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Analyses of ecosystem productivity using field measurement and remote sensing, and microalgae diversity at Mayangan and Sendang Biru Beaches, East Java, Indonesia

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Abstract. *Zakiyah U, Santoso ASKT, Pramudia Z, Irawandani TD, Erintika D. 2025. Analyses of ecosystem productivity using field measurement and remote sensing, and microalgae diversity at Mayangan and Sendang Biru Beaches, East Java, Indonesia. Biodiversitas 26: 1777-1788.* This study evaluates ecosystem productivity and microalgae biodiversity at Mayangan Beach and Sendang Biru Beach, East Java, Indonesia using chlorophyll-a as an indicator, as it functions as an active metabolic component in the photosynthesis process of microalgae, the primary producers in aquatic ecosystems. By integrating in-situ measurements and remote sensing via Sentinel-2 Imagery, the study assesses water quality, microalgae composition, and biodiversity indices, which mutually influence trophic balance and food chain efficiency. The abundance of microalgae reflects nutrient availability and environmental conditions, determining primary productivity and aquatic ecosystem health. Results indicate that Mayangan Beach exhibits higher chlorophyll-a concentrations due to nutrient-rich runoff, while Sendang Biru Beach maintains more stable but oligotrophic conditions. Chlorophyll-a, as a primary photosynthetic pigment, is essential for analyzing ecosystem productivity as it directly correlates with microalgae abundance. Bacillariophyta is the dominant microalgae group in both waters, highlighting its ecological role in aquatic productivity. These findings underscore the importance of integrating remote sensing with field data for effective coastal monitoring. Additionally, the study emphasizes how environmental factors such as nutrient input and hydrodynamics influence ecosystem productivity. The results provide insights for sustainable coastal management and demonstrate the potential of remote sensing technology in assessing marine ecosystem health.

Keywords: Chlorophyll-a, microalgae, remote sensing, Sentinel-2 Imagery

INTRODUCTION

Coastal waters represent dynamic interfaces between terrestrial and marine ecosystems, characterized by significant biological and non-biological potential. These areas serve as hubs for various human activities such as fisheries, tourism, and transportation, while simultaneously acting as reservoirs of biodiversity (Wijaya et al. 2020). However, the quality of coastal waters is strongly influenced by inputs from terrestrial sources, such as river discharge and surface runoff, which carry organic matter and nutrients. These inputs not only alter the physical and chemical properties of the water but also affect the ecological balance, making coastal areas vulnerable to changes such as pollution and eutrophication (Asensio-Montesinos et al. 2024; Marwa et al. 2024). Such changes impact the immediate aquatic environment and surrounding terrestrial ecosystems.

Among the organisms most affected by such changes are microalgae, which play a crucial role as primary producers in aquatic ecosystems (Rose et al. 2019). Microalgae are sensitive to variations in water quality, making them important indicators of environmental health and productivity. These organisms respond rapidly to fluctuations in nutrient availability, light penetration, and pollution levels. Thus, the dynamics of microalgae populations provide valuable insights into the short-term and long-term health of coastal ecosystems. They serve as early responders to anthropogenic pressures, offering insights into the ecological status of coastal waters (Li et al. 2021).

One of the widely used metrics for assessing microalgal productivity is the concentration of chlorophyll-a, a primary photosynthetic pigment. Chlorophyll-a serves as a proxy for estimating the abundance of microalgae and the nutrient status of the water body (Sathyendranath et al. 2019). Higher concentrations of chlorophyll-a indicate elevated productivity and nutrient availability, often linked to eutrophication in coastal ecosystems (Otsuka et al. 2018). Although methods such as flow cytometry and High-Performance Liquid Chromatography (HPLC) can be used for identify and quantification remote sensing is more effective. This technology enables large-scale and real-time assessments of water quality without direct physical sampling, allowing for monitoring trends over time that might otherwise go unnoticed.

The northern and southern coasts of East Java, Indonesia, provide a unique contrast in their physical, ecological and social characteristics, making them ideal sites for evaluating coastal productivity (Zakiyah et al. 2020). Mayangan Beach in Probolinggo City, situated on the northern coast, is characterized by its gently sloping seabed, minimal wave activity, and proximity to the Java Sea. This region experiences significant sedimentation due to the numerous river estuaries and deltas, and its substrate is predominantly muddy with extensive mangrove coverage (Putri et al. 2023). Anthropogenic activities such as fishing, shipping, and pollution from fish processing and household waste further impact water quality in this area. Such human activities not only degrade water quality but can also lead to the loss of critical habitats, which are essential for maintaining biodiversity (Isroni et al. 2023). In contrast, Sendang Biru Beach in Malang Regency lies along Java's southern coast, adjacent to the Indian Ocean. This area has strong wave activity, steep seabed topography, and sandy beaches interspersed with coral and limestone substrates. The strait between Sendang Biru Beach and Sempu Island provides a unique aquatic environment, with deeper waters and stronger currents compared to the northern coast (Hidayati et al. 2024).

The distinct characteristics of these two coastal areas influence their ecological productivity and water quality. The nutrient-rich sediments of Mayangan Beach support a different ecological dynamic compared to the clearer but more turbulent waters of Sendang Biru Beach. This contrast underscores the importance of region-specific management strategies when addressing environmental challenges in coastal areas (Halpern et al. 2017). Through chlorophyll-a analysis and the study of microalgae biodiversity, it is possible to evaluate the productivity and ecological health of these contrasting environments. This research offers critical insights into how physical, chemical, and anthropogenic factors shape the productivity of coastal waters, highlighting the importance of sustainable management to preserve their ecological and blue economic value. Ultimately, such studies are crucial for developing strategies to mitigate the impacts of human activity and safeguard the future health of coastal ecosystems.

MATERIALS AND METHODS

Studi period and area

This study was conducted by comparing two methods: the first involved collecting samples directly (in-situ) at the research site followed by identification, and the second utilized remote sensing. This study was conducted in October 2023 at Mayangan Beach and Sendang Biru Beach of East Java Province, Indonesia. Sampling was carried out at five designated stations on each beach. A detailed description of the sampling locations and maps are presented in Table 1 and Figure 1.

Data collecting

Field sampling

The research employed a descriptive method with a purposive sampling technique, selecting sampling locations based on specific criteria representative of the study area. Sampling stations were determined considering the similarities in land use between Mayangan Beach and Sendang Biru Beach. Water sampling was carried out at 8:00 AM. A total of 25 L of water was filtered using a plankton net and stored in 100 mL polyethylene bottles for subsequent analysis (Kruk et al. 2016).

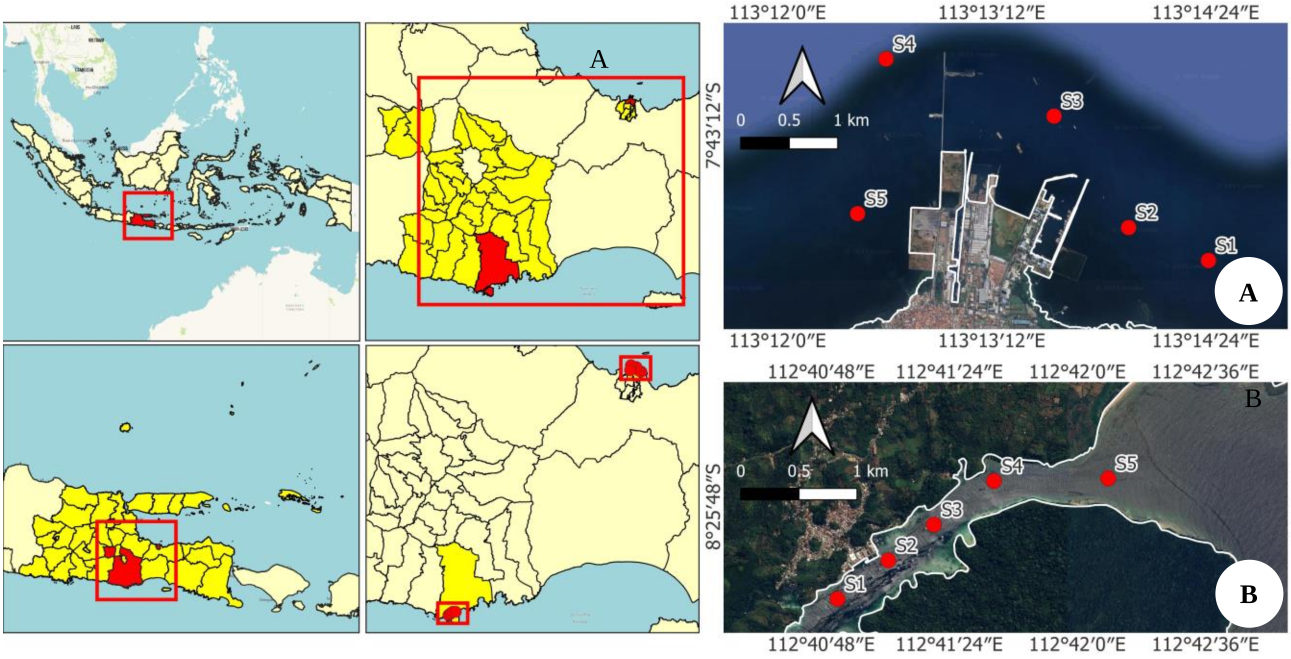


Figure 1. Map of research location in Mayangan Beach (A) and Sendang Biru Beach (B), East Java, Indonesia

Table 1. Coordinates of research stations in Mayangan and Sendang Biru Beaches, East Java, Indonesia

Station	Latitude	Longitude	Description
Mayangan Beach			
1	7°43'57.23" S	113°14'24.99" E	Fishery ponds area
2	7°43'46.17" S	113°13'58.12" E	Mangrove conservation ecotourism
3	7°43'8.69" S	113°13'33.03" E	Mayangan port
4	7°42'49.49" S	113°12'36.49" E	High seas borders
5	7°43'41.51" S	113°12'26.93" E	Settlement
Sendang Biru Beach			
1	8°26'13.8" S	112°40'52.6" E	Teluk semut, clungup mangrove conservation floating house, kondang buntung
2	8°26'2.97" S	112°41'6.9" E	Podokdadap coastal fisihing port
3	8°25'52.93" S	112°41'19.7" E	Marine ecotourism, nature reserve conservation
4	8°25'40.67" S	112°41'36.6" E	Floating net cages
5	8°25'39.97" S	112°42'8.7" E	High seas borders

Table 2. Tools and methods

Parameter	Tool or method
Temperature (°C)	Multiparameter Water Quality Checker (WQC-22A, DKK TOA Corporation, Japan)
Brightness (meter)	Secchi Disk
Salinity (‰)	Multiparameter Water Quality Checker (WQC-22A, DKK TOA Corporation, Japan)
pH	Multiparameter Water Quality Checker (WQC-22A, DKK TOA Corporation, Japan)
DO (ppm)	Multiparameter Water Quality Checker (WQC-22A, DKK TOA Corporation, Japan)
NO3- (ppm)	Indonesian National Standard (SNI):06-6989.11-1990, spectrophotometer (U-1900, Hitachi High- Technologies Corporation, Japan)
PO_4^{3-} (ppm)	Indonesian National Standard (SNI):06-6989.31-2005, spectrophotometer (U-1900, Hitachi High- Technologies Corporation, Japan)

The water quality parameters measured in this study encompassed physical, chemical, and biological aspects of water quality. Physical parameters included water temperature and transparency. Chemical parameters consisted of Dissolved Oxygen (DO), pH, salinity, nitrate, and phosphate concentrations. Biological parameters involved the analysis of microalgae and chlorophyll-a content. Field measurements included temperature, transparency, pH, dissolved oxygen, salinity, and chlorophyll-a. Laboratory analyses were conducted to determine nitrate and phosphate concentrations as well as to identify microalgae species. The tools and methods used to measure the water quality parameters are detailed in Table 2.

Remote sensing based on chlorophyll-a analysis

Chlorophyll-a analysis was conducted using Sentinel-2 Level-1 Imagery, which has a temporal resolution of 5 days. The images were obtained from the Copernicus Open Access Hub (www.dataspace.copernicus.eu). Chlorophyll-a values were extracted using the Case 2 Regional Coast Color (C2RCC) algorithm implemented in the Sentinel Application Platform (SNAP). The extracted chlorophyll-a data were subsequently processed for spatial visualization using the Quantum GIS (QGIS) software to generate a comprehensive layout of the chlorophyll-a distribution (Toming et al. 2016; Cordeiro et al. 2021).

Data analysis

Microalgae abundance

Microalgae enumeration was performed using a Sedgwick-Rafter counting cell, employing the zigzag method across three focal planes (top, middle, and bottom). The obtained data were subsequently analyzed using the following formula (Litchman et al. 2015; Hillebrand et al. 2018):

$$N = \frac{1}{Vd} X \frac{Vt}{Vs} X F$$

Where:
N : Number of individuals per liter (ind/L)
Vt : Filtered water volume (mL)
Vs : Volume of water in sedwick rafter counting cell (mL)
Vd : Volume of filtered water
F : Number of plankton counted

Diversity Index

Diversity Index according to Shannon-Wiener (Kurnianto et al. 2025):

$$H^{'} = -\sum_{n=1}^{n}(pi * In\, p_i)$$

Where:
H' : Species Diversity Indeks
Pi : ni/N (proportion of the i-th species)
Ni : Number of individuals of the i-th species
N : Total number of individuals

Criteria:
H'<1 = Low community stability
1<H'<3 = Medium community stability
H'>3 = High community stability

Uniformity Index

The Uniformity Index can be calculated as (Anitasari et al. 2024):

$$E = \frac{H'}{H'max}$$

Where:
E : Uniformity Index
H' : Diversity indeks
H' max: ln S (Maximum diversity index)
S : Number of species
Criteria :
0<E<0.4 = Low diversity, stressed community
0.4<E<0.6 = Medium uniformity, labile community
0.6<E<1 = High uniformity, stable community

Dominance Index

The Dominance Index can be calculated (Anitasari et al. 2024):

$$D = \sum_{i=1}^{s} pi^2$$

Where:
D : Simpson's Dominance Index
Ni : Number of individuals in the i-th genus
Ns : Total number of individuals in the sample
Criteria:
D≤0.5 = No species dominance, stable community condition
0.5≤D≤1 = There is species dominance, unstable community conditions

Accuracy of image data with field data

The accuracy assessment was conducted to evaluate the consistency between in-situ measurements and satellite-derived data. The accuracy analysis was performed using statistical metrics, including the Root Mean Square Error (RMSE) and the Normalized Mean Absolute Error (NMAE). The value that can be used as a reference for RMSE calculation is if ≤1, while for NMAE is ≤30% (Gatinel et al. 2024). The RMSE and NMAE equations used in this study are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(x_{\text{esti},i} - x_{\text{meas},i}\right)^2}{N}}$$

Where:
$X_{meas.i}$: Measurement value (chlorophyll-a insitu / laboratoy)
$X_{esti.i}$: Estimated value (image chlorophyll-a)
N : Number of data used for validation

$$NMAE(\backslash\%) = \frac{1}{n}\sum_{i=1}^{N}\left|\frac{x_{\text{esti},i} - x_{\text{meas},i}}{x_{\text{meas},i}}\right| \times 100$$

Where:
$X_{meas.i}$: Measurement value (chlorophyll-a insitu/ laboratoy)
$X_{esti.i}$: Estimated value (image chlorophyll-a)
N : Number of data used for validation

The value that can be used as a reference for RMSE calculation is if ≤1, while for NMAE is ≤30%.

RESULTS AND DISCUSSION

Water quality standards and measurements

Water quality standards in this study refer to Government of the Republic of Indonesia (2021) concerning the Implementation of Environmental Protection and Management. The results of the water quality measurements from Mayangan Beach and Sendang Biru Beach are summarized in Table 3 and analyzed based on these regulatory standards.

The average temperature recorded at Mayangan Beach was 30.39°C, while at Sendang Biru Beach, it was 29.21°C. Both values fall within the acceptable range for natural waters (28-30°C). An optimal temperature is crucial for supporting plankton growth, as it enhances metabolic processes and chemical reactions that accelerate the rate of photosynthesis (Morales et al. 2018; Mohd-Din et al. 2025). Variations in temperature can directly influence the productivity and biodiversity of aquatic ecosystems.

The average water brightness was 4.09 m at Mayangan Beach and 6.29 m at Sendang Biru Beach, exceeding the minimum quality standard of >3 m. However, the lowest brightness was observed at Station 5 of Mayangan Beach and Station 1 of Sendang Biru Beach, likely due to proximity to the shore where turbidity is higher. This increased turbidity can be attributed to suspended particles, plankton density, and wave action near coastal zones. Factors influencing water brightness include weather conditions, time of measurement, suspended solids, plankton abundance, and sunlight intensity (Morales et al. 2018; Zerveas et al. 2021).

Table 3. Water quality parameter measurement results in Mayangan and Sendang Biru Beaches, East Java, Indonesia

Parameter	**Station 1**		**Station 2**		**Station 3**		**Station 4**		**Station 5**	
	MB	**SBB**	**MB**	**SBB**	**MB**	**SBB**	**MB**	**SBB**	**MB**	**SBB**
Temperature (°C)	30.90	28.80	30.40	29.25	30.65	29.30	30.45	29.15	29.55	29.55
Brightness (meter)	3.70	3.27	3.44	6.21	6.89	6.96	3.88	7.88	2.53	7.12
Salinity (‰)	32.80	33.49	32.76	33.76	32.75	33.82	32.75	33.75	32.84	33.67
pH	7.98	8.04	8.01	8.03	7.99	8.04	7.99	8.03	7.93	8.00
DO (ppm)	6.33	6.53	6.35	6.51	6.36	6.55	6.38	6.56	6.43	6.55
NO3- (ppm)	0.72	2.49	1.10	2.16	0.87	1.69	0.75	1.77	0.39	2.20
PO_4^{3-} (ppm)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.01

Note: MB: Mayangan Beach; SBB: Sendang Biru Beach

The average salinity at Mayangan Beach was 32.78 ppt, while Sendang Biru Beach recorded a slightly higher average of 33.70 ppt. Based on the quality standard (33-34 ppt), Mayangan Beach did not meet the required threshold, whereas Sendang Biru Beach was within the acceptable range. The lower salinity at Mayangan Beach could be attributed to low-intensity rainfall one hour before sampling, which likely diluted the salinity concentration. Salinity levels in coastal waters are influenced by factors such as evaporation, rainfall, river discharge, and water circulation patterns (Mohd-Din et al. 2025). Elevated salinity levels can inhibit the photosynthetic activity of microalgae, potentially affecting the ecosystem's overall productivity (Zerveas et al. 2021).

The pH levels measured at both beaches were relatively similar, with averages of 7.98 at Mayangan Beach and 8.03 at Sendang Biru Beach. These values fall within the quality standard range of 6.5-8.5. The pH of coastal waters is dynamic, often increasing during the day due to photosynthetic activity, which reduces CO_2 (Mohd-Din et al. 2025) levels, and decreasing at night as respiration by aquatic organisms releases CO_2. Maintaining pH within the optimal range is essential for sustaining aquatic life and supporting ecosystem health (Morales et al. 2018; Zerveas et al. 2021).

Dissolved Oxygen (DO) is a critical parameter in aquatic environments, essential for the respiration of organisms and the decomposition of organic matter (Boyd et al. 2017). Measurements conducted at Mayangan Beach and Sendang Biru Beach yielded average DO concentrations of 6.37 ppm and 6.54 ppm, respectively. These values exceed the quality standard of >5 ppm, indicating favorable conditions for aquatic life. Dissolved oxygen in water originates from two primary sources: photosynthesis by microalgae and diffusion at the water-air interface (Mohd-Din et al. 2025). Elevated dissolved oxygen levels are often associated with high microalgae abundance, reflecting productive aquatic ecosystems (Morales et al. 2018).

The measured concentrations of nitrate and phosphate at Mayangan Beach and Sendang Biru Beach were found to be outside the recommended quality standards. According to the guidelines, the quality standard for nitrate is 0.06 mg/L, while for phosphate, it is 0.015 mg/L. Both nitrate and phosphate serve as essential nutrients that stimulate microalgae growth (Roziaty et al. 2023).

Elevated nitrate levels can result from nutrient inputs from land-based activities, including soil erosion, agricultural runoff, aquaculture, domestic waste, and boat operations (Paiki and Kalor 2017). For instance, at Station 1, nitrate levels were influenced by nearby aquaculture activities at Mayangan Beach and floating houses at Sendang Biru Beach.

The phosphate concentrations at both beaches were below the quality standard, which could be attributed to high levels of microalgae activity. Phosphate is rapidly consumed by microalgae, making it a limiting factor in nutrient dynamics when its concentration falls below 0.004 mg/L. Conversely, phosphate levels exceeding 1 mg/L can promote algal blooms (Sumantra et al. 2020; Roziaty et al. 2023). The insufficient phosphate levels observed in this study highlight the importance of balanced nutrient availability for maintaining ecosystem stability and productivity.

In-situ chlorophyll-a measurements

In-situ measurements of chlorophyll-a concentrations ranged from 1.115 to 4.1 mg/m^3 at Mayangan Beach and 1.595 to 6.255 mg/m^3 at Sendang Biru Beach. According to water fertility criteria, both beaches are categorized as mesotrophic, with chlorophyll-a levels between 2 and 6 mg/m^3. Calculation results for in-situ chlorophyll-a measurements can be seen in more detail in Table 4.

Figures 2 and 3 illustrate the spatial distribution of chlorophyll-a based on Sentinel-2 Imagery. The visualized distribution shows a darker coloration closer to the shoreline, indicating higher chlorophyll-a concentrations near land. This pattern suggests that nutrient input from terrestrial sources, such as runoff and human activities, plays a significant role in shaping the chlorophyll-a distribution near coastal areas.

Chlorophyll-a concentrations derived from Sentinel-2 imagery were consistently lower than those obtained from in-situ measurements. Additionally, the highest and lowest chlorophyll-a values from satellite imagery did not align with the in-situ data. This discrepancy may result from differences in spatial resolution, sampling depth, or environmental conditions during the data collection periods. These findings highlight the importance of integrating satellite-based remote sensing with field observations for a comprehensive assessment of water quality (Shi et al. 2022).

At Mayangan Beach, the highest chlorophyll-a concentration was recorded at Station 5, located near a residential area, while the lowest concentration was observed at Station 4, situated in the bagan tancap (traditional fishing net structure) area adjacent to the open sea (Figure 2). At Sendang Biru Beach, Station 3 exhibited the highest chlorophyll-a concentration. This station is within the Sempu Island nature reserve conservation area, which may benefit from nutrient input due to its protected status (Isdianto et al. 2024). In contrast, the lowest concentration was recorded at Station 5, located at the mouth of the Sempu Strait bordering the open sea (Figure 3).

Table 4. Chlorophyll-a measurement results in Mayangan and Sendang Biru Beaches, East Java, Indonesia

Sampling station	**Mayangan Beach**		**Sendang Biru Beach**	
	Insitu (mg/m^3)	**Sentinel-2 Imagery (mg/m^3)**	**Insitu (mg/m^3)**	**Sentinel-2 Imagery (mg/m^3)**
1	4.10	1.07	6.26	0.80
2	5.06	1.19	2.39	0.65
3	1.12	0.69	2.24	0.95
4	1.98	0.67	1.95	0.69
5	3.21	1.75	4,.35	0.38
Average	3.09	1.07	3.21	0.69

Discrepancies between in-situ and satellite measurements

The observed discrepancies between chlorophyll-a values derived from in-situ measurements and Sentinel-2 Imagery are likely attributable to differences in the timing of data collection. Variations in the timing of in-situ sampling and satellite image acquisition can significantly influence chlorophyll-a concentration estimates. Furthermore, cloud cover during satellite image acquisition may interfere with the accurate calculation of chlorophyll-a values (Zakiyah et al. 2019). Remote sensing technology is inherently limited by the nature of electromagnetic wave interactions and the distance between the sensor and the observed object. Despite image corrections, geometric errors can persist, impacting the precision of chlorophyll-a assessments (Binh et al. 2022). These limitations underscore the importance of combining remote sensing data with ground-truth measurements to enhance the accuracy of water quality evaluations.

Chlorophyll-a levels in coastal waters are primarily influenced by nutrient inputs from land, which are transported to the sea through river flows. Proximity to land is a key determinant, with higher chlorophyll-a concentrations observed closer to nutrient sources and lower concentrations farther from shore (Zhao et al. 2024). Additionally, chlorophyll-a concentration serves as a reliable indicator of microalgae abundance, with higher levels correlating with increased microalgae populations.

Accuracy of in-situ chlorophyll-a data compared to Sentinel-2 Imagery

The accuracy of chlorophyll-a measurements derived from Sentinel-2 Imagery was evaluated by comparing them to in-situ data, with the results presented in Table 5. The accuracy assessment used the Root Mean Square Error (RMSE) metric, which is considered reliable when its value is ≤1 (Jannah et al. 2022). At Mayangan Beach, the RMSE value was 0.903, indicating high accuracy. In contrast, the RMSE value for Sendang Biru Beach was 1.194, suggesting lower accuracy for this location.

The reduced accuracy of Sentinel-2 data at Sendang Biru Beach can be attributed to a significant time gap between in-situ sampling and the satellite image acquisition. Additionally, cloud cover during the closest image acquisition date hindered chlorophyll-a extraction, further contributing to the inaccuracy. These findings highlight the importance of aligning sampling and imagery acquisition times to improve the reliability of remote sensing data.

The Normalized Mean Absolute Error (NMAE) test establishes an acceptable error tolerance threshold of <30% for utilizing remote sensing imagery in extraction processes (Khastini et al. 2019). The NMAE test results for Mayangan Beach and Sendang Biru Beach were 11.998% and 14.608%, respectively. These values fall well within the acceptable range, confirming that the Sentinel-2 imagery used in this study is suitable for remote sensing-based extraction in line with the research objectives.

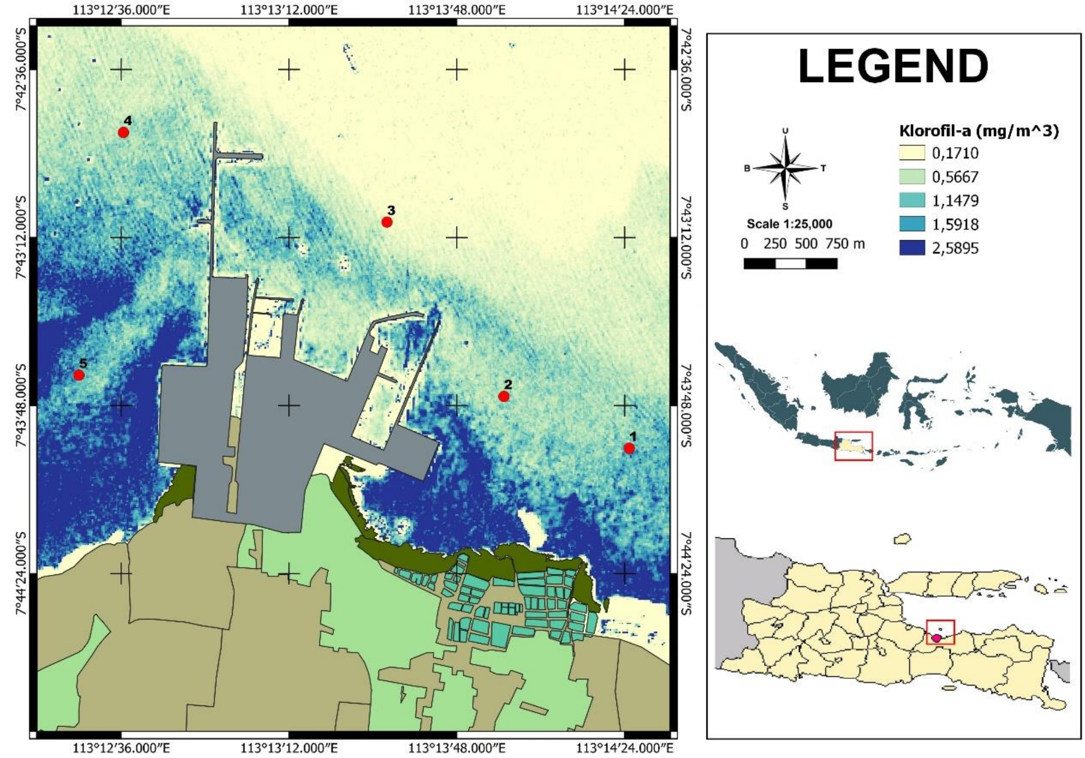


Figure 2. Sentinel-2 Image of chlorophyll-a in Mayangan Beach, East Java, Indonesia

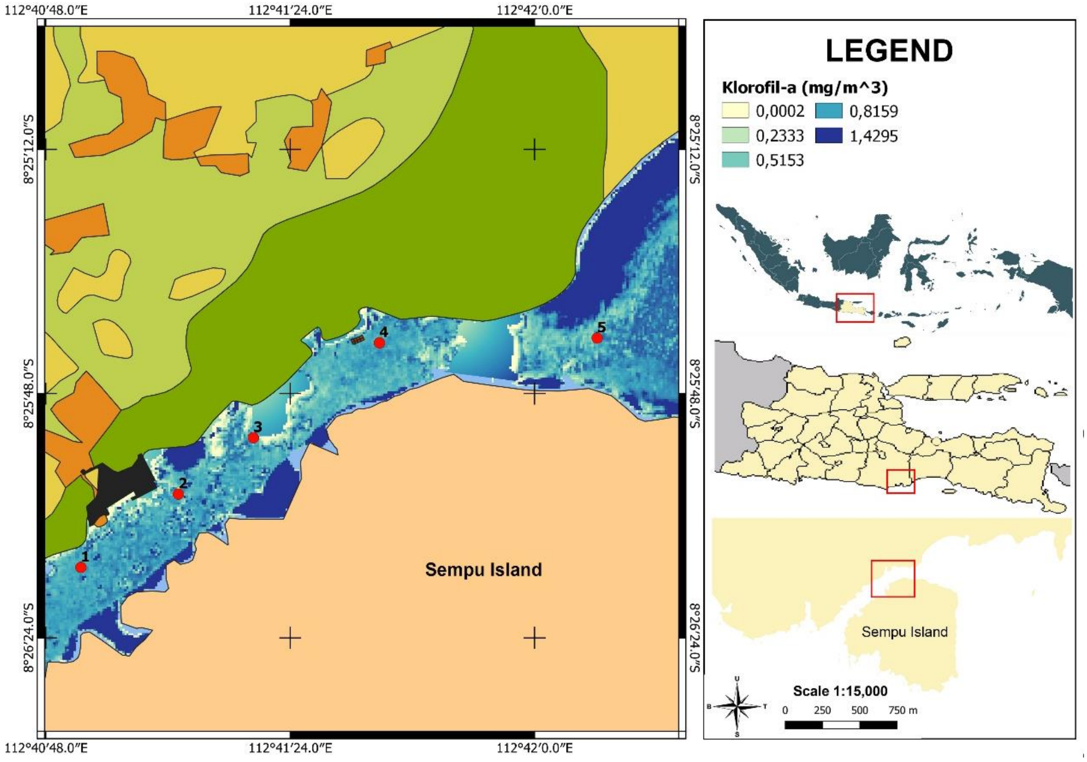


Figure 3. Sentinel-2 Image of chlorophyll-a in Sendang Biru Beach, East Java, Indonesia

Table 5. Accuracy of Sentinel-2 Image chlorophyll-a data with in-situ data in Mayangan and Sendang Biru Beaches, East Java, Indonesia

Sampling station	**RMSE (mg/m³)**		**NMAE (%)**	
	MB	**SBB**	**MB**	**SBB**
1	1.354	2.440	14.767	17.445
2	1.731	0.776	15.303	14.546
3	0.189	0.574	7.576	11.482
4	0.585	0.403	13.216	11.302
5	0.655	1.776	9.127	18.263
Average	0.903	1.194	11.998	14.608

Note: MB: Mayangan Beach; SBB: Sendang Biru Beach

Microalgae composition and abundance

Observations conducted at Mayangan Beach (north coast) and Sendang Biru Beach (south coast) revealed the presence of microalgae from nine divisions: Bacillariophyta, Charophyta, Chlorophyta, Cyanobacteria, Dinoflagellates, Euglenozoa, Haptophyta, Ocrophyta, and Rhodophyta. Among these, Bacillariophyta was the dominant division at both beaches. This dominance can be attributed to its high adaptability to changing environmental conditions and its rapid growth rate compared to other microalgae groups (Zhang et al. 2024). The relative composition of microalgae at Mayangan Beach and Sendang Biru Beach is illustrated in Figure 4, highlighting the variability in microalgae distribution across the two sites. The abundance of Bacillariophyta has been widely associated with high nutrient availability and productivity in coastal ecosystems, as it plays a crucial role in primary production and forms the base of aquatic food webs (Chan et al. 2021; Kaur and Reddersen 2022). In contrast, Rhodophyta was the least abundant division observed at both locations, likely due to its preference for more stable and nutrient-rich environments (Bian et al. 2022).

The microalgal community compositions in Mayangan Beach and Sendang Biru Beach exhibit notable differences that reflect their distinct coastal characteristics. Mayangan Beach, located along the north coast of Java, is characterized by relatively higher anthropogenic influences, such as river discharges and urban runoff, which contribute to elevated nutrient levels (Pan-utai et al. 2019; González-González and de-Bashan 2021). These conditions may favor the proliferation of opportunistic microalgae such as Bacillariophyta and Cyanobacteria. On the other hand, Sendang Biru Beach on the south coast is influenced by the Indian Ocean, which is known for stronger wave action and seasonal upwelling, resulting in higher water turbulence and lower nutrient retention (Ichii et al. 2018; Rumpa et al. 2022), although it was also found that there were many fishing and fish processing activities that should be considered for nutritional input and pollution. These oceanographic factors could explain the differences in the microalgal assemblages observed between the two sites (Chen et al. 2021).

A total of 64 genera of microalgae were identified at Mayangan Beach, while 59 genera were observed at Sendang Biru Beach. Among these, 39 genera were common to both locations, highlighting similarities in the microalgal communities. The shared genera include *Attheya*, *Bacteriastrum*, *Cerataulina*, *Chaetoceros*, *Chlorella*, *Closterium*, *Corethron*, *Coscinodiscus*, *Cyclotella*, *Diatoma*, *Euglena*, *Golenkinia*, *Guinardia*, *Gymnodinium*, *Gyrosigma*, *Gyrodinium*, *Kamptonema*, *Leptocylindrus*, *Mallomonas*, *Mediopyxis*, *Melosira*, *Navicula*, *Nitzschia*, *Oscillatoria*, *Phormidium*, *Pinnularia*, *Planktothrix*, *Pleurosigma*, *Porphyridium*, *Prorocentrum*, *Protoperidinium*, *Pseudanabaena*, *Pseudo-nitzschia*, *Rhizosolenia*, *Synedra*, *Skeletonema*, *Thalassionema*, *Trachelomonas*, and *Tyrannodinium*.

The presence of these shared genera reflects the ecological overlap between the two locations, potentially influenced by similar environmental conditions and nutrient availability. However, the differences in species composition and abundance highlight the impact of regional oceanographic and anthropogenic factors in shaping microalgal communities. The findings emphasize the importance of understanding microalgal dynamics in coastal ecosystems, as their abundance and composition can serve as bioindicators of water quality and productivity (Wu et al. 2020; Steinrücken et al. 2023). These insights are particularly relevant for monitoring coastal environmental changes along the north and south coasts of Java, where human activities and oceanographic processes differ significantly (Lafarga et al. 2021).

Microalgae abundance

The abundance of microalgae at Mayangan Beach ranged from 614,000 to 3,056,000 individuals per liter (ind/L), with the highest abundance recorded at Station 2 and the lowest at Station 5. At Sendang Biru Beach, the abundance ranged from 962,000 to 2,040,000 ind/L, with Station 1 showing the highest abundance and Station 5 the lowest (Figure 5). The elevated microalgae abundance at Station 2 (Mayangan Beach) and Station 1 (Sendang Biru Beach) is likely due to the higher input of organic matter in these areas compared to other stations. This observation is further supported by nitrate measurements, which indicated higher concentrations at these stations. Organic waste inputs, which carry nutrients, significantly influence the spatial variation in microalgae abundance (Paiki and Kalor 2017).

The fertility of aquatic environments can be categorized based on microalgae abundance. Oligotrophic (low fertility) waters typically exhibit abundances in the tens of thousands of individuals per liter. Mesotrophic (moderate fertility) waters range from tens to hundreds of thousands of individuals per liter, while eutrophic (high fertility) waters show abundances in the millions of individuals per liter (Mahmudi et al. 2025) based on the average microalgae abundance at Mayangan Beach and Sendang Biru Beach, both locations are classified as eutrophic waters. This classification highlights the nutrient richness and high biological productivity of these coastal ecosystems.

Microalgae diversity, uniformity, and dominance index

The Diversity Index (H') of microalgae at Mayangan Beach ranged from 1.5274 to 2.1851, while at Sendang Biru Beach, it ranged from 1.4886 to 2.0881 (Figure 6.A). These values fall within the moderate diversity category, which is defined by an H' value between 1 and 3 Moderate diversity levels indicate a stable ecological community with a balance of dominant and less prevalent microalgal species. The diversity of microalgae in these waters is supported by the ability of microalgal communities to aggregate in locations that provide optimal conditions for their growth, such as nutrient availability and suitable light conditions (Fauziah et al. 2019).

The Uniformity Index (E) for microalgae at Mayangan Beach ranged from 0.5666 to 0.7288, while at Sendang Biru Beach, it ranged from 0.4682 to 0.7367 (Figure 6.B) These results indicate that both coastal locations exhibit microalgal uniformity within medium and high categories. Medium uniformity is characterized by values of $0.4<E<0.60.4<E<0.60.4<E<0.6$, while high uniformity falls within $0.6<E<10.6<E<10.6<E<1$. The observed uniformity index values suggest that microalgae species at both locations are distributed relatively evenly, with high adaptability to varying environmental conditions. Environmental factors, such as nutrient availability, light intensity, and water quality, alongside the ecological adaptability of different microalgal species, significantly influence the uniformity index in aquatic ecosystems (Cahyo et al. 2021). These findings reflect stable ecological conditions, allowing a balanced distribution of microalgal populations.

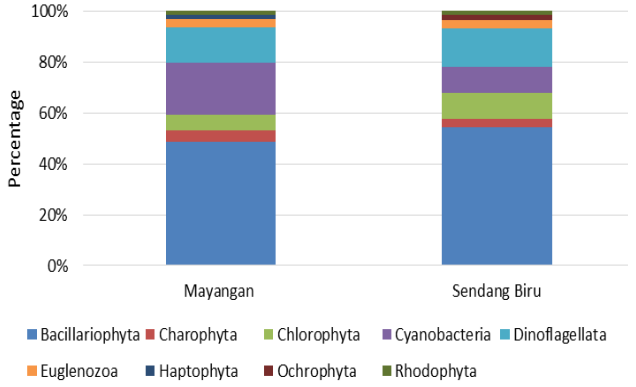


Figure 4. Composition of microalgae in Mayangan and Sendang Biru Beaches, East Java, Indonesia

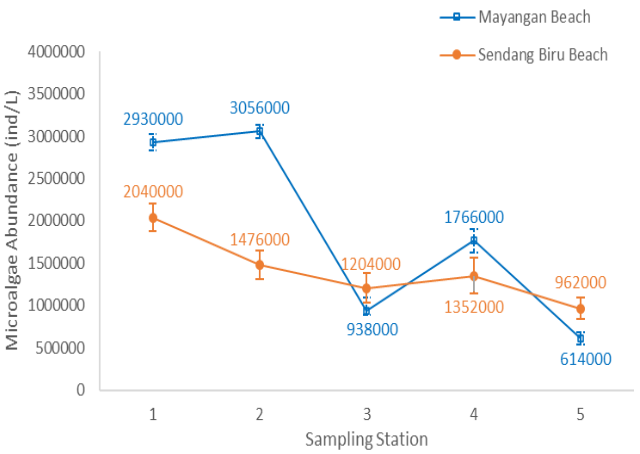
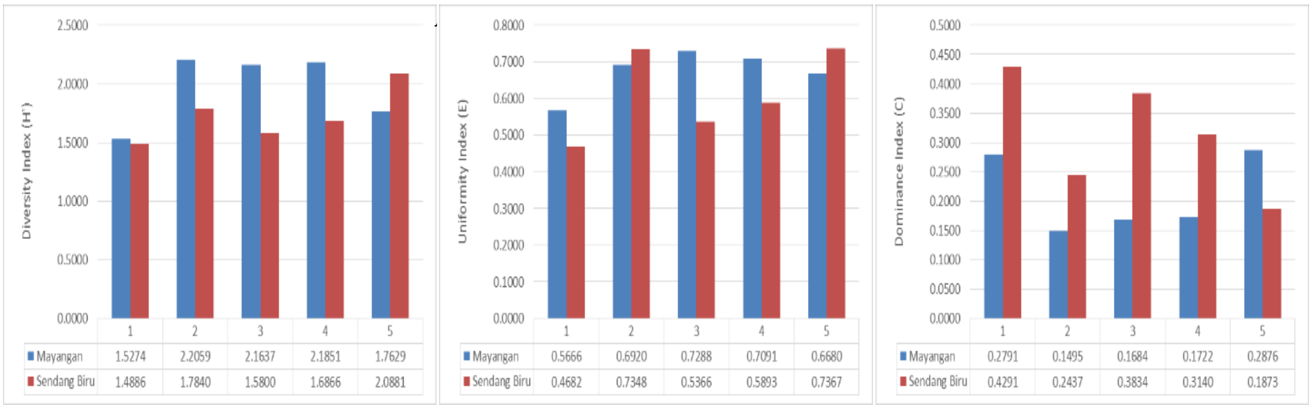


Figure 5. Microalgae abundance (ind/L) in Mayangan and Sendang Biru Beaches, East Java, Indonesia



A B C

Figure 6. A. Microalgae Diversity Index; B. Microalgae Uniformity Index; C. Microalgae Dominance Indeks in Mayangan and Sendang Biru Beaches, East Java, Indonesia

The Dominance Index (C) for microalgae at Mayangan Beach ranged from 0.1495 to 0.2876, while at Sendang Biru Beach it ranged from 0.1873 to 0.4291 (Figure 6.C). These values indicate that neither beach exhibits dominance by any particular type of microalgae. A dominance index value between 0 and 0.50 reflects low dominance, 0.50 to 0.75 indicates moderate dominance, and 0.75 to 1 represents high dominance. The low dominance values observed suggest a relatively even distribution of microalgal species, contributing to a balanced ecological community. Variations in the dominance index within aquatic systems are largely influenced by nutrient concentrations, particularly nitrate and phosphate, which play a crucial role in shaping the composition and abundance of microalgal populations (Tambaru et al. 2021). These findings highlight the importance of nutrient dynamics in maintaining the biodiversity and stability of coastal ecosystems.

Statistical analysis of the relationship between chlorophyll-a and microalgae abundance

Statistical tests were conducted to evaluate the relationship between chlorophyll-a concentrations and microalgae abundance. The analysis included three key stages: the Kolmogorov-Smirnov normality test, a t-test, and a simple regression analysis. The results of the Kolmogorov-Smirnov normality test indicated that the "D max" values were less than the critical "D table" values (Table 6). This finding confirms that the chlorophyll-a and microalgae abundance data from both Mayangan Beach and Sendang Biru Beach are normally distributed, meeting the assumption required for subsequent parametric analyses. The t-test analysis revealed that the T-count values were less than the critical T-table values (Table 7). This indicates that there is no statistically significant difference in microalgae abundance, microalgae diversity index, and chlorophyll-a concentrations between Mayangan Beach and Sendang Biru Beach.

The regression analysis for Mayangan Beach yielded a coefficient of determination (R2R^2R2) of 0.5423, indicating that 54.23% of the variability in chlorophyll-a concentrations can be explained by microalgae abundance. The remaining 44.77% is attributed to other influencing factors. Additionally, the correlation coefficient (RRR) was calculated as 0.7364, signifying a strong positive relationship between chlorophyll-a concentrations and microalgae abundance. The regression analysis for Sendang Biru Beach produced a coefficient of determination (R2R^2R2) of 0.2861, indicating that 28.61% of the variation in chlorophyll-a concentrations can be explained by microalgae abundance. The remaining 71.39% is influenced by other factors. The correlation coefficient (RRR) was calculated as 0.5349, reflecting a moderate relationship between chlorophyll-a concentrations and microalgae abundance (Figure 7).

Table 6. Kolmogorov-Smirnov normality test result

	Abudance		**Diversity**		**Uniformity**		**Dominance**		**Chlorophyll-a**	
	May	**SB**	**May**	**SB**	**May**	**SB**	**May**	**SB**	**May**	**SB**
Dmax	0.189	0.168	0.182	0.13	0.222	0.2	0.181	0.188	0.277	0.292
Dtable (a = 0.05)	0.409	0.409	0.409	0.41	0.409	0.41	0.409	0.409	0.409	0.409

Table 7. T-test result Chlorophyll-a and microalgae abundance

	Abudance	**Diversity**	**Uniformity**	**Dominance**	**Chlorophyll-a**
t-calculated	0.855351838	1.415578105	0.985289435	-1.88161624	-0.245658297
t-table	2.306004135	2.306004135	2.306004135	2.306004135	2.10092204

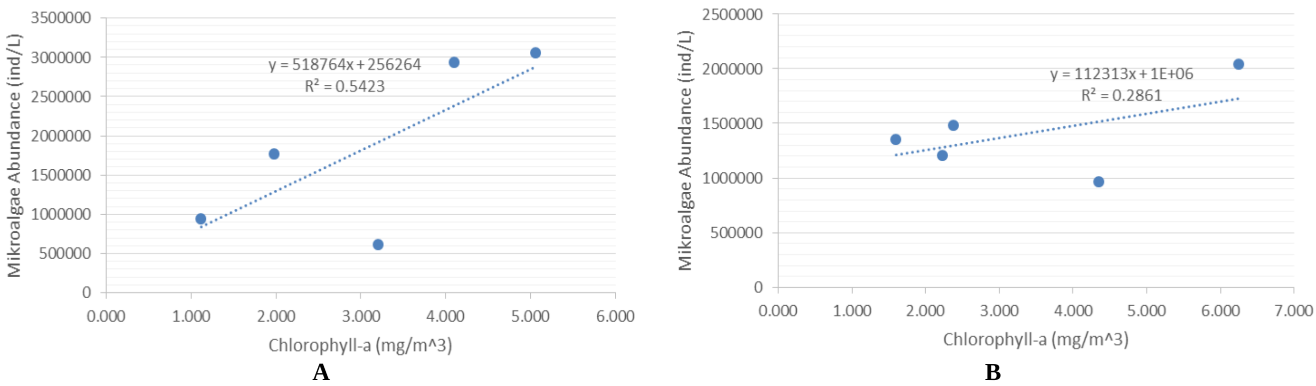


Figure 7. Correlation between chlorophyll-a with microalgae abundance in Mayangan (A) and Sendang Biru (B) Beaches, East Java, Indonesia

Ecosystem productivity and potential environmental improvement

The diversity of microalgae is an important indicator in assessing the productivity and stability of aquatic ecosystems. Microalgae act as primary producers that support the food chain in marine ecosystems, both directly through photosynthesis and indirectly as a source of nutrients for other organisms. In this context, the presence of 64 genera of microalgae at Mayangan Beach and 59 genera at Sendang Biru Beach reflects the high productivity potential of the ecosystems at both locations.

Diatoms such as *Chaetoceros*, *Skeletonema*, *Navicula*, *Thalassionema*, *Rhizosolenia*, *Coscinodiscus*, and *Nitzschia* dominate the microalgal communities at both beaches. Diatoms are known as highly efficient primary producers in absorbing carbon dioxide (CO_2) and generating oxygen. They also play a crucial role in the food chain, serving as the primary food source for zooplankton (Bostanci and Akkaya 2025).

The presence of microalgae genera such as *Chlorella*, *Oscillatoria*, and *Phormidium*, which belong to the groups of green algae and cyanobacteria, underscores the high photosynthetic potential at both locations. These microalgae not only produce oxygen through photosynthesis but also provide biomass rich in protein and lipids for primary consumers like zooplankton. The slightly higher diversity of microalgae at Mayangan Beach compared to Sendang Biru Beach may indicate differences in primary productivity levels, although the difference is relatively small (Annisa et al. 2021).

Factors such as nutrient availability, temperature, salinity, and water quality greatly influence the composition and productivity of microalgal communities. Mayangan Beach may have a higher nutrient supply, potentially originating from tidal activity or nutrient input from terrestrial sources, thereby supporting the presence of more microalgal genera. On the other hand, Sendang Biru Beach may have more stable environmental conditions that support similar genera, albeit in slightly smaller numbers. Overall, the presence of 39 common genera indicates that both locations have similar environmental conditions to support primary productivity, further emphasizing the potential of these locations as habitats for healthy and productive ecosystems (McGinn et al. 2011; Kong et al. 2024).

In addition to supporting primary productivity, microalgae also play a significant role in environmental restoration. Several genera found at Mayangan Beach and Sendang Biru Beach demonstrate substantial potential in water quality management and pollution mitigation. For example, *Nitzschia* and *Navicula*, which are benthic diatoms, can absorb excess nutrients such as nitrates and phosphates, thereby helping to prevent eutrophication (Vadiveloo et al. 2021).

Cyanobacterial groups such as *Oscillatoria* and *Phormidium* play an important role in nitrogen fixation, aiding in increasing nitrogen content in nutrient-poor waters. On the other hand, green algae like *Chlorella* possess extraordinary bioremediation capabilities, such as absorbing heavy metals (e.g., lead and mercury) from polluted waters. *Porphyridium*, with its extracellular polysaccharides, helps stabilize sediments and prevent the remobilization of pollutants from the seabed. Dinoflagellates like *Protoperidinium* contribute to the dissolved organic matter cycle by processing it into simpler compounds. Additionally, genera such as *Pleurosigma* help neutralize complex organic matter, while *Gyrosigma* absorbs excess silica that could cause ecosystem imbalances (Chiu et al. 2015).

By utilizing these genera in environmental rehabilitation programs, both beaches hold significant potential to become models for clean, stable, and healthy aquatic ecosystems. Optimizing the functions of these microalgae can be achieved through controlling pollutant input from terrestrial sources, ecosystem rehabilitation, and continuous monitoring of changes in microalgal diversity.

In conclusion, this study highlights the critical role of chlorophyll-a as a reliable indicator of microalgae abundance and aquatic productivity. Mayangan Beach, characterized by nutrient-rich runoff, exhibits higher productivity compared to Sendang Biru Beach, which features clearer but more stable waters. Both beaches demonstrate moderate biodiversity, with Bacillariophyta identified as the dominant group, reflecting their adaptability and importance in maintaining ecosystem balance. Despite elevated nitrate and orthophosphate levels exceeding ideal thresholds, the ecosystems at both locations remain mesotrophic and ecologically stable, showcasing the resilience of microalgal communities. These findings underline the importance of sustainable management and continuous monitoring to preserve the ecological value and productivity of coastal waters.

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