total number of species in a sample (based on Kelly & Whitton 1995)

PTV is an index to determine the level of organic matter pollution in the waters. The equation used to determine the PTV value index (Kelly & Whitton 1995):

$$\%PTV - \frac{Abundance\ of\ tolerant\ taxa}{total\ taxa\ abundance}$$

The %PTV value was calculated based on comparing the abundance of tolerant diatoms (Gomphonema sp., Navicula spp., Sellaphora spp., and Nitzschia spp.) with the number of diatoms obtained (Kelly & Whitton 1995).

RESULTS AND DISCUSSION

Table 2. The profile of physicochemical water quality in Stasiun 1, Stasiun 2, Stasiun 3.

Location	Physicochemical Parameters								
	Water Temperature (ºC)	Air Temperature (ºC)	Salinity (%)	pH	Conduktivitas (mg/L)	DO (mg/L)	BOD (mg/L)	Nitrate (mg/L)	Orthophosphate (mg/L)
Stasiun 1	30,2	32,8	15	7,6	1,7	2,4	0,9	0,03	0,058
Stasiun 2	30,2	32,4	20	7,2	2,1	2	1,5	0,36	0,058
Stasiun 3	30,3	32,4	12	7,02	1,1	2,1	0,6	0,73	0,058
Water Quality Standart (Indonesia Ministry of Environment Regulation No 22/2021)	**25-32**	**25-32**	**34**	**7-8.5**	**-**	**>5**	**20**	**0.008**	**0.015**

The results of this study indicate varying water quality conditions across the three sampling stations located in the mangrove rehabilitation and ecotourism areas of Merdeka Beach. The observed physicochemical parameters, including temperature, pH, salinity, dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrate, and orthophosphate, showed both compliance and deviation from the Indonesian water quality standards (Regulation No. 22/2021). Dissolved oxygen (DO) levels in all stations were below the recommended threshold of 5 mg/L, with values ranging from 2.0 to 2.4 mg/L. Such low DO concentrations may be attributed to the high input of organic matter and subsequent microbial degradation, which consumes oxygen in the water column (Onyema, 2013; Pour et al., 2014). Nitrate concentrations showed considerable spatial variation, ranging from 0.03 mg/L in Station 1 to 0.73 mg/L in Station 3. These values exceed the standard limit of 0.008 mg/L for marine ecosystems, indicating significant nutrient enrichment, especially in Station 3, which is influenced by ecotourism and adjacent aquaculture activities. (DO) levels in all stations were below the recommended threshold of 5 mg/L, with values ranging from 2.0 to 2.4 mg/L. Such low DO concentrations may be attributed to the high input of organic matter and subsequent microbial degradation, which consumes oxygen in the water column (Onyema, 2013; Pour et al., 2014). Nitrate concentrations showed considerable spatial variation, ranging from 0.03 mg/L in Station 1 to 0.73 mg/L in Station 3.

Figures and tables of maximum of three pages should be clearly presented. Number tables consecutively in accordance with their appearance in the text. Title of a picture is written down below the picture, while title of a table is written above the table. Colored figures can only be accepted if the information in the manuscript can lose without those images; chart is preferred to use black and white images. Author could consign any picture or photo for the front cover, although it does not print in the manuscript. All images property of others should be mentioned source. There is no appendix, all data or data analysis are incorporated into Results and Discussions. For broad data, it can be displayed on the website as a supplement (Figure 2; Table 1). These values exceed the standard limit of 0.008 mg/L for marine ecosystems, indicating significant nutrient enrichment, especially in Station 3, which is influenced by ecotourism and adjacent aquaculture activities Elevated nitrate levels can stimulate algal blooms and lead to eutrophication (Gupta & Rastogi, 2008; Çulha et al., 2022). The salinity levels observed at the three stations exhibited notable variation, ranging from 15 ppt at Station 1 to 24 ppt at Station 2. Although all values remain within the acceptable limits set by the Indonesian water quality standard (maximum 34 ppt), the elevated salinity at Station 2 may indicate a stronger influence of seawater intrusion or tidal flushing in this area. Such variation in salinity can influence the distribution and abundance of aquatic organisms, particularly stenohaline species that are sensitive to salinity fluctuations. Furthermore, it may serve as a hydrological indicator of estuarine mixing dynamics and coastal water exchange processes. oreover, the recorded pH values across the stations were relatively neutral to slightly alkaline, ranging from 7.02 to 7.6, and remained within the standard threshold of 7.3 to 8.5. Nevertheless, the slightly lower pH observed at Station 3 could suggest localized inputs of acidic organic matter or anthropogenic pollutants, possibly due to decomposition processes or nearby human activities.

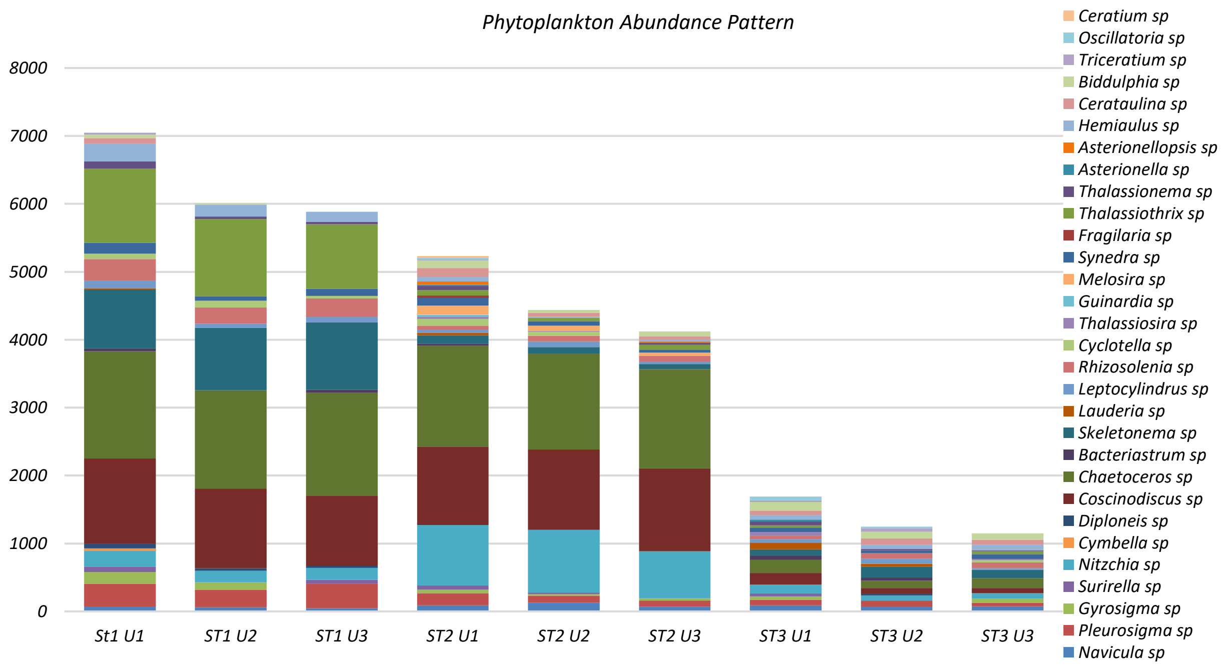

Figure 4. Phytoplankton Abundance Patterns Across Rehabilitated and Ecotourism Mangrove Zones.

The abundance of phytoplankton across the three sampling stations revealed significant spatial differences, reflecting the varying degrees of environmental pressure and rehabilitation maturity at each site. In Station 1 (rehabilitation 2010–2025), the phytoplankton abundance was relatively moderate and dominated by diatoms such as *Melosira sp.* and *Coscinodiscus sp.*, both of which are considered indicators of healthy and nutrient-stable waters. The presence of these species suggests that the long-term rehabilitation process has contributed to the stabilization of ecological functions in this zone.In contrast, Station 2 (rehabilitation 2024–2025) exhibited higher abundance levels but with reduced species diversity, characterized by dominance of *Nitzschia sp.* and *Navicula sp.*—taxa known for their tolerance to organic pollution. This indicates that although rehabilitation efforts have begun, the ecosystem is still under transitional pressure and has not yet reached ecological equilibrium. The elevated phytoplankton abundance in this zone may also be driven by nutrient influx due to recent disturbances in sediment and vegetation layers during mangrove planting activities.

The highest abundance of phytoplankton was recorded in Station 3 (mangrove ecotourism zone), particularly of pollution-tolerant diatoms such as *Nitzschia sp.*, *Sellaphora sp.*, and *Gomphonema sp.* These taxa dominated the assemblage, suggesting nutrient-rich and organically polluted waters, likely influenced by nearby aquaculture ponds and tourist activity.These findings emphasize that phytoplankton abundance and composition are reliable indicators of environmental condition and can effectively differentiate between rehabilitated, transitioning, and disturbed mangrove ecosystems. Furthermore, integrating abundance data with biotic indices such as the Trophic Diatom Index (TDI) and %PTV enhances the ecological diagnosis of site-specific water quality conditions.

Table 3. Spatial variation of phytoplankton diversity index in Rehabilitated and Ecotourism Mangrove.

Location	Location point	Biotic Index		
		E	Id	H’
Stasiun 1 U1	Rehabilitated in 2010	0,761	0,131	2.387
Stasiun 1 U2		0,739	0,162	2,093
Stasiun 1 U3		0,739	0,160	2,094
Stasiun 2 U1	Rehabilitated in 2024	0,702	0,164	2,340
Stasiun 2 U2		0,718	0,220	2,075
Stasiun 2 U3		0,634	0,244	1,797
Stasiun 3 U1	Ecotourism Mangrove	0,937	0,060	2,938
Stasiun 3 U2		0,940	0,69	2,767
Stasiun 3 U3		0,933	0,073	2,689

The spatial distribution of phytoplankton diversity across the three observed stations reveals significant ecological differences that reflect the degree of anthropogenic pressure and restoration maturity in each zone. Station 1, located in a long-term rehabilitated mangrove area (2010–2025), exhibited relatively high Shannon-Wiener Diversity Index (H’) values ranging from 2.093 to 2.387. This suggests a more stable and heterogeneous phytoplankton community, indicative of a balanced aquatic environment with minimal disturbance and better ecological recovery. The evenness values (E = 0.739–0.761) further support this observation, demonstrating that species are more evenly distributed without the dominance of a particular taxon. Low dominance index (Id = 0.131–0.162) values correspondingly reflect reduced ecological stress.

In contrast, Station 2, which has only recently undergone rehabilitation (2024–2025), exhibited a gradual decline in diversity and evenness indices. The H' values (1.797–2.340) and E values (0.634–0.718) indicate an unstable and uneven phytoplankton community, likely influenced by transitional disturbances such as sediment disruption, nutrient input, and incomplete vegetative cover. The relatively higher dominance index (Id = 0.164–0.244) compared to Station 1 points to early-stage colonization by pollution-tolerant species, which may temporarily dominate the community under suboptimal water quality conditions. Station 3, located in the ecotourism mangrove zone, exhibited the highest diversity values (H' = 2.689–2.938), coupled with exceptionally high evenness (E = 0.933–0.940). This may appear counterintuitive, considering the anthropogenic influence from nearby tourism and aquaculture activities. However, the diversity observed at this site could be attributed to the influx of nutrients and organic matter promoting phytoplankton proliferation across various taxa, including pollution-tolerant and opportunistic species. Despite the high H' and E values, the dominance index (Id = 0.060–0.073) was low, indicating the absence of a single dominant taxon, which is characteristic of eutrophic conditions where multiple species thrive due to increased nutrient availability.

These findings collectively suggest that while higher diversity indices are generally associated with healthier ecosystems, they may also reflect stress-induced proliferation of opportunistic species under nutrient-rich conditions. Therefore, interpreting the Shannon-Wiener index must be integrated with other indices such as dominance and evenness, along with physicochemical parameters, to draw ecologically meaningful conclusions. In the context of mangrove rehabilitation and ecotourism management, the results highlight the importance of continuous monitoring and multi-metric evaluation to ensure that observed biodiversity trends genuinely reflect ecological recovery rather than masked disturbances.

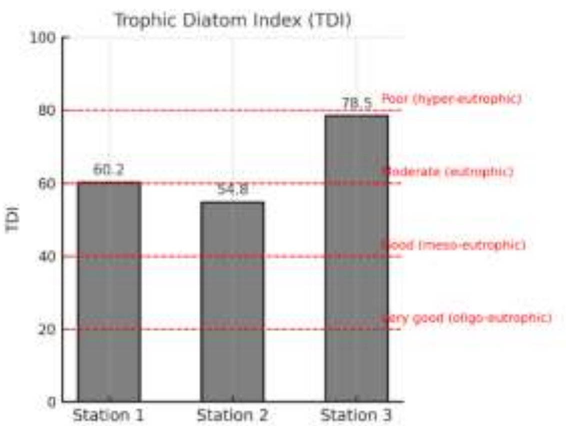

Figure 5. Spatial variation of Trophic Diatom Index values in Rehabilitated and Ecotourism Mangrove.

Figure 5 illustrates the spatial variation of the Trophic Diatom Index (TDI) across three sampling stations within rehabilitated and ecotourism mangrove zones at Merdeka Beach. The TDI values reflect the trophic state and organic pollution level based on the composition and abundance of diatom communities. Station 1, which has undergone long-term rehabilitation (2010–2025), recorded a moderate TDI value of 60.2. This indicates a mesotrophic to eutrophic condition, suggesting that while ecological recovery has progressed, nutrient enrichment is still present, likely from residual organic matter or land-based inputs.

Station 2 restored more recently (2024–2025), showed a slightly lower TDI value of 54.8. This suggests early-stage recovery with lower trophic stress compared to Station 1. The reduced TDI may reflect less diatom proliferation due to limited nutrient availability or the stabilizing effect of new vegetation cover.In contrast, Station 3, located in the mangrove ecotourism zone, exhibited the highest TDI value at 78.5, indicating a hypertrophic condition. This elevated index value implies a high degree of organic pollution and nutrient loading, likely attributed to anthropogenic influences such as aquaculture discharges, tourist activity, and limited natural flushing.These findings demonstrate that TDI is a sensitive and reliable indicator for assessing the trophic status of mangrove waters, especially in contexts where ecological pressures vary due to different land-use histories and human interactions.

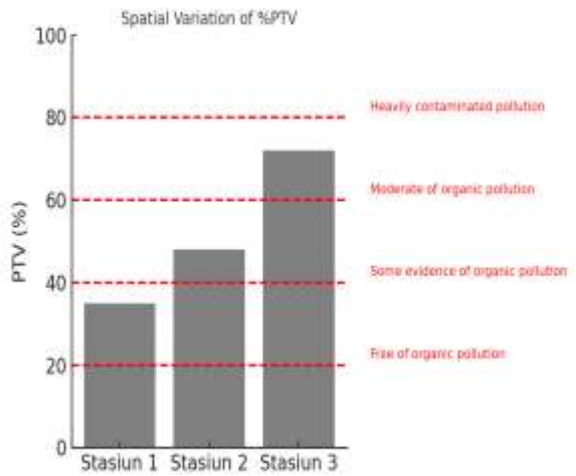

Figure 6. Spatial Variation of Pollution Tolerance Values in Rehabilitated and Ecotourism Mangrove

Figure 6 illustrates the spatial variation of the Percentage Pollution Tolerance Value (%PTV) across three observation stations located within the mangrove ecosystem at Merdeka Beach: Station 1 (rehabilitated from 2010 to 2025), Station 2 (rehabilitated in 2024–2025), and Station 3 (mangrove ecotourism area). The %PTV index reflects the proportion of pollution-tolerant diatoms—such as *Nitzschia sp.*, *Gomphonema sp.*, *Navicula spp.*, and *Sellaphora spp.*—within the total diatom community. A higher %PTV indicates a higher level of organic pollution in aquatic environments.At Station 1, a moderate %PTV value (35%) suggests that the area is subject to slight organic pollution. This is likely due to the effectiveness of long-term mangrove rehabilitation efforts in stabilizing ecological conditions and reducing the dominance of pollution-tolerant species. The relatively low %PTV aligns with the observed ecological maturity and minimal anthropogenic disturbance in this zone.Station 2, which has undergone more recent restoration efforts, recorded a higher %PTV (48%), indicative of moderate organic pollution. The transitional nature of the sitecharacterized by active sediment disturbance and early-stage vegetation establishment may contribute to increased nutrient inputs and the proliferation of tolerant diatoms, thereby elevating the index value.In contrast, Station 3 demonstrated the highest %PTV (\~72%), classifying it within the heavily polluted category. This station is located in a mangrove ecotourism area, where intense human activity including tourism, aquaculture, and reduced water circulation likely contributes to elevated levels of organic matter. Consequently, the diatom assemblage is dominated by taxa that thrive under eutrophic and polluted conditions.Overall, the spatial trends in %PTV values emphasize the utility of this biotic index as a sensitive tool for assessing ecological degradation and the effectiveness of mangrove rehabilitation.

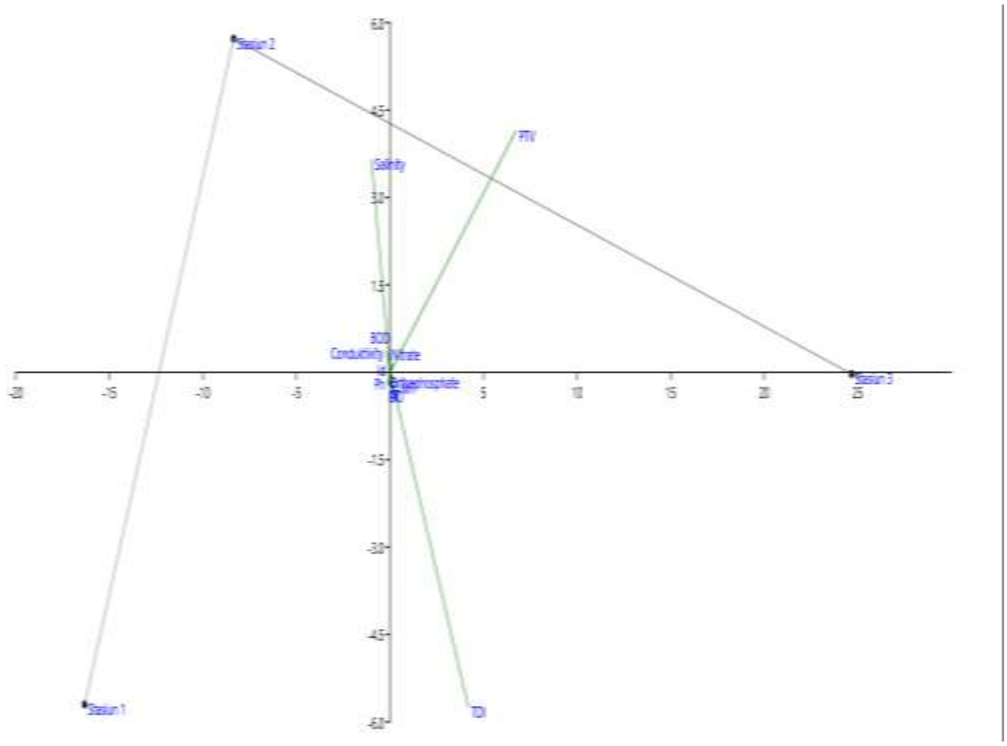

Figure 5. Correlation between water quality and phytoplankton community structure in Rehabilitated and Ecotourism Mangrove**.**

The principal compenents (PCA) diagram illustrates the relationship between water quality parameters and the phytoplankton community structure in rehabilitated and ecotourism mangrove areas. The plot shows the distribution of three sampling stations(Stations 1, 2, and 3) in relation to several environmental variables, including salinity, pH, biological oxygen demand (BOD), conductivity, nitrate, phosphate, trophic diatom index (TDI), and phytoplankton total volume (PTV).The findings suggest that %PTV not only reflects the current state of water quality but also serves as an early-warning indicator of anthropogenic impact. Integration of %PTV monitoring into routine environmental assessments could significantly enhance coastal management strategies, especially in regions undergoing rapid development or restoration. From the ordination diagram, it is evident that certain environmental parameters, such as PTV, TDI, and salinity, exert a relatively strong influence on phytoplankton community distribution, as indicated by the length and direction of their corresponding vectors. The longer the vector, the greater its influence on species composition. Station 1 is positioned far from the origin and aligns closely with the negative direction of the TDI vector, suggesting that the phytoplankton community at this site is particularly influenced by higher trophic diatom levels. In contrast, Station 2 is positively associated with salinity, nitrate, and PTV, indicating that these factors significantly shape the phytoplankton composition in this location. Station 3 lies on the positive side of the horizontal axis, potentially reflecting unique environmental conditions not fully captured by the most dominant vectors.

Overall, the PCA reveals distinct ecological gradients among the sampling stations, highlighting the role of specific water quality parameters in driving the spatial variation in phytoplankton communities. These findings underscore the importance of monitoring and managing water quality—especially salinity, nutrient concentrations, and trophic status—in order to maintain ecological balance and biodiversity in rehabilitated mangrove ecosystems utilized for ecotourism purposes.

CONCLUSIONS

This study demonstrates that phytoplankton diversity and community composition serve as reliable bioindicators of water quality in mangrove ecosystems undergoing rehabilitation and ecotourism development. The spatial variation observed among the three sampling stations reflects differing levels of environmental pressure and ecological maturity. Station 1, representing a long-term rehabilitation area, exhibited higher ecological stability as indicated by moderate phytoplankton abundance, high diversity indices, and lower TDI and %PTV values. Station 2, currently in the early stages of rehabilitation, showed signs of transitional stress, with elevated phytoplankton abundance dominated by pollution-tolerant species. Station 3, located within the ecotourism zone, was characterized by hypertrophic conditions and a high proportion of tolerant taxa, corresponding with intensified anthropogenic activity.The integration of physicochemical parameters with biotic indices—such as the Shannon-Wiener Index, Trophic Diatom Index (TDI), and Percentage Pollution Tolerance Value (%PTV)—enabled a comprehensive assessment of ecosystem health. These findings underscore the importance of continuous ecological monitoring using phytoplankton-based indicators to evaluate the effectiveness of mangrove rehabilitation efforts and to guide sustainable ecotourism practices. The study provides valuable baseline data to inform future conservation strategies and enhance the resilience of mangrove ecosystems in North Sumatra.

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Authors' Contributions: All authors contributed substantially to the conception and design of the study. Putri Aulia was responsible for the field data collection, analysis, and drafting of the manuscript. Melfa Aisyah Hutasuhut assisted in data interpretation, literature review, and critical revision of the manuscript.

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