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Water Quality and Phytoplankton as Indicator of Coastal Health in the Southeast Coast of Sumenep, Indonesia

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ABSTRACT

This study investigated seasonal variations in water quality and phytoplankton community composition in the coastal waters of East Java, Indonesia, to assess their implications for coastal health. Water samples were collected during wet and dry seasons, and phytoplankton composition, diversity indices, trophic status (using the Nygaard Index), along with key water quality parameters (pH, dissolved Oxygen, salinity, temperature, turbidity, nitrates, and phosphates) were analyzed. Results revealed higher nutrient levels (nitrates and phosphates) during the wet season, coinciding with increased turbidity and lower dissolved oxygen. These conditions corresponded with a shift in phytoplankton assemblages from diatom dominance in the dry season to a more diverse community during the wet season. The Nygaard Index indicated fluctuations between eutrophic and mesotrophic conditions, correlating with observed changes in water quality and phytoplankton composition. These findings suggest a coastal ecosystem susceptible to seasonal variations and nutrient fluctuations, highlighting the importance of integrated coastal management strategies, including regular monitoring and consideration of other ecosystem components, to ensure long-term coastal health and sustainability.

INTRODUCTION

Coastal ecosystems are vital interfaces between land and sea, providing essential ecological services and supporting diverse biological communities **(Camp *et al.*, 2015; Depellegrin *et al.*, 2023; Maliga & Purwanto, 2025)**. However, these valuable environments face growing threats from various human activities, including agricultural runoff **(Zhao *et al.*, 2004; Sannigrahi *et al.*, 2019; He *et al.*, 2020; Seerurrun *et al.*, 2021)**, industrial discharge **(Domínguez-tejo *et al.*, 2016; Depellegrin *et al.*, 2023)**, and urban development **(Hirons *et al.*, 2016; Zheng *et al.*, 2019)**. These pressures can degrade seawater quality, impacting the health and integrity of marine life and the overall functioning of these dynamic ecosystems **(Suciu *et al.*, 2017; He *et al.*, 2020; Marshall *et al.*, 2022)**. These environments are susceptible to natural fluctuations and anthropogenic stressors, with water quality being a critical factor influencing their health and stability. Understanding and addressing these risks is crucial for the sustainable management and conservation of our oceans.

Seawater serves as the immediate habitat for a diverse array of marine organisms **(Brien *et al.*, 2016; El Zrelli *et al.*, 2018; He *et al.*, 2020)**, and its quality directly affects their health and survival. Changes in seawater properties, such as temperature, salinity, dissolved oxygen, and nutrient levels, can significantly impact marine life **(Ferreira *et al.*, 2011; Ndah *et al.*, 2022)**. Contaminants present in seawater can also be directly absorbed by organisms, leading to toxic effects **(Ferreira *et al.*, 2011; Sheekh, 2023; Uddin *et al.*, 2024)**. Seawater quality reflects the cumulative impacts of various stressors on the marine environment, integrating the effects of land-based pollution, atmospheric deposition, and other human **(El Zrelli *et al.*, 2018; Verga *et al.*, 2019)**. Analyzing seawater quality provides a comprehensive understanding of the overall health of the marine ecosystem. Established analytical techniques enable the objective assessment and quantification of seawater quality parameters, facilitating the tracking of changes over time **(Leparc *et al.*, 2007; Uddin *et al.*, 2024; Maliga *et al.*, 2025)**. Quantitative data on seawater quality is essential for conducting robust coastal health assessments, which are crucial for informed decision-making and effective management of coastal and marine resources **(Leparc *et al.*, 2007; Mishra *et al.*, 2015; Uddin *et al.*, 2023)**.

Coastal health refers to the overall condition of the coastal ecosystem, encompassing both its living and non-living components **(Brien *et al.*, 2016; Chi & Liu, 2022; Depellegrin *et al.*, 2023)**. It's a measure of the ecosystem's ability to function effectively and provide essential services to both humans and the environment. This study uses water quality parameters and the structure of the phytoplankton community as indicators of coastal health. Seawater quality directly influences the health and survival of a wide range of marine organisms **(Sheekh, 2023; Tian *et al.*, 2023)**. Alterations in seawater properties, such as temperature, salinity, dissolved oxygen, and nutrient levels, can have significant impacts on marine life **(Lena *et al.*, 2022; Han & Han, 2024)**.

Furthermore, contaminants present in seawater can be absorbed by organisms, leading to toxic effects and bioaccumulation through the food web **(Lena *et al.*, 2022; Tian *et al.*, 2023)**. Analyzing seawater quality provides a comprehensive understanding of the cumulative impacts of various stressors on the marine environment, integrating the effects of land-based pollution, atmospheric deposition, and other human activities **(Lena *et al.*, 2022)**. Quantitative data on seawater quality is essential for robust coastal health assessments, which are crucial for informed decision-making and effective management of coastal and marine resources.

Furthermore, phytoplankton, the foundation of the marine food web, are susceptible to changes in seawater quality and serve as valuable indicators of coastal ecosystem health **(Lena *et al.*, 2022; Sheekh, 2023)**. Changes in phytoplankton diversity, abundance, and community composition can signal broader ecosystem shifts and serve as an early warning system for potential problems **(Lena *et al.*, 2022; Han & Han, 2024)**. For example, nutrient loading can stimulate harmful algal blooms, while other forms of pollution can suppress phytoplankton populations, disrupting the food web and impacting higher trophic levels. Monitoring phytoplankton communities provides insights into the overall condition of the ecosystem and helps identify potential risks associated with declining seawater quality **(Giglio *et al.*, 2022; Sheekh, 2023)**.

Understanding the interplay between water quality parameters, phytoplankton community dynamics, and trophic status is crucial for assessing the overall health and resilience of coastal ecosystems **(Garmendia *et al.*, 2013; Giglio *et al.*, 2022)**. This study investigated the seasonal variations in water quality and phytoplankton community structure in the coastal waters of East Java, Indonesia, a region experiencing increasing environmental pressures from both natural and anthropogenic sources. By examining key water quality parameters and analyzing phytoplankton community composition, this research aimed to assess the trophic status of these coastal waters and to evaluate the potential impacts of environmental change on this valuable ecosystem. The findings would provide valuable insights for developing effective coastal management strategies and ensuring the long-term health and sustainability of this important coastal region.

MATERIALS AND METHODS

This study was conducted from February 2023 to August 2024 in the southeast coastal region of Sumenep, East Java, Indonesia. Water sampling and sample analysis activities were carried out at the GENAU Laboratory. The research employed an observational approach, with water sampling in four locations, to establish baseline water quality and phytoplankton community structure.

Water samples were collected from four station coastal locations along the southeast coast of Sumenep, representing varying degrees of human influence and environmental conditions. These stations were strategically selected to capture the diversity of coastal environments and potential stressors in the region. At each sampling station, seawater samples were collected at a depth of 0.5 meters below the surface using sterile bottles. The collected samples were immediately stored on ice and transported to the laboratory for analysis. Observation stations are located at geographical coordinates starting from Rainy Station 1 at 113^0 89’5819” E and 7^0 13’3975” S; Rainy Station 2 at 113^0 90’0738” E and 7^0 13’1366” S; Dry Station 1 at 113^0 90’2630” E and 7^0 12’5422” S; Dry Station 2 at 113^0 88’2513” E and 7^0 14’1458” S.

Direct observations and measurements of water quality were carried out for parameters such as color, clarity, turbidity, salinity, pH, brightness, temperature, pH, and salinity. Water quality analysis in the laboratory included ammonia, nitrate, nitrite, and total phosphate. Water samples were taken using a bucket to analyze several water quality parameters. The water sample taken was included in an HDPE bottle and stored in a cool box containing ice cubes for temperature preservation during the laboratory analysis process according to the APHA standards **(Baird *et al.*, 2017)**. The measured water quality parameters were evaluated against relevant national water quality standards and guidelines, such as those established by the Government Regulations of The Republic of Indonesia Number 22, to determine the overall water quality status and to identify any exceedances of permissible limits. Descriptive statistics, including mean, standard deviation, and range, were calculated for each parameter to summarize the data and characterize the water quality in each sampling location.

Phytoplankton samples were collected by filtering 70 liters of seawater **(Madhankumar & Venkatachalapathy, 2024)**. The phytoplankton were captured using a plankton net with a 30µm mesh size. The collected plankton were stored in HDPE bottles and preserved by adding Lugol's Iodine solution until they appeared brown for subsequent laboratory analysis **(Parin *et al.*, 2019)**. Microscopic observations at 10x10 magnification, along with a Sedgewick-Rafter Counting Cell measuring 50 x 20 x 1mm³, were used to identify the phytoplankton species **(Gauns *et al.*, 2020)**. The taxonomic references by Yamaji and Mizuno were consulted for species identification. Phytoplankton abundance was calculated using the equations recommended in the APHA standards **(Baird *et al.*, 2017; Sheekh, 2023; Yongo *et al.*, 2023)** as follows:

$$N = n \times \frac{Arc}{Aa} \times \frac{Vt}{Vsrc} \times \frac{1}{Vd} \quad (1)$$

N	:	Abundance (cells/L)
n	:	Number of cells counted (sel)
Aa	:	Cover glass area (mm^2)
Arc	:	SRC (Sedgewick-Rafter Counting) cross-sectional area (mm^2)
Vt	:	Filtered water volume (ml)
Vsrc	:	Volume of water under the cover glass (ml)
Vd	:	Volume of filtered water (L)

Diversity indices, such as the Shannon-Wiener Index, Pielou's Evenness, and Margalef's Richness, were calculated to characterize the phytoplankton community structure **(Almeida *et al.*, 2016; Sheekh, 2023; Yongo *et al.*, 2023)** as follows :

$$H' = -\sum \frac{n_i}{N} \ln \frac{n_i}{N} \quad (2)$$

H' : Diversity index (Shannon-Wiener index)
N : Total Number of individuals
ni : Number of i-th individuals

$$E = {}^{H''}/_{H_{max}} \tag{3}$$

E : Evenness index (Pielou's Evenness)
H' : Diversity index
Hmax : ln S
S : Number of individuals

$$D = \sum_{n=1}^{n} \left(\frac{n_i}{N}\right)^2 \tag{4}$$

D : Dominant Index (Simpson's Dominance Index)
N : Total Number of individuals
ni : Total Number of i-th individuals
n : Total amount of plankton

The Nygaard Diatom Index was determined by analyzing the number of phytoplankton species belonging to the orders Centrales and Pennales within the class Bacillariophyceae **(Yongo *et al.*, 2023)**. The Nygaard Trophic Index was then calculated using the following formula:

$$\ln = \sum \text{sp. ordo Centrales} \,/ \sum \text{sp ordo Penales} \tag{5}$$

Table 1. Nygaard Index

Nygaard Index (ln)	Trophic Level Status
$0 \leq \ln \leq 0.2$	Oligotrofik
$0.2 \leq \ln \leq 2.5$	Mesotrofik or Eutrofik
$\ln \geq 2.5$	Eutrofik

RESULTS

The results of the study revealed that the overall values of water quality parameters in the southeast coastal region of Sumenep, East Java, Indonesia, were within the acceptable limits set by national environmental standards. The average values of water quality parameters are shown in Table (2).

Table 2. Average values of water quality parameters and acceptable limits at four stations during different seasons

Parameter	Standard*	Rainy Station 1	Rainy Station 2	Dry Station 1	Dry Station 2
Color (NTU)	30	32.00	33.00	30	30
Temperature (°C)	28-32	30.75	31.54	32.5	32.05
Clarity (m)	> 5	1.70	1.84	2.5	2.2
Turbidity	5	7.25	6.84	5.2	5.3
Total Suspended Solids (mg/L)	20	24.75	25.18	21.52	20.94
pH	7-8.5	7.48	7.18	7.6	7.8
Salinity (%)	33-34	33.16	32.84	36.25	35.80
Dissolved Oxygen (mg/L)	> 5	6.63	6.21	6.23	6.41
Biochemical Oxygen Demand (mg/L)	20	20.50	21.00	21.15	21.83
Total Ammonia (NH_3-N) (mg/L)	0.02	0.20	0.18	0.27	0.21
Nitrate (NO_3-N) (mg/L)	0.06	0.18	0.19	0.2	0.19
Orthophosphate (PO_4^{3-}-P) (mg/L)	0.015	0.35	0.33	0.28	0.31

Note *: referring to Appendix VIII Government Regulations of The Republic of Indonesia Number 22, 2021, about the Implementation of Protection and Environmental Management

The data presented in Table (1) compares water quality parameters collected at four stations during rainy and dry seasons with established seawater quality standards in Indonesia. The analysis reveals that several parameters, such as color, turbidity, total suspended solids, biochemical oxygen demand, ammonia, nitrate, and orthophosphate, exceed the permissible limits. Parameters refer to the existence of potential water quality concerns that warrant further investigation. Additionally, there are observable variations in some parameters between the rainy and dry seasons. For instance, salinity tends to be higher during the dry season, which is expected due to reduced freshwater input. Furthermore, the low clarity and elevated turbidity values indicate a high concentration of suspended particles in the water column, potentially attributed to natural processes or anthropogenic influences.

The phytoplankton community analysis revealed the presence of 14 distinct species belonging to 3 major groups: Bacillariophyceae, Dinophyceae, and Cyanophyceae. The average phytoplankton abundance ranged from 1,290 to 1,740 cells/L across the sampling stations and seasons, as shown in the composition of average phytoplankton abundance presented in Fig. (1).

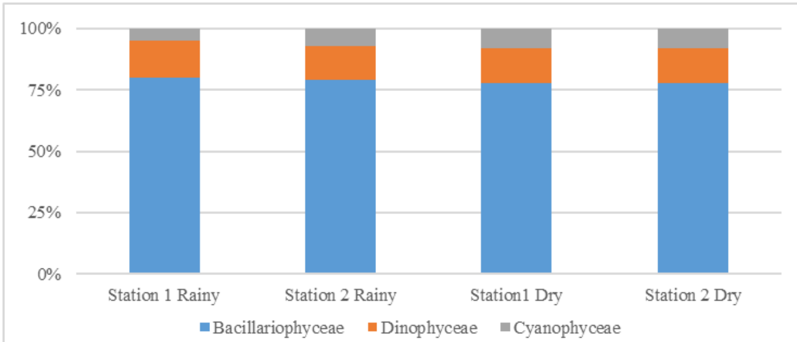

Fig. 1. Relative abundance of dominant diatom species across different seasons and stations

The phytoplankton community was heavily dominated by Bacillariophyceae (diatoms), making up 78-80% of the total abundance. In contrast, Dinophyceae and Cyanophyceae occupied smaller fractions, ranging from 14-15% and 5-8%, respectively. As shown in Fig. (1), diatoms were the dominant group, accounting for a significant 80% of the total phytoplankton community. This community structure is typical of coastal ecosystems, where diatoms play a crucial role in primary productivity. The abundance of phytoplankton (cell/L) recorded at each sampling station is detailed and presented in Fig. (2).

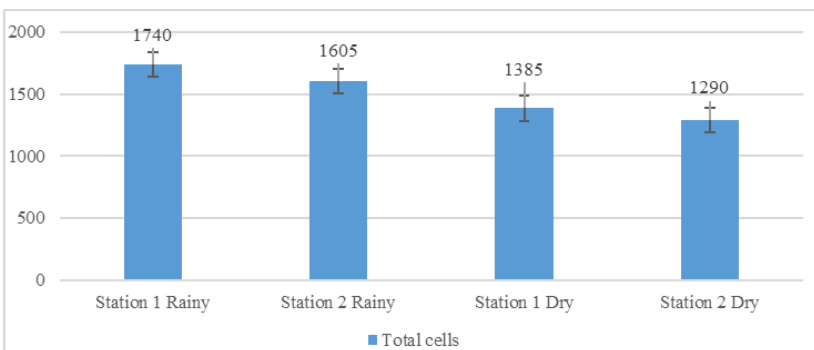

Fig. 2. Total phytoplankton abundance

As shown in Fig. (2), the total phytoplankton abundance is more significant during the rainy season than the dry season, with Rainy Station 1 demonstrating the highest recorded abundance. The phytoplankton species found at each observation station are shown in Table (3).

The data in Table (3) show the phytoplankton species composition and their abundance at the four sampling stations. The dominant diatom species included

Chaetoceros affinis, *Coscinodiscus centralis*, *Pseudo-nitzschia* sp., Thalassionema nitzschioides and *Rhizosolenia setigera*. The dinoflagellate species *Ceratium* sp. and *Prorocentrum micans* were also present in significant numbers, while the cyanobacterium *Oscillatoria* sp. was the dominant species within the Cyanophyceae group.

Table 3. Abundant phytoplankton species (cell/ml) at 4 sampling stations

Species	Rainy Station 1	Rainy Station 2	Dry Station 1	Dry Station 2
Bacillariophyceae				
Nitzschia seriata	83	77	66	62
Pseudo-nitzschia sp.	104	97	83	77
Biddulphia mobiliensis	63	58	50	46
Bacteriastrum furcatum	79	73	63	58
Chaetoceros affinis	475	440	378	351
Coscinodiscus centralis	204	189	162	151
Melosira varians	75	69	60	55
Gyrosigma sp.	42	39	33	31
Rhizosolenia cylindrus	54	50	43	40
Rhizosolenia setigera	96	89	76	71
Thalassionema nitzschioides	100	93	80	74
Dinophyceae				
Ceratium sp.	145	130	115	108
Prorocentrum micans	99	89	79	74
Cyanophyceae				
Oscillatoria sp.	121	112	97	92
Total	**1,740**	**1,605**	**1,385**	**1,290**

The diversity indices, evenness indices, and richness indices calculated to characterize the phytoplankton community structure are presented in Table (4).

Table 4. Diversity indices, evenness indices, and richness indices of phytoplankton community in coastal waters of East Java, Indonesia

Index	Rainy Station 1	Rainy Station 2	Dry Station 1	Dry Station 2
Shannon-Wiener Diversity Index	2.18	2.12	2.32	2.27
Pielou’s Evenness Index	0.79	0.77	0.84	0.82

Simpson's Dominance Index	0.14	0.16	0.11	0.12

The phytoplankton community exhibited moderate diversity, as evidenced by the Shannon-Wiener Diversity Index values ranging from 2.12 to 2.32. The Pielou's Evenness Index values, between 0.77 and 0.84, suggest a relatively even distribution of phytoplankton species. Furthermore, the low Simpson's dominance Index values, ranging from 0.11 to 0.16, indicate that no single species excessively dominates the community, further supporting the diverse nature of the phytoplankton assemblage.

The trophic level assessment, based on the Nygaard Index, reveals fluctuations between eutrophic and mesotrophic states. The Nygaard Index, calculated using phytoplankton community composition data, provides a comprehensive measure of trophic status by incorporating the relative proportions of different phytoplankton groups with varying nutrient preferences. Higher Nygaard Index values indicate a more significant proportion of eutrophic species, suggesting higher nutrient levels and increased productivity. The trophic level status results are shown in Table (5).

Table 5. Trophic level status based on the average values of water quality parameters in the coastal waters of East Java, Indonesia

Station	Nygaard Index	Trophic Level Status
Rainy 1	2.68	Eutrophic
Rainy 2	2.52	Eutrophic
Dry 1	1.78	Mesotrophic or light Eutrophic
Dry 2	1.63	Mesotrophic or light Eutrophic

DISCUSSION

The analysis of the trophic level status based on the average values of water quality parameters indicates that the coastal waters were in a eutrophic state during the rainy seasons, while transitioning to a mesotrophic state during the dry seasons. These findings suggest that the coastal waters of East Java, Indonesia, are experiencing fluctuations in their trophic status, with the rainy season being characterized by elevated nutrient levels and increased phytoplankton productivity, leading to a eutrophic condition.

This study assesses baseline water quality and phytoplankton community structure in the coastal waters of East Java, Indonesia, revealing key insights into the interplay between these factors, seasonal variations, trophic status, and potential implications for coastal health. The observed fluctuations between eutrophic and mesotrophic states underscore the dynamic nature of this coastal ecosystem and its potential vulnerability to environmental changes **(Garmendia *et al.*, 2013; Esqueda-lara *et al.*, 2021)**.

Seasonal variations in water quality parameters played a significant role in shaping the phytoplankton community structure and, consequently, the overall coastal health

(Ferreira *et al.*, 2011; Garmendia *et al.*, 2013; Sheekh, 2023). Elevated salinity during dry seasons, likely due to reduced freshwater input and increased evaporation, coupled with thermal stratification, can lead to nutrient depletion in surface waters **(Schroeder & Island, 1990; Parin *et al.*, 2019; Yu *et al.*, 2019; Gauns *et al.*, 2020)**. This nutrient limitation can constrain phytoplankton growth, potentially impacting the entire food web and overall ecosystem productivity **(Hayes *et al.*, 2015; Giglio *et al.*, 2022; Uddin *et al.*, 2024)**. Reduced productivity can disrupt the delicate balance of the coastal ecosystem, affecting higher trophic levels and potentially diminishing the coastal area's ecological and economic value **(Asiddiqi *et al.*, 2019; Henson *et al.*, 2021)**. Conversely, increased nutrient concentrations during rainy seasons, likely from terrestrial runoff and coastal erosion, can fuel excessive phytoplankton growth, leading to eutrophic conditions. While increased productivity might seem beneficial, excessive nutrient enrichment can have detrimental effects on coastal health **(Cabral *et al.*, 2020)**. Eutrophication can lead to harmful algal blooms, oxygen depletion, and the degradation of coastal habitats, posing risks to marine life and potentially impacting human health through seafood contamination or recreational limitations **(Teichberg *et al.*, 2009)**. These fluctuations in nutrient levels and the resulting shifts in phytoplankton communities underscore the dynamic nature of coastal ecosystems and the importance of maintaining a balance between productivity and water quality to ensure coastal health **(Cloern, 2015; Dai *et al.*, 2023)**.

Phytoplankton community composition is crucial for assessing coastal health **(Garmendia *et al.*, 2013; Firdaus, 2018; Giglio *et al.*, 2022)**. Moderate diversity and Evenness indices suggest a balanced, resilient ecosystem. However, fluctuations in the Nygaard Index, indicating shifts between eutrophic and mesotrophic states, warrant attention. Shifts toward eutrophy, particularly during the rainy season, likely reflect increased nutrient runoff, emphasizing the need for managing nutrient inputs to prevent detrimental impacts like harmful algal blooms and oxygen depletion **(Cabral *et al.*, 2020; Tereza *et al.*, 2020)**. Furthermore, the Nygaard Index serves as a measure based on phytoplankton to assess the trophic state of water bodies, generally indicating higher values in more eutrophic conditions. Various water quality parameters influence this index by affecting the abundance and composition of phytoplankton, which determine the index value. Elevated nutrient levels, such as nitrogen and phosphorus, can promote phytoplankton growth and shift the community toward species adapted to eutrophic conditions, resulting in a higher Nygaard Index values **(Yongo *et al.*, 2023; Fahim *et al.*, 2024)**. Similarly, changes in turbidity, salinity, and temperature can impact the distribution, abundance, and species composition of phytoplankton, consequently influencing the Nygaard Index **(Yongo *et al.*, 2023; Fahim *et al.*, 2024)**.

Future research should incorporate other ecosystem components (zooplankton, benthic organisms) and environmental factors (currents, wind, anthropogenic activities) for a more comprehensive understanding. The trophic level assessment, based on the Nygaard Index, provides a comprehensive view of the ecosystem's status and implications for coastal health. The observed fluctuations between eutrophic and mesotrophic states are consistent with seasonal variations in water quality and phytoplankton composition. Eutrophic conditions, while indicative of high productivity, can compromise water quality due to the potential for harmful algal blooms and oxygen depletion **(Orfanidis *et al.*, 2001; Cabral *et al.*, 2020; Tereza *et al.*, 2020)**. Mesotrophic conditions generally represent a more balanced, sustainable state.

In addition to seasonal variations, other environmental factors, such as prevailing currents and wind patterns, may influence water quality and phytoplankton dynamics in this coastal region **(Cloern, 2015; Cabral *et al.*, 2020; Giglio *et al.*, 2022)**. Furthermore, anthropogenic activities, such as land-based pollution and coastal development, could also contribute to nutrient enrichment and alter ecosystem dynamics **(Cabral *et al.*, 2020; Wakwella *et al.*, 2023)**. Assessing the potential impacts of these activities is crucial for developing effective coastal management strategies. Integrating water quality monitoring, phytoplankton community assessments, and trophic status evaluations into coastal health assessments can provide valuable insights for managing and protecting these valuable coastal ecosystems **(Craig & Ruhl, 2010; Kennish, 2021)**.

To ensure the long-term health and sustainability of East Java's coastal ecosystem, the following key management recommendations are proposed: Implement nutrient management strategies to reduce runoff, especially during rainy seasons; establish comprehensive monitoring and early warning systems for water quality and phytoplankton; adopt an Integrated Coastal Zone Management approach incorporating stakeholder engagement and land-use planning; and conduct further research addressing long-term trends, hydrodynamic influences, anthropogenic impacts, and a more holistic ecosystem assessment (including zooplankton, benthic organisms, etc.).

This study provides valuable insights into the seasonal dynamics of water quality and phytoplankton communities in the coastal waters of East Java. However, several limitations should be acknowledged. The study's temporal scope, focusing on seasonal variations, may not capture short-term fluctuations or long-term trends in these dynamics. Expanding the study period and increasing the sampling frequency would provide a more comprehensive understanding. While the study identifies key environmental drivers, such as nutrient levels, other factors like prevailing currents, wind patterns, and specific anthropogenic activities were not comprehensively investigated.

Furthermore, the study's focus on phytoplankton communities does not fully represent the entire coastal ecosystem. Investigating other biological components would provide a more holistic view of ecosystem health. Finally, while the study identifies potential threats to coastal health, such as nutrient enrichment, further research is needed to develop and evaluate targeted strategies for mitigating these threats and ensuring the long-term health and sustainability of this valuable coastal region.

CONCLUSION

This study provides a comprehensive assessment of seasonal water quality and phytoplankton dynamics in the coastal waters of East Java, revealing distinct patterns linked to nutrient fluctuations and their influence on trophic status. The observed shifts between eutrophic and mesotrophic conditions underscore the ecosystem's dynamic nature and vulnerability to nutrient enrichment, particularly during rainy seasons. The moderately diverse phytoplankton community, currently dominated by diatoms, indicates a healthy yet potentially vulnerable system. These findings establish a crucial baseline for future monitoring and inform the development of integrated coastal management strategies to mitigate the impacts of nutrient loading and other stressors, ensuring the long-term health and sustainability of this valuable coastal region. The study's findings suggest the following policy implications for stakeholders: implement stringent regulations on nutrient discharge from agricultural, industrial, and urban sources; develop and enforce buffer zones along coastlines; establish a comprehensive, real-time water quality monitoring network; promote sustainable aquaculture practices; implement Integrated Coastal Zone Management plans, and invest in research to understand the long-term effects of nutrient enrichment.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interest regarding the authorship or publication of this research.

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