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Environmental effects of coal power plant expansion on plankton and benthos in Tanjung Jati's marine ecosystem

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ABSTRACT

This study examines the impact of the Tanjung Jati B coal-fired power plant on marine water quality in Jepara, Central Java. It focuses on changes in plankton and benthos communities by assessing species abundance, diversity, uniformity, and dominance as indicators of environmental health. The study takes into four phases: January –June 2021, July – December 2021, January – June 2022, and July – December 2022. Plankton samples were collected using nets with mesh sizes of 30–50 µm and 0.2 mm, while benthos were gathered with an Ekman grab. In the analysis used standard methods and calculated key indices including the Shannon-Weaver diversity index, uniformity index, and dominance index – to assess the health of the ecosystem. The linear regression analysis used to evaluate how these biological parameters changed over time. Findings reveal a noticeable decline in the number of taxa, species abundance, and diversity for both plankton and benthos over the study period. On the other hand, the dominance and uniformity indices showed an upward trend, indicating that a few species are increasingly dominating the community – a clear sign of ecological stress. Overall, these trends suggest that the marine ecosystem is currently experiencing moderate pollution.

Keywords: marine pollution, plankton, benthos, abundance, taxa, diversity index, uniformity index, dominance index, coal power plant.

INTRODUCTION

Coal-fired power plants remain Indonesia's primary source of electricity, playing a crucial role in meeting the country's growing energy demands. However, concerns over efficiency and environmental impact have driven advancements in technology to minimize emissions and optimize coal usage. One such innovation is ultra-supercritical (USC) technology, which allows power plants to operate at extremely high temperatures and pressures. This not only increases thermal efficiency – surpassing 40% – but also helps reduce CO_2, SOx, and NOx emissions (Somova *et al.*, 2023).

The Tanjung Jati B coal power plant in Central Java, which consists of Units 5 and 6, with a total net capacity of 2,000 megawatts. By adopting USC technology, the plant improves efficiency while generating an additional 200 megawatts per unit for internal operations. Compared to older systems, USC technology reduces fuel consumption by approximately 3% compared to supercritical technology and 6% compared to subcritical technology, leading to a 5.47% reduction in CO_2 and other gas emissions (Morikawa *et al.*, 2021). The adoption of USC marks a significant step forward in modernizing Indonesia's power infrastructure, aiming for a balance between energy demand and environmental responsibility.

However, despite these technological improvements, coal-fired power plants still have environmental consequences, particularly on marine ecosystems in surrounding areas. Waste discharge and thermal pollution can degrade seawater quality, affecting marine organisms that rely on stable environmental conditions. Changes in species morphology, physiology, behavior, and population dynamics serve as early warning signals of ecosystem stress. Among these, plankton and benthos are particularly valuable as bioindicators of seawater quality, as their diversity and abundance directly reflect the health of aquatic ecosystems (Widiawaty *et al.*, 2020). The distribution and population density of plankton and benthos, measured by species count per unit volume, are key indicators of ecosystem productivity and play an essential role in energy transfer and nutrient cycling within marine food webs (Rowe, 2017). To better understand these ecological changes, this study applies several key indices. The diversity index provides a mathematical representation of ecosystem structure by summarizing the variety and abundance of plankton and benthos (Ndah *et al.*, 2022) The evenness index measures how evenly species are distributed, while the dominance index (C) indicates whether a particular species is disproportionately prevalent. A dominance value close to 1 suggests that a single species dominates the community, whereas a value near 0 indicates a more balanced and diverse ecosystem (Jalil *et al.*, 2020; Lu *et al.*, 2022).

Additionally, this study uses time series analysis to track environmental data over time, identify patterns, and forecast future conditions based on historical trends. Regular monitoring through mathematical trend analysis offers valuable insights into how marine water quality evolves over time, particularly in response to changes caused by coal power plant operations. This approach helps detect early signs of environmental degradation, enabling data-driven decision-making for sustainable marine ecosystem management (Agboola *et al.*, 2020)

The aim of this study is to evaluate the impact of coal-fired power plant (CFPP) operations on marine water quality, using plankton and benthos as bioindicators. By providing a quantitative assessment of environmental degradation, this research fills gaps left by previous studies and offers valuable insights for policymakers and environmental management efforts. At the same time, it acknowledges certain limitations, such as external environmental influences and the need for long-term monitoring, ensuring that its findings serve as a strong foundation for future research and informed decision-making in marine conservation.

MATERIALS AND METHODS

Materials

This study was conducted in the waters surrounding the Tanjung Jati B Coal-Fired Power Plant Units 5 & 6 in Tubanan Village, Jepara Regency, Central Java, selected for its environmental characteristics, including water depth and current stability. The dominant ocean currents in the area flow toward the Northeast and Southwest at speeds of 20–40 cm/s, influencing marine life and nutrient distribution. To evaluate both short-term and long-term ecological impacts, sampling was conducted over four periods: January – June 2021, July – December 2021, January – June 2022, and July – December 2022.

The plankton and benthos sampling sites were selected near the power plant to examine its direct impact on marine ecosystems. Table 1 provides the geographic coordinates of the sampling locations. Figure 1 illustrates the sampling locations, strategically positioned to analyze the impact of power plant operations on marine water quality. Plankton and benthos serve as key bioindicators for assessing marine water quality, ecosystem balance, and the impacts of pollution and environmental changes. Plankton, including phytoplankton and zooplankton, respond quickly to environmental shifts, while benthos reflect long-term seabed conditions. The diversity, abundance, and dominance of their species provide insight into ecosystem health, with changes in their communities signaling organic pollution, heavy metal contamination, hypoxia, or oil spills. The dominance of certain species due to organic pollution often indicates ecosystem disturbances, making regular monitoring of plankton and benthos essential for detecting pollution and maintaining the stability and sustainability of marine ecosystems. The following tools and materials were used in this study:

Table 1. Plankton and benthos sampling coordinates

Notation	East longitude	South latitude
PB04	110°43’11,48”	6° 25’ 59, 69”
PB05	110°43’48,40”	6° 26’ 25, 50”
PB07	110°44’45,13”	6° 25’ 58, 36”
PB08	110°45’05,96”	6° 26’ 29, 07”
NEC05	110°42’36,50”	6° 25’ 22, 40”

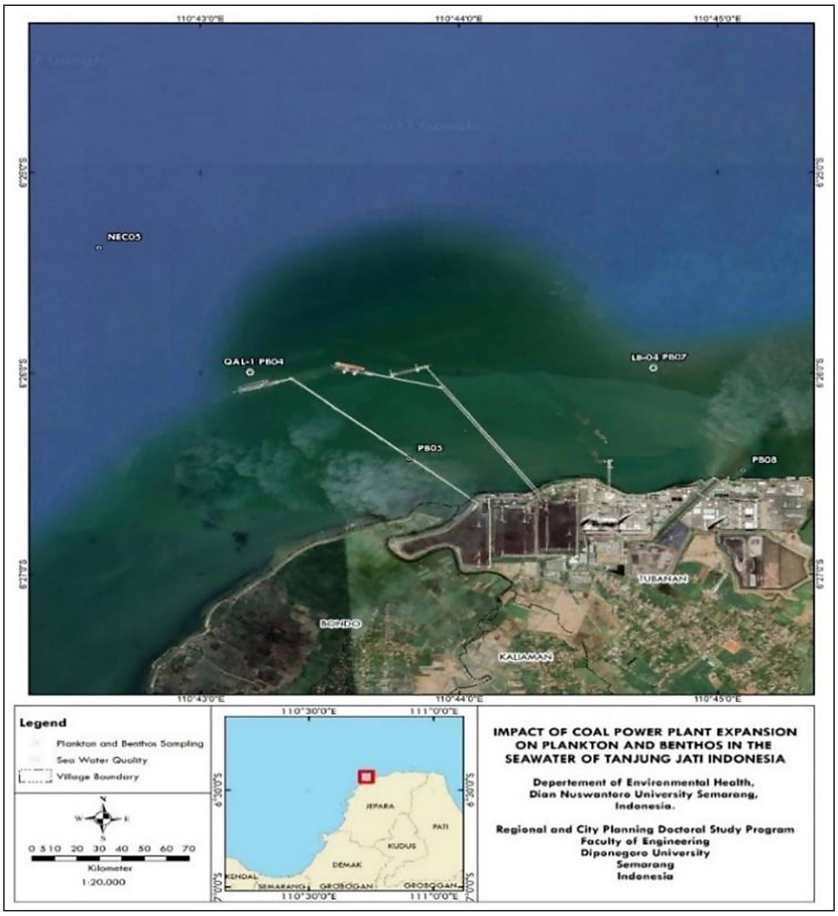

Figure 1. Sampling location

1) Tools:
- plankton net (mesh sizes: 30–-50 µm, 0.2 mm),
- haemacytometer (for plankton counting),
- ekman grab (for benthos sampling).

2) Materials:
- plankton and benthos samples,
- seawater samples,
- formalin (for sample preservation).

Methods

Plankton and benthos sampling were conducted using the purposive random sampling method. Seawater samples were collected following the SNI 6964-8-2015 standard. All samples were analyzed in the laboratory and compared with the Seawater Quality Standards for ports, as specified in Minister of Environment Decree No. 51 of 2004.

Sampling was conducted every six months, ensuring periodic evaluation. The following parameters were measured:
- plankton abundance,
- species diversity index,
- species uniformity index,
- species dominance index.

Biological factors analysis

The abundance of plankton and benthos was calculated using the Equation (1) from the APHA 2005 Standard Methods (Anggraini et al., 2022; Mahenda *et al.*, 2021):

$$N = (O_i/O_p \times n/p) \times (V_r/V_o \times 1/V_s) \quad (1)$$

where: n – number of individuals per liter, O_i – number of boxes in the SRC (1000), O_p – number of visual field boxes, V_r – volume of water in the sample bottle, V_s – volume of filtered water, p – number of fields of view.

Water fertility is a critical parameter in assessing ecosystem productivity and is primarily determined by plankton abundance. Plankton, particularly phytoplankton, play a fundamental role in nutrient cycling, oxygen production, and energy transfer within aquatic food webs. The classification of water fertility is based on plankton density, which reflects the nutrient levels and biological activity in a given water body (Ain et al., 2022):

- oligotrophic waters (low fertility) – plankton abundance 0–2,000 ind/l, characterized by low nutrient levels, limited primary productivity, and clear water conditions; these waters are typically found in deep lakes and open ocean areas with minimal human impact;
- mesotrophic waters (moderate fertility) – plankton abundance 2,000–15,000 ind/l, representing a balanced nutrient level, supporting moderate aquatic biodiversity and productivity; these waters can sustain a healthy ecosystem while being more susceptible to external disturbances;
- eutrophic waters (high fertility) – plankton abundance >15,000 ind/L, indicating high nutrient concentrations, often caused by runoff from agriculture, industry, or urban areas; this condition can lead to excessive algal growth (algal blooms), reduced oxygen levels, and potential harm to aquatic life.

Additionally, phytoplankton abundance is a crucial determinant of water fertility and is measured per cubic meter (Wulandari *et al.*, 2022):

- highly fertile waters ($>40 \times 10^6/m^3$) characterized by high phytoplankton growth, typically found in nutrient-rich waters but may lead to eutrophication if unchecked;
- moderately fertile waters ($0.1–40 \times 10^6/m^3$) representing a balanced ecosystem with stable phytoplankton populations;
- less fertile waters ($<0.1 \times 10^6/m^3$) indicating low primary productivity, often found in deep-sea environments or nutrient-poor lakes.

Diversity indices measure the level of species variation in a community. A frequently used index is the Shannon-Wiener diversity index (H'), which is calculated using the formula 2:

$$H' = -\sum(p_i \cdot \ln p_i) \quad (2)$$

where: p_i – is the proportion of individuals of the *i*-th species compared to the total individuals in the community.

The uniformity of plankton and benthos in aquatic ecosystems is a critical indicator of biodiversity distribution and ecological stability. The plankton and benthos uniformity index quantifies the evenness of species distribution, reflecting the extent to which individuals are evenly spread among species within these two groups. A high degree of uniformity suggests a balanced ecosystem, while a low uniformity indicates dominance by a few species, which may signal ecological stress or instability. The uniformity index (E) is calculated using the following formula (3) (Ridwan *et al*, 2022).

$$E = H' / H'_{max} \quad (3)$$

where: E – uniformity index (evenness); H' – Shannon-Wiener diversity index, H'_{max} – maximum possible diversity.

This formula provides a standardized measure of how evenly individuals are distributed among species in a given community. The uniformity index is an ecological balance indicator that measures the uniformity of individual distribution within a community (Zou *et al.*, 2021). Ranging from 0 to 1, a higher E value indicates a more even species distribution, reflecting a stable and healthy ecosystem. Conversely, a lower E value suggests ecological stress or species dominance, which may disrupt ecosystem balance. The interpretation is as follows:

- $E < 0.4$ – low uniformity, indicating a depressed community where a few species dominate, and overall biodiversity is unevenly distributed; this condition may reflect environmental stress or habitat degradation;
- $0.4 \leq E \leq 0.6$ – moderate uniformity, signifying an unstable community with some degree of evenness, but still vulnerable to environmental disturbances or anthropogenic pressures;
- $E > 0.6$ – high uniformity, representing a stable and resilient community where species are evenly distributed, promoting ecological balance and resistance to disturbances.

The species dominance index measures the extent to which one or a few species dominate a community, with one commonly used method being the Simpson's dominance index (D), calculated using the formula (4):

$$D = \sum(p_i 2i) \quad (4)$$

where: p_i – the proportion of individuals from species *i* in the community, obtained from $p = n_i/N$ with n_i as the number of individuals of species, and N as the total individuals in the community.

The D value ranges between 0 and 1, where a value close to 1 indicates high dominance by one or a few species, while a value close to 0 signifies a more diverse community without any species dominating significantly, which generally reflects a more stable and balanced ecosystem. The environmental quality prediction shows the linear Equation 5:

$$y = ax+b \quad (5)$$

where: y – predicted environmental quality (e.g., air quality index, pollution level, temperature, etc.); x – biological indicators (e.g., species count, water pH, forest area, etc.); a – slope of the line, indicating how much y changes for each unit change in x; b – intercept, the initial value of y when $x = 0$ (Xia *et al.*, 2021).

This model enables the identification of long-term trends in environmental quality and predicts whether an ecosystem is improving or deteriorating based on biological factors:
- Trend and pattern analysis – linear graphs are used to observe trends in changes to the biodiversity index, uniformity index, and dominance index. if the linear trend shows a decline in biodiversity or uniformity indices, this may indicate ecosystem disturbances, such as pollution or the exploitation of natural resources.
- Evaluation of anthropogenic activity impacts – the linear regression model allows us to correlate environmental quality changes with external factors, such as the operational impact of coal-fired power plants. if the data shows a negative relationship between the number of power plants and the seawater quality index, this can be used as a basis for decision-making to mitigate environmental impacts.
- Seawater quality prediction – by using historical data on the seawater quality index and its influencing factors, we can project whether seawater conditions will deteriorate or improve in the future. This prediction is crucial for sustainable marine ecosystem management and environmental pollution prevention, based on biological parameters.
- Predictive analysis using a linear regression model to understand environmental quality changes – is an effective method for understanding environmental quality changes based on biological indicators. By tracking biodiversity, uniformity, dominance, and seawater quality, predictive models can support conservation planning and assist in managing industrial impacts, including coal-fired power plants.

This study uses correlation analysis to examine the relationship between biological parameters and environmental factors affecting plankton and benthos populations, as follows:
- +1 – positive correlation (e.g., higher temperature increases the dominance of certain species),
- -1 – negative correlation (e.g., the presence of heavy metals reduces the plankton population),
- ≈ 0 – no significant correlation.

Physical and chemical parameters of seawater

The measurement methods used in this seawater quality analysis adhere to national standards, ensuring that the test results are comparable with applicable regulations. This is crucial for monitoring marine environments to maintain ecosystem balance and prevent pollution that could negatively impact biodiversity and human activities around coastal areas. Measurements are conducted in situ using experimental methods, and the results are then compared with quality standards based on the Decree of the Minister of Environment of the Republic of Indonesia No. 51 of 2004 on Seawater Quality Standards for Ports (Muninggar *et al.*, 2017; Tubalawony *et al.* 2023). Physical and chemical parameters play a crucial role in determining seawater quality, as they can directly impact marine organisms and biochemical processes within aquatic ecosystems. These parameters are outlined in Table 2.

RESULTS AND DISCUSSION

Efficiency, sustainability, and environmental considerations

The ultra super-critical (USC) technology implemented at coal-fired power plant Tanjung Jati B offers higher efficiency, reduced coal consumption, and lower emissions compared to conventional technologies. USC operates under the Rankine cycle, utilizing steam at ultra-high pressures and temperatures (>600 °C), achieving up to 42–45% efficiency. This improvement enhances turbine performance, reduces fuel consumption, and minimizes environmental impact. The plant is equipped with flue gas desulfurization (FGD) and selective catalytic reduction (SCR) systems to lower emissions of CO_2, SO_2, NO_x, and particulates (Rasheed *et al.*, 2021) One key advantage of USC technology is fuel efficiency, consuming approximately 3% less coal than Super-Critical and 6% less than sub-critical

Table 2. Methods for seawater quality analysis

Physical and chemical parameters				
No	Parameter	Unit	Standards	Analysis method
1	pH	-	7.0–8.5	SNI 06-6989.11-2004 (pH meter)
2	Temperature	°C	±2 °C natural	Termometer
3	Salinity	‰	33–34	Refraktometer
4	Turbidity	NTU	5	SNI 06-6989.24-2005 (SSA)
5	Ammonia (NH_3-N)	mg/l	0.3	SNI 06-6989.30-2005 (SSA)
6	Nitrate (NO_3-N)	mg/l	0.008	SNI 06-6989.9-2004 (SSA)
7	Phosphate (PO_4^{3-})	mg/l	0.015	SNI 06-6989.31-2005 (SSA)
8	Sulfide (H_2S)	mg/l	0.002	SNI 06-6989.18-2004 (SSA)
Heavy metal parameters				
9	Mercury (Hg)	mg/l	0.001	SNI 06-6989.7-2004 (SSA)
10	Cadmium (Cd)	mg/l	0.01	SNI 06-6989.7-2004 (SSA)
11	Lead (Pb)	mg/l	0.05	SNI 06-6989.7-2004 (SSA)
12	Zinc (Zn)	mg/l	0.05	SNI 06-6989.7-2004 (SSA)
13	Copper (Cu)	mg/l	0.05	SNI 06-6989.7-2004 (SSA)
14	Arsenic (As)	mg/l	0.012	SNI 06-6989.7-2004 (SSA)
15	Chromium (Cr)	mg/l	0.005	SNI 06-6989.7-2004 (SSA)

systems. A 2,000 MW USC plant can save around 168,000 tons of coal annually compared to SC and 378,000 tons per year compared to sub-critical, significantly reducing carbon emissions and enhancing sustainability (Somova et al., 2023). Additionally, the increased steam pressure optimizes turbine performance, generating more electricity with lower fuel consumption (Mardi *et al.*, 2025; Kendra, 2014). However, despite its efficiency and reduced emissions, USC technology poses environmental concerns, particularly on marine ecosystems near Jepara. Coal-fired power plants Tanjung Jati B can impact marine environments through thermal discharge, pollutant emissions, and water quality changes. The cooling system extracts seawater, returning it at higher temperatures, potentially disrupting ecosystems, reducing dissolved oxygen levels, and affecting marine life such as fish and coral reefs. Pollution risks arise from chemical discharge from water treatment systems and fly ash leaks, which, if mismanaged, could contaminate marine waters. These factors may also impact fisheries and biodiversity, requiring strict environmental monitoring (Roy *et al.*, 2022). To mitigate these effects, regular water quality monitoring is essential, covering physical, chemical, and biological parameters. Physical parameters include water temperature, which affects marine equilibrium, turbidity from particulate waste, salinity changes due to cooling water discharge, and dissolved oxygen (DO) levels critical for marine organisms. Chemical parameters involve pH levels, heavy metals (Hg, Pb, Cd, As) accumulation in marine food chains, nutrients (nitrate, phosphate, ammonia) contributing to eutrophication, oil and grease levels from fuel leaks, and BOD & COD measuring organic pollutants. Biological parameters assess plankton diversity (phytoplankton & zooplankton) as water quality indicators, marine species presence (fish, coral, mollusks, macrozoobenthos) to gauge ecological balance, and bioaccumulation of heavy metals in marine organismsn (Chen *et al.*, 2025).

Mitigation efforts include eco-friendly cooling systems, strict waste management, and collaborations with local fisheries to ensure marine sustainability. Through continuous monitoring and effective mitigation strategies, coal-fired power plant USC aims to minimize negative environmental impacts while maintaining energy efficiency and sustainability.

Description of research location

The waters of the Java Sea, particularly near the Jepara Sea around the coal power plant, are generally calm with low wave height, small wave frequency, and short wavelength. The area features a sandy substrate and a gently sloping beach, indicating a stable water environment. (Zhu *et al.*, 2024). These calm sea conditions near the Jepara coal power plant, characterized by low wave height, small wave frequency, and a sandy, gently sloping beach, play a crucial role in marine biodiversity and ecosystem stability. They influence water mixing, nutrient distribution, and habitat suitability for species adapted to stable environments. Understanding these factors is essential for assessing the environmental impact of industrial activities, particularly coal power plants, on seawater quality and marine ecosystem sustainability (Wicaksono *et al.*, 2018). Wind conditions in the Tanjung Jati Jepara coastal area follow seasonal patterns, with the west season (December – February), east season (June – August), and transition seasons (March – May, September – November), based on data from the Semarang Marine Meteorological Station (Ranadipura *et al.*, 2019). Monsoon winds influence plankton and benthos movement, seafloor sedimentation, and salinity, potentially increasing sedimentation or pollution, which may harm marine organisms (Naik *et al.*, 2020).

Physical and chemical parameters

Seawater quality in the ANDAL phase (pre-construction)

Table 3 presents the seawater quality analysis results for the Tanjung Jati B power plant during the environmental impact assessment (EIA) implementation phase. The data provide insights into key water quality parameters, helping evaluate the potential environmental impacts of the project. The data analysis shows stable conditions with no significant pollution. However, TSS (18–24 mg/L) and temperature (29.1–30.8 °C) require monitoring, especially during construction. pH (8.0–8.1) and salinity (33.6–34.2%) remain stable, while oil, grease (0.4–0.6 mg/L), and chlorine (0.13–0.23 mg/L) are within safe limits but need regulation. Heavy metals are undetected, and sulfate levels (2.566–2.676 mg/L) indicate ecosystem balance. Potential risks from TSS, temperature fluctuations, and oil contamination highlight the need for regular monitoring and mitigation. Table 4 presents the correlation analysis of seawater quality parameters.

The correlation analysis shows that seawater temperature increases correlate with higher TSS (0.83) due to sediment resuspension and

Table 3. Seawater quality in the planned area of Tanjung Jati B power plant units 5 & 6 during the pre-construction phase of the environmental impact assessment (EIA)

No	Parameter	Unit	PB 04	PB 05	PB 07	PB 08	NEC 05
1	Total suspended solids	mg/L	24	22	22	18	20
2	Waste	-	-	-	-	-	-
3	Sea water temperature	°C	30.8	30.3	29.4	29.1	29.7
4	Oil slicks	-	-	-	-	-	-
1	pH	-	8.1	8	8	8	8
2	Salinity	%	33.7	33.6	34.2	33.9	34.1
3	Phosphate (PO_4)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
4	Oil and Fat	mg/L	0.4	0.4	0.6	0.4	0.5
5	Mercury (Hg)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
6	Cr (hexavalent)	mg/L	-	-	-	-	-
7	Arsenic (As)	mg/L	<0.003	<0.003	<0.003	<0.003	<0.003
8	Cadmium (Cd)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
9	Copper (Cu)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
10	Lead (Pb)	mg/L	<0.003	<0.003	<0.003	<0.003	<0.003
11	Zinc (Zn)	mg/L	<0.001	0.002	<0.001	<0.001	<0.001
1	Free chlorine	mg/L	0.16	0.13	0.23	0.21	0.17
2	Iron (Fe)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
3	Manganese (Mn)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
4	Total chrome	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
5	Sulfate	mg/L	2.665	2.566	2.618	2.572	2.676

Table 4. Correlation analysis of seawater quality parameters in the planned Tanjung Jati B unit 5 & 6 power plant area during the pre-construction phase

Parameter	TSS	Temp (°C)	pH	Salinity	Oil-Fat	Chlorine free	Sulfat
TSS	1	0.84	0.69	(0.34)	0.05	(0.38)	0.36
Temp	0.84	1	0.76	(0.70)	(0.44)	(0.77)	0.34
pH	0.69	0.76	1	(0.44)	(0.38)	(0.28)	0.50
Salinity	(0.34)	(0.70)	(0.44)	1	0.88	0.78	0.34
Oil-fat	0.05	(0.44)	(0.38)	0.88	1	0.63	0.30
Chlorine free	(0.38)	(0.77)	(0.28)	0.78	0.63	1	(0.04)
Sulfat	0.36	0.34	0.50	0.34	0.30	(0.04)	1

slightly elevated pH (0.76) from carbonate balance changes. Rising temperatures also reduce salinity (-0.69) and free chlorine (-0.77) due to mixing and chemical reactions. Additionally, salinity positively correlates with oil and grease (0.88), affecting pollutant dispersion. These interactions highlight the need for regular monitoring and mitigation strategies, including strict waste management, industrial temperature control, and eco-friendly technologies to protect the marine ecosystem.

Seawater quality analysis during the monitoring period (July – December 2020)

Table 5 presents the seawater quality analysis (July–December 2020), covering physical and

Table 5. Seawater quality data in the planned area of coal-fired power plant Tanjung Jati B Unit 5 & 6 during the monitoring period (July – December 2020)

Sea water quality						
Parameter	Unit	PB 04	PB 05	PB 07	PB 08	NEC 05
Total suspended solids (TSS)	mg/L	3	9	5	2	4.75
Brightness	meter	4	2.5	3.5	4.2	3.55
Oil slick	-	No	No	No	No	No
pH	-	7.8	7.5	8	8.3	7.9
Sea water temperature	Â°C	30.2	31.8	30.5	30	30.625
Zinc (Zn)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Copper (Cu)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Mercury (Hg)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cadmium (Cd)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lead (Pb)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Arsenic (As)	mg/L	0.0014	0.0024	0.0018	0.0021	0.00193
Arsenic (sediment)	mg/kg	6.2	8.1	7.4	6.8	7.125
Cadmium (sediment)	mg/kg	0.2	0.4	0.3	0.1	0.25
Lead (sediment)	mg/kg	15	22	18	14	17.25
Copper (sediment)	mg/kg	10	15	12	7	11
Zinc (sediment)	mg/kg	50	63	55	48	54
Oil content (sediment)	%	<0.01	<0.01	<0.01	<0.01	<0.01
Sediment parameter						
Arsenic (As) (sediment)	mg/kg	6.2	8.1	7.4	6.8	7.125
Cadmium (Cd) (sediment)	mg/kg	0.2	0.4	0.3	0.1	0.25
Lead (Pb) (sediment)	mg/kg	15	22	18	14	17.25
Copper (Cu) (sediment)	mg/kg	10	15	12	7	11
Zinc (Zn) (sediment)	mg/kg	50	63	55	48	54
Oil content (sediment)	%	<0.01	<0.01	<0.01	<0.01	<0.01

chemical parameters to assess marine ecosystem conditions. The data highlights water quality changes and potential environmental impacts, supporting mitigation and management strategies for ecosystem sustainability. Seawater quality remains good, with pH (7.5–8.3), temperature (30.0–31.8 °C), and clarity (2.5–4.2 m) within acceptable limits. No oil or heavy metal contamination was detected, except for slightly elevated arsenic (0.0014–0.0024 mg/L) at PB 05. Sediments at PB 05 showed higher heavy metal concentrations, suggesting industrial pollution. PB 08 had the best water quality with the highest clarity and lower temperatures. Close monitoring is needed, especially at PB 05, due to its highest temperature (31.8°C) and lowest clarity (2.5 m), which may impact the ecosystem. While heavy metal levels are within safe limits, arsenic should be monitored to prevent accumulation. Table 6 presents the correlation analysis of water and sediment quality (July–December 2020), revealing parameter relationships to assess pollutant distribution and ecological impacts.

Total suspended solids significantly impact water conditions, reducing clarity (-1.00) and increasing temperature (0.99). TSS also correlates with arsenic in water (0.61), indicating arsenic binds to suspended particles. Higher TSS and temperature lower pH (-0.83, -0.84), making water more acidic. Arsenic in water correlates with arsenic in sediments (0.82), while temperature influences heavy metal concentrations in sediments (0.86–0.98). Regular monitoring of TSS, temperature, pH, and arsenic is crucial to prevent ecosystem degradation, highlighting the need for integrated water and sediment management.

Seawater quality analysis during the monitoring period (January – June 2021)

Table 7 presents the results of the seawater quality analysis for the January – June 2021 period, covering physical and chemical parameters. This data serves as a reference for marine ecosystem monitoring and management. The seawater and sediment quality monitoring at Tanjung Jati B indicates safe conditions with no significant pollution. TSS (2–9 mg/L) decreased, while clarity (2.5–4.2 m) and pH (7.5–8.3) remained stable. Temperature (30–31.8°C) was normal, though PB 05 recorded 31.8°C, requiring monitoring. Heavy metals were below detection limits, and arsenic levels (0.0014–0.0024 mg/L) remained safe but need observation. Sediment heavy metal levels were acceptable, and no oil contamination was detected. Regular monitoring and mitigation, including strict waste management and coastal protection, are essential to maintain ecological balance. Table 8 presents the test results of the correlation matrix of seawater quality during the monitoring period (January – June 2021). This analysis helps identify relationships between different water quality parameters, providing insights into environmental conditions and potential impacts on the marine ecosystem. The correlation analysis around coal-fired power plant shows that higher seawater temperature strongly correlates with increased TSS (0.99), leading to reduced water clarity (-0.99). Temperature also correlates with arsenic levels (0.66), suggesting the potential release of arsenic from sediments. Additionally, TSS and arsenic (0.61) are moderately correlated, indicating that suspended particles may carry arsenic into the water column. These findings highlight the need for temperature control and suspended

Table 6. Correlation analysis of water and sediment quality during the monitoring period (July–December 2020)

Parameters	TSS	Brightness	pH	Suhu	As seawater	As (Sed)	Cd (Sed)	Pb (Sed)	Cu (Sed)	Zn (Sed)
TSS	1	(1.00)	-0.83	0.99	0.61	0.89	0.96	1.00	0.96	1.00
Brightness		1	0.824	(0.99)	(0.63)	(0.90)	(0.95)	(1.00)	(0.95)	(1.00)
pH	(0.83)	0.82	1	(0.84)	(0.19)	(0.49)	(0.84)	(0.80)	(0.88)	(0.81)
Temperature	0.99	(0.99)	-84%	1	0.66	0.86	0.91	0.97	0.92	0.98
As (seawater)	0.61	(0.63)	-19%	0.66	1	0.82	0.39	0.60	0.37	0.61
As (sediment)	0.89	(0.90)	-49%	0.86	0.82	1	0.81	0.91	0.78	0.90
Cd (sediment)	0.96	(0.95)	-84%	0.91	0.39	0.81	1	0.97	1.00	0.97
Pb (sediment)	1.00	(1.00)	-80%	0.97	0.60	0.91	0.97	1	0.96	1.00
Cu (sediment)	0.96	(0.95)	-88%	0.92	0.37	0.78	1.00	0.96	1	0.96
Zn (sediment)	1.00	(1.00)	-81%	0.98	0.61	0.90	0.97	1.00	0.96	1

Table 7. Seawater quality analysis during the monitoring period (January – June 2021)

Sea water quality Jan-Jun 2021						
Parameters	unit	PB 04	PB 05	PB 07	PB 08	NEC 05
Total suspended solids	mg/L	3	9	5	2	4.75
Brightness	meter	4	2.5	3.5	4.2	3.55
Oil layer	no	no	no	no	no	no
pH	-	7.8	7.5	8	8.3	7.9
Sea water temperature	°C	30.2	31.8	30.5	30	30.625
Zinc (Zn)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Copper (Cu)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Mercury (Hg)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cadmium (Cd)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lead (Pb)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Arsenic (As)	mg/L	0.0014	0.0024	0.0018	0.0021	0.00193
Sediment quality for Jan-Jun 2021						
Parameters	Satuan	Sed-1	Sed-2	Sed-3	Sed-4	
Arsenic (As)	mg/kg	6.2	8.1	7.4	6.8	7.125
Cadmium (Cd)	mg/kg	0.2	0.4	0.3	0.1	0.25
Lead (Pb)	mg/kg	15	22	18	14	17.25
Copper (Cu)	mg/kg	10	15	12	7	11
Zinc (Zn)	mg/kg	50	63	55	48	54
Oil content	%	<0.01	<0.01	<0.01	<0.01	<0.01

Table 8. Correlation matrix of seawater quality during the monitoring period (January – June 2021)

Parameters	TSS (mg/L)	Brightness (m)	pH	Sea water temperature (°C)	Arsen (mg/L)
TSS (mg/L)	1.00	(1.00)	(0.83)	0.99	0.61
Brightness (m)	(1.00)	1.00	0.82	(0.99)	(0.63)
pH	(0.83)	0.82	1.00	(0.84)	(0.19)
Sea water temperature (°C)	0.99	(0.99)	(0.84)	1.00	0.66
Arsenic (As) (mg/L)	0.61	(0.63)	(0.19)	0.66	1.00

particle management to maintain water clarity and prevent arsenic buildup, ensuring the protection of the marine ecosystem.

Seawater quality analysis during the monitoring period (January – June 2022)

Table 9 presents the results of the seawater quality analysis for the January – June 2022 period, covering physical and chemical parameters. This data serves as a reference for marine ecosystem monitoring and management.

The overall seawater quality remains good, with stable pH (7.66–8.42) and oil & grease levels below the threshold (<1 mg/L), indicating no significant oil pollution. However, NEC 05 showed high heavy metal contamination, with copper (3.8 mg/L), lead (5.6 mg/L), and zinc (20 mg/L), likely due to industrial activities or waste discharge. PB 05 recorded the highest TSS (9 mg/L), potentially reducing water clarity and increasing heavy metal sedimentation, while PB 08 showed rising heavy metal levels in sediments, which could affect the marine ecosystem. Arsenic was detected at PB 04 and PB 05, within safe limits but requiring monitoring. Regular monitoring of heavy metals, TSS, and arsenic, especially at NEC 05 and PB 05, along with mitigation strategies, is essential to maintain seawater quality and prevent long-term environmental impacts. Table 10 presents the correlation matrix of seawater quality parameters during the monitoring period (January – June 2022). This analysis helps identify relationships between various

Table 9. Seawater quality analysis during the monitoring period (January – June 2022)

Sea water quality results						
Parameter	Unit	PB 04	PB 05	PB 07	PB 08	NEC 05
pH	-	8.42	8.36	8.27	8.28	7.66
TSS	mg/L	2	9	5	4	1.2
Cd	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.01
Cu	mg/L	<0.001	<0.001	<0.001	<0.001	3.8
Hg	mg/L	<0.00005	<0.00005	<0.00005	<0.00005	<0.001
Pb	mg/L	<0.001	<0.001	<0.001	<0.001	5.6
Zn	mg/L	<0.005	<0.005	<0.005	<0.005	20
Oil & fat	mg/L	<1	<1	<1	<1	<1
As	mg/L	0.001	0.0009	0.001	0.0009	0.001
Sea sediment analysis results						
Parameter	Satuan	PB 04	PB 05	PB 07	PB 08	NEC 05
Sediment pH	-	7.58	7.62	7.68	7.55	7.61
Total organic	%	1.23	1.17	1.12	1.3	1.25
Cd	mg/kg	<0.01	<0.01	<0.01	<0.01	<0.01
Cu	mg/kg	3.5	4.1	3.9	4.5	4.2
Hg	mg/kg	<0.001	<0.001	<0.001	<0.001	<0.001
Pb	mg/kg	5.2	4.8	5.5	6	5.1
Zn	mg/kg	21	24	22	25	23

Table 10. Correlation matrix of seawater quality parameters (Monitoring period: January – June 2022)

Parameter	pH	TSS	Cd	Cu	Hg	Pb	Zn	As
pH	1.00	0.52	(0.98)	(0.98)	(0.98)	(0.98)	(0.98)	(0.36)
TSS	0.52	1.00	(0.55)	(0.55)	(0.55)	(0.55)	(0.55)	(0.67)
Cd	(0.98)	(0.55)	1.00	1.00	1.00	1.00	1.00	0.41
Cu	(0.98)	(0.55)	1.00	1.00	1.00	1.00	1.00	0.41
Hg	(0.98)	(0.55)	1.00	1.00	1.00	1.00	1.00	0.41
Pb	(0.98)	(0.55)	1.00	1.00	1.00	1.00	1.00	0.41
Zn	(0.98)	(0.55)	1.00	1.00	1.00	1.00	1.00	0.41
As	(0.36)	(0.67)	0.41	0.41	0.41	0.41	0.41	1.00

water quality parameters, providing insights into environmental conditions and potential impacts on the marine ecosystem.

The correlation analysis of seawater and sediment quality parameters indicates that heavy metals such as Cd, Cu, Hg, Pb, and Zn are highly correlated, suggesting a common pollution source, likely from industrial or domestic waste. Seawater pH shows a negative correlation with heavy metal concentrations, meaning lower pH increases metal solubility, while TSS moderately correlates with pH and metals, highlighting its role in transporting contaminants. In sediments, pH and total organic matter have a strong negative correlation (-0.93), indicating that organic matter decomposition lowers pH, while Cu and Zn exhibit a high correlation (0.93), reflecting similar geochemical behavior. Organic matter also plays a crucial role in binding heavy metals like Cu and Pb, increasing their sediment concentration. The correlation between heavy metals in water and sediment varies, as metals in water exist mostly in dissolved forms, whereas in sediments, they bind to minerals or organic matter. Overall, heavy metals in seawater and sediments show similar patterns, with pH influencing their mobility and organic matter aiding metal adsorption. Continuous monitoring, further research on metal-organic interactions, and stricter regulations are essential to limit heavy metal emissions and protect marine ecosystems..

Seawater quality analysis during the monitoring period (July – December 2022)

The seawater quality analysis for the July – December 2022 period includes various physical and chemical parameters. This data provides insights into changes in water quality and potential environmental impacts, serving as a basis for mitigation strategies and environmental management to ensure the sustainability of the marine ecosystem. The following table presents a detailed analysis of the results. Table 11 presents the results of the seawater quality analysis during the monitoring period (July – December 2022). This data provides insights into key water quality parameters, serving as a reference for assessing environmental conditions and potential impacts on the marine ecosystem. Seawater quality remains good, with stable pH (7.75– 8.27), no detected oil layer, and heavy metal concentrations in water within safe limits, but some parameters require further monitoring. PB 05 recorded the highest TSS (9 mg/L), potentially reducing water clarity, while PB 08 had the highest temperature (32.0°C), which may impact marine ecosystem balance. NEC 05 showed a significant increase in heavy metal concentrations in sediments, particularly arsenic (74 mg/kg), cadmium (0.4 mg/kg), and zinc (62 mg/kg), likely due to industrial activities or wastewater runoff. Although arsenic

Table 11. Results of seawater quality analysis during the monitoring period (July – December 2022)

Parameters	Satuan	PB 04	PB 05	PB 07	PB 08	NEC 05
Seawater quality						
Temperature	°C	30.5	31.0	30.2	32.0	31
pH	-	7.75	7.80	8.10	8.27	8.10
TSS	mg/L	5	9	3	2	5
Oil layer	-	None	None	None	None	None
Arsenic (As)	mg/L	0.0014	0.0020	0.0022	0.0024	0.0022
Lead (Pb)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Cadmium (Cd)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Zinc (Zn)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Copper (Cu)	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Mercury (Hg)	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Sediment						
Arsenic (As)	mg/kg	6.2	7.1	7.8	8.1	74
Cadmium (Cd)	mg/kg	0.2	0.3	0.3	0.4	0.4
Lead (Pb)	mg/kg	14	16	20	22	18
Copper (Cu)	mg/kg	8	10	12	15	14
Zinc (Zn)	mg/kg	50	55	60	63	62
Oil content	%	<0.01	<0.01	<0.01	<0.01	<0.01

Table 12. Correlation matrix of seawater quality parameters (Monitoring period: January – June 2022)

Parameter	Temperature	pH	TSS	As	As sediment	Cd sediment	Pb sediment	Cu sediment	Zn sediment
Temperature	1.00	0.52	(0.20)	0.52	0.06	0.68	0.51	0.63	0.50
pH	0.52	1.00	(0.76)	0.87	0.26	0.83	0.96	0.95	0.95
TSS	(0.20)	(0.76)	1.00	(0.38)	0.03	(0.31)	(0.71)	(0.56)	(0.53)
As	0.52	0.87	(0.38)	1.00	0.26	0.90	0.90	0.92	0.96
As sediment	0.06	0.26	0.03	0.26	1.00	0.55	0.02	0.45	0.43
Cd sediment	0.68	0.83	(0.31)	0.90	0.55	1.00	0.76	0.96	0.94
Pb sediment	0.51	0.96	(0.71)	0.90	0.02	0.76	1.00	0.88	0.90
Cu sediment	0.63	0.95	(0.56)	0.92	0.45	0.96	0.88	1.00	0.98
Zn sediment	0.50	0.95	(0.53)	0.96	0.43	0.94	0.90	0.98	1.00

levels in water (0.0014–0.0024 mg/L) remain within safe limits, monitoring is needed to prevent accumulation in the marine ecosystem. Further monitoring of arsenic at NEC 05, TSS at PB 05, and temperature at PB 08 is essential, alongside mitigation efforts to minimize pollution and ensure long-term ecosystem stability. Table 12 presents the correlation matrix of seawater quality parameters (January–June 2022), identifying relationships to assess environmental conditions and potential marine ecosystem impacts. The analysis indicates that pH significantly influences arsenic solubility and heavy metal precipitation in sediments, with strong correlations to arsenic in water (0.87) and heavy metals in sediment (0.95–0.96). Higher pH levels promote heavy metal accumulation in sediments. TSS negatively correlates with pH (-0.76) and arsenic in water (-0.38), suggesting that increased suspended particles lower pH and aid arsenic deposition. Arsenic in water strongly correlates with heavy metals in sediment (0.90–0.96), indicating a common pollution source. Temperature also affects heavy metal sedimentation (0.50–0.63). Continuous monitoring of pH, arsenic, and heavy metals is crucial, especially in high-arsenic areas like NEC 05, alongside further investigation into temperature effects and pollution control measures.

Seawater quality conditions

The seawater quality at Tanjung Jati B power plant across different monitoring periods (preconstruction and 2020–2022) indicates that overall water conditions remain within acceptable environmental standards. pH levels remain stable (7.5–8.42), oil and grease concentrations are low, and heavy metals in water (Zn, Cu, Hg, Cd, Pb) are generally below detection limits. However, arsenic levels show fluctuations, requiring continuous monitoring to prevent accumulation. Several key risks require attention. TSS levels vary significantly, with PB 05 recording the highest concentration (9 mg/L), potentially reducing water clarity. Water temperature ranges from 29.1°C to 32.0°C, with PB 08 consistently exhibiting the highest temperatures, which may impact marine biodiversity and pollutant behavior. Sediment analysis reveals significant heavy metal accumulation at NEC 05, with arsenic levels reaching 74 mg/kg, along with increased cadmium, lead, copper, and zinc concentrations, indicating long-term pollution risks from industrial activities.

Correlation analysis highlights the crucial role of pH in arsenic solubility and heavy metal precipitation, showing strong positive correlations between pH and arsenic in water (0.87) and between pH and heavy metals in sediments (0.95–0.96). TSS negatively correlates with pH (-0.76) and arsenic in water (-0.38), suggesting that increased suspended particles lower pH and enhance arsenic deposition. Temperature also influences heavy metal sedimentation (0.50–0.63), emphasizing the need for temperature regulation to prevent excessive metal accumulation. To mitigate these risks, a comprehensive environmental management approach is essential. Regular monitoring should focus on TSS, temperature, pH, and arsenic levels, with special attention to NEC 05 and PB 05. Pollution source control is crucial, particularly by addressing industrial discharges and sediment disturbances. Ecosystem protection measures should include temperature regulation and suspended particle reduction through improved sedimentation control. Additionally, sustainable waste management must be reinforced to prevent heavy metal accumulation in sediments and ensure long-term aquatic stability. Although seawater quality remains within safe limits, the increasing TSS, arsenic, and heavy metals in sediments pose significant environmental concerns that require close monitoring. NEC 05 should be prioritized due to its high arsenic and heavy metal concentrations, while PB 05 requires special attention for TSS and temperature levels. Integrated environmental management and pollution mitigation strategies must be strengthened to ensure the long-term stability of the marine ecosystem. The seawater quality remains generally stable and within environmental limits, but localized risks require targeted intervention to prevent long-term ecological degradation.

Biological parameters of plankton and benthos

Sampling and environmental quality analysis are adjusted to biological parameters, including plankton and benthos taxa, abundance, diversity index, uniformity index, and dominance index for each period and location. Measurements are conducted at key sites such as the water intake, effluent waste water treatment, planned dredging site, planned dumping site, and a control site located far from coal-fired power plant activities for comparison. This approach aims to assess the impact

Table 13. Sea water quality based on biological parameters

Plankton taxa (period/location)	PB 04	PB 05	PB 07	PB 08	NEC 05
EIA period (project planning stage)	197.00	136.00	47.00	113.00	79.00
Period Jan – Jun 2021	39.00	37.00	33.00	20.00	30.00
Period July - Dec 2021	25.00	23.00	19.00	18.00	12.00
Perio Jan- Jun 2022	26.00	23.00	32.00	34.00	24.00
Periode July – Dec 2022	23.00	22.00	20.00	19.00	19.00
Plankton abundance (period/location)	PB 04	PB 05	PB 07	PB 08	NEC 05
EIA period (project planning stage)	771.073	722.966	686.849	761.432	685.774
Period Jan– June 2021	680.476	677.857	606.920	632.738	656.012
Period July - Dec 2021	618.214	591.518	471.250	400.536	470.232
Perio Jan - Jun 2022	577.040	518.720	458.620	391.090	456.650
Periode July – Dec 2022	505.000	420.000	407.500	447.500	400.500
Plankton diversity index (period/location)	PB 04	PB 05	PB 07	PB 08	NEC 05
EIA period (project planning stage)	2.21	2.23	1.95	2.05	2.02
Period Jan– June 2021	2.18	1.96	1.88	1.83	1.54
Period July - Dec 2021	1.86	1.89	1.09	1.85	1.38
Perio Jan - Jun 2022	2.44	2.14	2.27	2.41	1.98
Periode July – Dec 2022	2.63	2.67	2.57	2.49	2.43
Plankton uniformity index (period/location)	PB 04	PB 05	PB 07	PB 08	NEC 05
EIA period (project planning stage)	0.64	0.67	0.69	0.69	0.71
Period Jan – June 2021	0.67	0.63	0.66	0.68	0.76
Period July - Dec 2021	0.62	0.68	0.75	0.75	0.79
Periode Jan - Jun 2022	0.73	0.78	0.80	0.81	0.84
Periode July – Dec 2022	0.85	0.86	0.91	0.91	0.92
Plankton dominance index (period/location)	PB 04	PB 05	PB 07	PB 08	NEC 05
EIA period (project planning stage)	0.11	0.14	0.13	0.16	0.19
Period Jan– June 2021	0.26	0.28	0.29	0.29	0.29
Period July - Dec 2021	0.24	0.26	0.27	0.28	0.29
Perio Jan - Jun 2022	0.26	0.30	0.33	0.29	0.36
Periode July – Dec 2022	0.31	0.48	0.48	0.44	0.51
Benthos taxa (period/location)	PB-04	PB-05	PB-07	PB-08	NEC-05
EIA period (project planning stage)	12	10	12	7	6
Period Jan – June 2021	14	13	8	6	5
Period July - Dec 2021	9	6	4	4	3
Perio January - Jun 2022	8	6	2	2	2
Periode July - December 2022	3	2	1	1	1
Benthos abudance (period/location)	PB-04	PB-05	PB-07	PB-08	NEC-05
EIA period (project planning stage)	595	695	360	250	225
Period Jan – June 2021	575	675	300	150	125
Period July - Dec 2021	300	300	153	125	100
Period Jan - Jun 2022	275	159	80	87	110
Period July – Dec 2022	189	100	40	90	76
Benthos diversity index (period/location)	PB-04	PB-05	PB-07	PB-08	NEC-05
EIA period (project planning stage)	2.44	2.33	2.33	2.32	2.23
Period January – June 2021	2.51	2.13	1.91	1.79	1.61
Period July - Dec 2021	2.29	1.88	1.51	1.59	1.24
Period January - Jun 2022	0.64	1.89	0.69	0.69	1.39
Period July – Dec 2022	0.8	1.76	1.31	0.85	1.35

Cont. Table 13.

Benthos uniformity index (period/location)	PB-04	PB-05	PB-07	PB-08	NEC-05
EIA period (project planning stage)	0.92	0.94	0.94	0.95	0.94
Periode Jan– June 2021	0.93	0.92	0.95	0.95	0.95
Period July - Dec 2021	0.95	0.92	1	0.93	0.95
Period January - Jun 2022	0.92	0.91	0.97	0.97	0.98
Period July - Dec 2022	0.95	0.95	0.97	0.97	0.98
Benthos dominance index (period/location)	PB-04	PB-05	PB-07	PB-08	NEC-05
EIA period (project planning stage)	0.21	0.28	0.23	0.28	0.28
Period January – June 2021	0.26	0.31	0.22	0.28	0.29
Period July - Dec 2021	0.34	0.33	0.25	0.25	0.38
Period Jan- Jun 2022	0.51	0.53	0.52	0.56	0.56
Period July - Dec 2022	0.62	0.66	0.68	0.67	0.73

Note: (a) the environmental impact assessment (EIA) period is the planning stage for the construction (base line), (b) period January–June 2021, period July – Dec 2021, period January – June 2022, period July – December 2022 are environmental monitoring stages.

of industrial activities on the marine ecosystem, ensure ecological balance, and provide scientific data to support mitigation and conservation efforts (Table 13).

Plankton and benthos are crucial to marine ecosystems, with plankton serving as the base of the food chain and providing energy for larger organisms, while benthos contribute to decomposition and nutrient cycling, also acting as indicators of water quality and ecosystem health (Cooley *et al.*, 2023). Changes in the abundance and diversity of plankton and benthos can indicate ecological shifts, with declines signaling disturbances, making their monitoring essential for assessing the environmental impact of industrial activities on marine water quality (Serandour, 2023). Monitoring plankton and benthos taxa is crucial for assessing the health of marine ecosystems and the impact of human activities, as well as detecting early signs of ecological imbalances to support conservation and management efforts. The parameters measured during the sampling period from July to December 2022 represents the results shown in Table 14.

Based on these results, 14 to 25 plankton taxa were detected in the study area, indicating species diversity. This suggests that the aquatic ecosystem around the sample stations supports various types of plankton. This diversity reflects favorable environmental conditions that sustain the life of different plankton species, which in turn indicates the good quality of the aquatic ecosystem in the area. The greater the diversity of organisms in an ecosystem, the more stable the

Table 14. Plankton and benthos analysis for the July–December 2022 period

Plankton					
Location	Abundance (cell/m^3)	Total taxa (s)	Diversity index (H’)	Uniformity index (E)	Dominance index (D)
PB 04	407.500	14	2.43	0.92	0.1
PB 05	447.500	17	2.49	0.88	0.11
PB 07	457.500	18	2.67	0.92	0.08
PB 08	420.000	20	2.57	0.86	0.1
NEC 05	535.000	22	2.63	0.85	0.1
Benthos					
Location	Abundance (cell/m^3)	Total taxa (s)	Diversity index	Uniformity index	Dominance index
PB-04	189	3	0.8	0.95	0.62
PB-05	100	1	1.76	0.95	0.66
PB-07	40	1	1.31	0.97	0.68
PB-08	90	1	0.85	0.97	0.67
NEC-05	76	1	1.35	0.98	0.73

ecosystem tends to be. On the other hand, when diversity is low, the ecosystem becomes more vulnerable to changes. The number of taxa or species in an ecosystem influences the diversity index; the higher the number of taxa, the greater the potential species diversity. However, the diversity index is also influenced by the relative abundance of each taxon. This means that even if there are many species, if their distribution is uneven or most species are rare, the diversity index will be lower compared to a situation where the abundance is more evenly distributed (Borics *et al.*, 2021). The diversity index is a mathematical measure used to assess species diversity in an ecosystem, based on species richness (the number of species) and species abundance (the number of individuals per species). This index illustrates how evenly species are distributed within the ecosystem. The higher the diversity value, the greater the number of species, and the more evenly the individuals of each species are distributed across the ecosystem. (Jalil et al., 2020). The diversity index at the five locations ranged from 2.43 to 2.67, indicating that plankton diversity falls within the moderate category. According to the diversity index range defined by Siregar and Mubarak (2021), where H' values between 1 and 3 suggest moderate diversity, this level of diversity indicates a stable ecosystem (Siregar and Mubarak, 2021). The species uniformity index, ranging from 0.85 to 0.92, indicates stability in the plankton community. A high uniformity index ($E \geq 0.6$) suggests a balanced community with no dominant species, supporting interactions among various species. Additionally, low dominance index values (0.08 to 0.11) further indicate no species dominance, pointing to a healthy ecosystem where species coexist without any one species overpowering others (Dittrich *et al.*, 2023). These results suggest that the plankton ecosystem in the study area demonstrates moderate diversity, high uniformity, and low dominance, reflecting a stable environment that supports plankton life. While these conditions are relatively stable, continuous monitoring remains essential to identify potential disturbances that could impact the ecosystem's balance, particularly concerning industrial activities such as the nearby coal-fired power plant.

Plankton abundance serves as an indicator of fertility in aquatic environments. Waters are considered fertile if the plankton abundance exceeds $40 \cdot 10^6$ per m^3, moderately fertile if the abundance ranges from $0.1–40 \cdot 10^6$ per m^3, and less fertile if the abundance is below $0.1 \cdot 10^6$ per m^3 (Sidabutar *et al.*, 2016). Based on the analysis of phytoplankton abundance, the results obtained ranged from 407,500 to 535,000 cells/m^3 ($0.408–0.535 \cdot 10^6$), indicating that the waters in the study area are moderately fertile. The identification of plankton species in the research area revealed the following phytoplankton species: *Bacillaria* sp. with 166,667 cells/m^3, *Proboscia* sp. with 166,667 cells/m^3, *Chaetoceros* sp. with 150,000 cells/m^3, *Dithylium* sp. with 6,667 cells/m^3, and *Ceratium* sp. with 53,333 cells/m^3. The presence of these species in the research area's waters is likely to continue increasing due to their ability to adapt to environmental conditions better than other species. A high level of sensitivity in these species reflects the trophic status of the water body. The trophic level of the marine environment indicates the metabolic rate of the waters, which can trigger blooming events and the production of toxic metabolic waste, potentially disrupting the ecosystem (Uysal, 2020). *Bacillaria* sp. is a phytoplankton species that can serve as a bioindicator of water pollution. This species is capable of adapting to both strong and slow currents, as well as harsh conditions. As a result, its prevalence in marine environments may continue to rise, potentially leading to algal blooms (Garduño-Solórzano et al., 2024). Algal blooms can disrupt the biological balance of marine environments, causing the death of nekton and invertebrates due to oxygen depletion. Similarly, the abundance of *Chaetoceros* sp., which causes blooms in the waters of Ambon Bay, Maluku, has resulted in massive fish deaths in floating fish cages. This phenomenon occurs during the rainy season (May to July), when upwelling in the Banda Sea brings nutrient-rich waters into Ambon Bay. Eutrophication has been reported as one of the key factors contributing to phytoplankton blooms (Kesaulya et al., 2022). Furthermore, *Dithylium* sp. and *Ceratium* sp. have the potential to cause harmful algal blooms (HABs), which can lead to the death of marine life by producing toxins that reduce oxygen levels in the water, creating "dead zones". These species can proliferate rapidly under conditions such as eutrophication, higher water temperatures, or changes in current patterns. When environmental conditions are favorable, they can trigger blooms that disrupt

Table 15. Types of phytoplankton, zooplankton, and benthos identified

Phytoplankton			Zooplankton		
Bacillaria sp.	Cell/m³	166.667	*Bivalvia veliger*	Cell/m³	357
Bacteriastrum sp.	Cell/m³	26.667	*Calanus sp.*	Cell/m³	18.214
Chaetoceros sp.	Cell/m³	150.000	*Corycaeus sp.*	Cell/m³	7.679
Climacodium sp.	Cell/m³	50.000	*Euterpina sp.*	Cell/m³	536
Coscinodiscus sp.	Cell/m³	33.333	*Lucifer sp.*	Cell/m³	536
Ditylum sp.	Cell/m³	6.667	*Nauplius sp.*	Cell/m³	2.500
Guinardia sp.	Cell/m³	36.667	*Creseis sp.*	Cell/m³	357
Haslea sp.	Cell/m³	20.000	*Diphyes sp.*	Cell/m³	357
Hemiaulus sp.	Cell/m³	100.000	*Leprotintinnus sp.*	Cell/m³	536
Lauderia sp.	Cell/m³	40.000	*Tintinnopsis sp.*	Cell/m³	536
Neocalyptrella sp.	Cell/m³	13.333	*Sagitta sp.*	Cell/m³	1.429
Nitzschia sp.	Cell/m³	13.333	Benthos		
Palmerina sp.	Cell/m³	6.667	*Cardita sp.*	Ind/m²	14.81
Pleurosigma sp.	Cell/m³	63.333	*Chlamys sp.*	Ind/m²	14.81
Proboscia sp.	Cell/m³	166.667	*Mactra sp.*	Ind/m²	14.81
Rhizosolenia sp.	Cell/m³	386.667	*Nucula sp.*	Ind/m²	103.7
Thalassiosira sp.	Cell/m³	3.333	*Nuculana sp.*	Ind/m²	74.07
Thalassiothrix sp.	Cell/m³	83.333	*Sinum sp.*	Ind/m²	29.63
Triceratium sp.	Cell/m³	16.667	*Terebra sp.*	Ind/m²	14.81
Trieres sp.	Cell/m³	76.667	*Umbonium sp.*	Ind/m²	14.81

Table 16. Analysis of plankton taxa, abundance, and diversity across sampling periods

Plankton indicator parameters /Period	Period 1	Period 2	Period 3	Period 4	Period 5
Avg taxa plankton /location smpling /1000	0.11	0.03	0.02	0.03	0.02
Avg abudance plankton /location smpling /10^6	0.73	0.65	0.51	0.48	0.44
Avg H plankton /location smpling	2.56	2.09	2.25	1.88	1.61
Avg E plankton /location smpling	0.68	0.68	0.72	0.79	0.89
Avg D plankton /location smpling	0.15	0.28	0.27	0.31	0.44

marine ecosystems, making it crucial to monitor their presence to prevent ecological imbalances (Zaparina *et al.*, 2024). *Dithylium* sp. and *Ceratium* sp. are part of the functional group of phytoplankton and harmful algal species in the northern Mediterranean Sea. These species are known to cause the death of marine organisms, as their blooms produce toxins that lead to oxygen depletion, disrupting the marine ecosystem and affecting various marine life forms (Nwankwegu *et al.*, 2023).

Tables 15 and 16 present the analysis of plankton and benthos (July – December 2022), including abundance, diversity, distribution, and species identification, providing insights into marine ecosystem health and biodiversity dynamics. Seven benthos species were identified, including Bivalvia (*Chlamys* sp., *Mactra* sp., *Nucula* sp., *Nuculana* sp.) and Gastropoda (*Sinum* sp., *Terebra* sp., *Umbonium* sp.). These organisms adapt to high physical stress and serve as bioindicators of marine water quality, though they can also survive in degraded environments. physicochemical variables, and substrate conditions play a significant role in influencing gastropod diversity (Supusepa et al., 2023). Gastropods and bivalves, widely distributed in marine waters, serve as indicators of contamination due to their high adaptability. Despite thriving in poor conditions, their presence and diversity offer valuable insights into marine ecosystem quality, highlighting the importance of monitoring them for effective environmental management (Vahidi *et al.*, 2021).

Trends in marine water quality – plankton and benthos as bioindicators

The trend evaluation approach in the environmental sector is used to identify patterns in changes in environmental quality over a certain time and spatial range. To analyze trends, periodic monitoring data (time series data) is required, because analyzing changes in trends can only be done using data from various monitoring. Evaluate trends in environmental management and activity monitoring, making it simpler for agencies that govern environmental impacts to address environmental problems and plan environmental management on a broader scale. The trend evaluation of this study was carried out based on serial data from biological parameter sampling (Sang *et al.*, 2024).

Plankton parameter trend evaluation

The data analysis in Table 17 reveals a decline in taxa, abundance, and plankton diversity over time, suggesting potential disturbances in the ecosystem. Although evenness has increased, the rising dominance of certain species indicates a structural shift. If this trend persists, it may affect the health and function of the aquatic ecosystem, as shown in Figure 2. The heat map analysis further highlights these changes, with darker colors representing improved biological parameter quality.

The correlation analysis results indicate a strong positive relationship between benthos taxa count, abundance, and diversity index (H'), with correlation values exceeding 0.90. This suggests that as the number of taxa increases, both abundance and diversity also rise. Conversely, the dominance index (D) shows a strong negative correlation with these three parameters (-0.98 to -0.87), meaning that species dominance increases when taxa count and diversity decline. This pattern is typically observed in ecosystems where a few species dominate due to their ability to adapt to specific environmental conditions. Meanwhile, the evenness index (E) exhibits a weak correlation with taxa count and abundance (0.01–0.24), indicating that species distribution uniformity is not necessarily influenced by the total number of taxa or abundance. In other words, even if taxa count and abundance decrease, evenness may still increase if the remaining species are more evenly distributed within the community. These findings highlight that benthos communities with high diversity tend to have a more balanced species distribution, whereas communities with high dominance generally exhibit lower diversity. In the plankton community, data analysis reveals a

Table 17. Changes in planton parameters across different periods: correlation

Parameter	Avg taxa benthos	Avg abundance benthos	Avg H benthos (diversity)	Avg C benthos (uniformity)	Avg D benthos (dominance)
Avg taxa benthos (1000)	1	0.98	0.93	0.01	-0.98
Avg abundance benthos (10^6)	0.98	1	0.98	0.05	-0.95
Avg H benthos (diversity)	0.93	0.98	1	0.24	-0.87
Avg C benthos (uniformity)	0.01	0.05	0.24	1	0.16
Avg D benthos (dominance)	-0.98	-0.95	-0.87	0.16	1

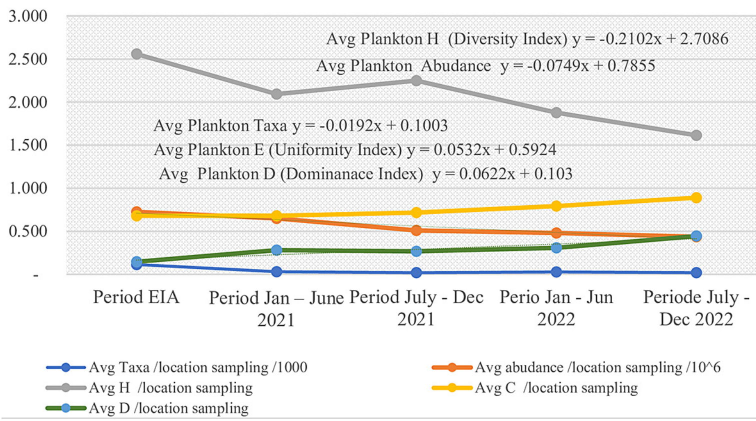

Figure 2. Evaluation of plankton trends

declining trend in diversity, taxa count, and abundance over the monitoring period. The plankton diversity index (H') follows a downward trend, represented by the linear equation $y = -0.2102x + 2.7986$, though it remains within the moderate category (1 < H < 3) according to the Shannon-Weiner index. This means that while a decline is observed, the current diversity level is still relatively stable. However, if this trend continues without intervention, further decreases may lead to ecosystem imbalances that could reduce the ecological functions of the plankton community within the marine food web (Ulfah *et al.*, 2019) The number of plankton taxa and abundance also exhibit a declining trend, as reflected in the linear equations $y = -0.0192x + 0.1003$ (taxa count) and $y = -0.049x + 0.7855$ (abundance). This decline is often associated with external factors such as pollution and environmental disturbances, which can shift species composition from those sensitive to environmental changes to more tolerant species (Ajani *et al.*, 2023). However, it is important to note that not all forms of pollution directly lead to a decrease in species numbers. In some cases, pollution may reduce the presence of more sensitive species while increasing the abundance of tolerant species, ultimately affecting overall diversity. Thus, while taxa count and abundance are key components of the diversity index, the relationship between pollution and ecosystem change is not always linear and requires further monitoring. Meanwhile, the plankton dominance index (D) and evenness index (E) show an increasing trend. The dominance index follows the equation $y = 0.0622x + 0.103$ and remains within the moderate category ($0.5 \leq D < 1$). This indicates that certain species are becoming more dominant within the plankton community, yet this level of dominance has not reached a critical threshold that would indicate severe ecosystem disruption. In stable ecosystems, an increase in the dominance index can reflect natural community dynamics. However, if dominance continues to rise beyond the moderate category, it may indicate a more significant ecological imbalance requiring further investigation (Hossain et al., 2017). The evenness index (E) also shows an increasing trend, following the equation $y = 0.532x + 0.5924$, while still remaining within the moderate category ($0.5 < E \leq 0.75$) (Haryono *et al.*, 2023). An increase in evenness does not necessarily indicate ecosystem improvement. Instead, it suggests that although the total number of species is decreasing, the remaining species are becoming more evenly distributed within the community. In this context, higher evenness reflects a shift in community structure rather than an improvement in environmental conditions.

Based on these findings, it can be concluded that while the diversity index remains within the moderate range, the ongoing downward trend should be closely monitored. If left unaddressed, this trend could lead to ecosystem imbalances, where tolerant species become increasingly dominant while more sensitive species continue to decline. Therefore, regular monitoring, pollution control, and conservation efforts are essential to prevent further degradation of plankton and benthos communities and to maintain the ecological balance of marine ecosystems.

Benthos parameter trend evaluation

Table 18 shows a decline in taxa, abundance, and benthic diversity over the observation period. While the evenness index remains stable, the increasing dominance index indicates structural changes in the benthic ecosystem, with certain species becoming more dominant. If this trend continues, species diversity may further decline, potentially disrupting ecosystem stability. Figure 3 illustrates this trend, reinforcing the decrease in taxa, abundance, and diversity.

The correlation analysis in Table 19 reveals a strong positive relationship between benthos taxa count, abundance, and diversity (H'), with values of 0.98 and 0.93, indicating that higher species

Table 18. Analysis of benthos taxa, abundance, and diversity across sampling periods

Parameter /Periode	Periode 1	Periode 2	Periode 3	Periode 4	Periode 5
Avg taxa benthos/location sampling /1000	9.40	9.20	5.20	4.00	1.60
Avg abudance benthos /location smpling /10^6	4.25	3.65	1.96	1.42	0.99
Avg H benthos /location smpling	2.33	1.99	0.93	0.96	0.87
Avg C benthos /location smpling	0.94	0.94	0.91	0.95	0.94
Avg D benthos /location smpling	0.26	0.27	0.31	0.35	0.39

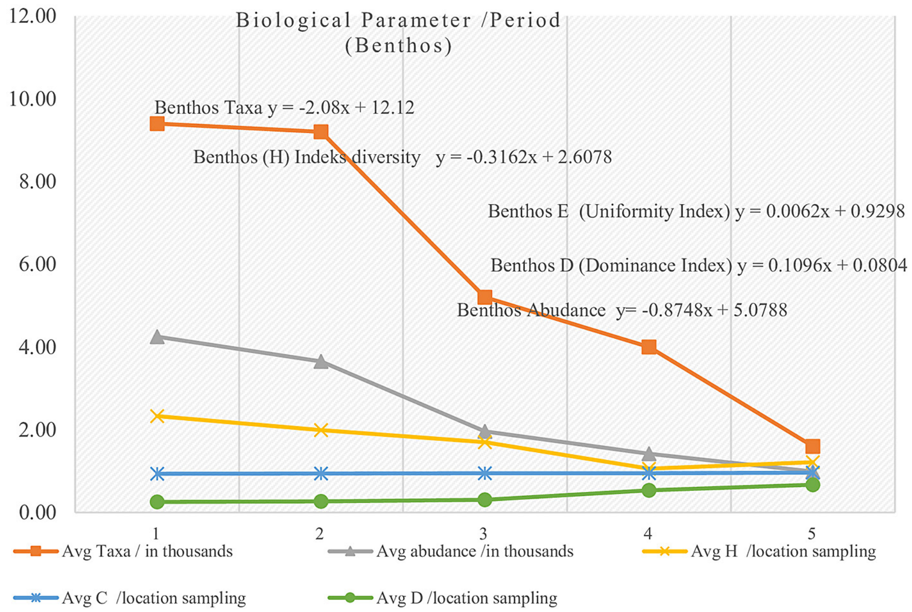

Figure 3. Correlation analysis of changes in benthos parameters across different periods

Table 19. Analysis of benthos taxa, abundance, and diversity across sampling periods

Parameter	Avg taxa benthos	Avg abundance benthos	Avg H benthos	Avg C benthos	Avg D benthos
Avg taxa benthos	1.00	0.98	0.93	0.01	(0.98)
Avg abundance benthos	0.98	1.00	0.98	0.05	(0.95)
Avg H benthos	0.93	0.98	1.00	0.24	(0.87)
Avg C benthos	0.01	0.05	0.24	1.00	0.16
Avg D benthos	(0.98)	(0.95)	(0.87)	0.16	1.00

richness is associated with increased abundance and diversity, which supports ecosystem stability. Conversely, the dominance index (D) exhibits a strong negative correlation with these parameters (-0.98 to -0.87), suggesting that as dominance increases, taxa richness, abundance, and diversity decline, potentially due to environmental stressors such as pollution or habitat degradation. The evenness index (C) shows weak correlations with taxa (0.01), abundance (0.05), and diversity (0.24), implying that species distribution uniformity remains relatively stable regardless of fluctuations in species count and abundance. These findings highlight the importance of maintaining species diversity to prevent ecological imbalances caused by increasing dominance of a few species. To mitigate biodiversity loss and sustain benthic ecosystem health, effective pollution control, habitat conservation, and continuous monitoring of species dominance are essential.

The Figure 3 illustrates a downward trend in benthic taxa count, abundance, and diversity index (H') over time, highlighting significant ecological changes in the benthic ecosystem. The benthic taxa count has declined sharply, as indicated by the equation $y = -2.08x + 12.12$, reflecting a continuous reduction in species richness. Benthic abundance also shows a significant decreasing trend ($y = -0.8748x + 5.0788$), indicating not only a decline in species diversity but also an overall reduction in benthic organism populations. The benthic diversity index (H') is also decreasing ($y = -0.3162x + 2.6078$), confirming biodiversity loss, likely driven by environmental stressors such as habitat degradation, pollution, or resource depletion.

Despite the decline in taxa count and abundance, the evenness index (E) remains relatively stable ($y = 0.0062x + 0.9298$), suggesting that while fewer species are present, their distribution within the community remains balanced. However, this does not indicate ecosystem stability, as the dominance index (D) is increasing ($y = 0.1096x + 0.0804$), signifying that the community is becoming increasingly dominated by a few species while others disappear. This pattern is commonly observed in ecosystems under environmental stress, where only tolerant species persist, while more sensitive species experience population declines or even local extinction.

CONCLUSIONS

The construction of the Tanjung Jati coal-fired power plant has led to moderate pollution in the surrounding marine waters. Based on biological assessments, there has been a decline in the diversity index, taxa count, and the abundance of both plankton and benthos, accompanied by an increase in dominance and uniformity indices. Regression analysis reveals that the decline in benthic taxa count is steeper than that of diversity and abundance, indicating the loss of sensitive species before its full impact is reflected in the ecosystem. Environmental stressors such as pollution, sedimentation, and anthropogenic activities, including the operation of the Tanjung Jati power plant, contribute to declining water quality, altered sediment composition, and benthic habitat degradation, accelerating the shift toward dominance by more tolerant species. Although water quality is still classified as moderately polluted, structural changes in the benthic community indicate increasing ecological stress, which, if left unaddressed, may accelerate further degradation. The rising dominance index suggests community homogenization, which can reduce ecosystem stability, disrupt trophic balance, and impair essential ecological functions such as nutrient cycling. To prevent further degradation, an ecosystem-based adaptive management approach is necessary, including benthic habitat rehabilitation through sediment restoration and seagrass enrichment, the implementation of environmentally friendly technologies to reduce industrial pollution, and continuous monitoring using benthic bioindicators and real-time water quality sensors.

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