ASSESSMENT AND CHARACTERIZATION OF WATER QUALITY AND POLLUTION IN THE COASTAL ENVIRONMENT OF PEKALONGAN, CENTRAL JAVA, INDONESIA

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ABSTRACT

Coastal waters are complex ecosystems essential to environmental, economic, and social sustainability. The dynamic characteristics of the Pekalongan coast are shaped by both natural processes and human activities. This study analyzes pollution characteristics at the Loji and Sengkarang estuaries. In-situ sampling was conducted to measure pH, temperature, salinity, and dissolved oxygen (DO), while ex-situ laboratory analysis was used to examine BOD, COD, TSS, nitrate, phosphate, and total coliform levels. The overall water quality was assessed using the Pollution Index and visualized through a geospatial approach. Results show that pollution indices in Pekalongan's coastal waters fall into the "slightly polluted" to "heavily polluted" category, with varying scores at different stations. The Loji Estuary exhibited higher pollution levels than the Sengkarang Estuary. Coastal areas were generally more polluted than open sea areas. The primary sources of pollution are human activities, including industry, fishing, port operations, agriculture, and residential settlements. A multidisciplinary approach is recommended to foster effective dialogue among researchers, environmental advocates, and stakeholders for the sustainable management of coastal ecosystems.

Keywords: *Water quality; Pollution; Coastal environment; Pekalongan; Anthropogenic.*

1. INTRODUCTION

Coastal waters are complex ecosystems that play a vital role in maintaining environmental, economic, and social sustainability. The Pekalongan coast is one of Central Java's most promising coastal areas and contributes significantly to the fisheries sector. This is supported by the presence of the Pekalongan Nusantara Fisheries Port at the mouth of the Loji River, with marine fisheries

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production reaching 9,635.5 tons (a 7.05% increase) in 2024, and by fish auction sites located near the Loji and Sengkarang Rivers (BPS Statistics of Pekalongan Municipality, 2025). The dynamic nature of the Pekalongan coast is largely influenced by environmental variations driven by both natural processes and human activities. Intensive land-based human activities have significantly increased the flow of chemical elements into estuaries via river discharge (Maslukah et al., 2023).

In Indonesia, coastal pollution is primarily caused by high levels of nutrients and organic matter from household wastewater, industrial operations, agriculture, aquaculture, and solid waste (Adyasari et al., 2021). Pekalongan is known as an industrial city with diverse anthropogenic activities. It has a population of 321,095, around 2,894 industrial businesses, 1,407 hectares of agricultural land, 207 aquaculture enterprises, and tourism destinations such as Mangrove Park, Pasir Kencana Beach, Slamaran Indah Beach, and the Batik Museum (BPS Statistics of Pekalongan Municipality, 2025). This broad range of activities raises concerns about water quality degradation and its impact on marine ecosystems due to poorly managed waste. Environmental changes in coastal areas can lead to habitat destruction, biodiversity loss, and a long-term decline in the ecological health of coastal waters (Senarathna Atapaththu et al., 2025).

Previous studies on water quality in Pekalongan have been conducted by (Maslukah et al., 2019) and (Zainuri et al., 2022). Research by (Maslukah et al., 2019) examined the relationship between water quality—particularly phosphate levels—and chlorophyll-a concentrations at the Sragi River estuary. In 2022, (Zainuri et al., 2022) conducted an analysis of flood inundation as part of a disaster mitigation analysis and changes in nutrient distribution patterns. This study demonstrated that these distribution patterns had changed due to hydro-oceanographic factors, weather, and increasing pollution loads due to densely populated settlements, particularly the massive input of poorly managed Batik waste into river ecosystems. The embankment construction process was carried out in stages, resulting in varying inundation patterns and periods (Zainuri et al., 2024; Helmi et al., 2025). This paper's novelty lies in the assumption that seawall construction will continue to evolve following national long-term development policies. Based on this assumption, this research forms part of a sustainable long-term management plan to address disasters resulting from the impacts of seawall development. Research in these areas is essential, as intense human activity may lead to water pollution and a decline in marine ecosystem quality.

One of the mitigation measures implemented is pollution index analysis. Some advantages of using an index include the ability to determine water quality status with only a single sampling and the absence of a time series (Swandani et al., 2023). This reduces the cost and time required. This consideration provides a second novelty that will later be compared through temporal analysis of results from previous years. Therefore, this study aims to characterize pollution in the Loji and Sengkarang estuaries. The findings can serve as a reference for preliminary observations on how different human activities affect estuarine conditions. Water quality directly influences the health of organisms in the region. Thus, it is urgent to control and reduce pollution in coastal waters through regular assessments and a deeper understanding of variations in estuarine water quality.

2. STUDY AREA

This study was conducted in two river estuaries: the Loji River Estuary (stations A1–A7, located at coordinates 109°41'9.56"–109°42'6.80" E and 6°50'43.15"–6°51'45.25" S) and the Sengkarang River Estuary (stations B1–B7, at coordinates 109°39'6.98"–109°40'2.35" E and 6°50'7.98"–6°51'15.84" S). The research locations are shown in **Fig. 1**. Sampling sites were selected using a purposive sampling method to represent river, coastal, and open sea areas. Each estuary was divided into seven stations with the following designations: station 1 in the river, station 3 at the river mouth, stations 2 and 4 in coastal waters, and stations 5 to 7 in the open sea. Differences in station characteristics, determined using a spatial approach, are presented in **Table 1**. In situ data sampling was conducted on 15 May 2025 to represent Transitional Season I, between 06:00 and 12:00 Western Indonesian Time (WIB), when the tide transitioned from high to low.

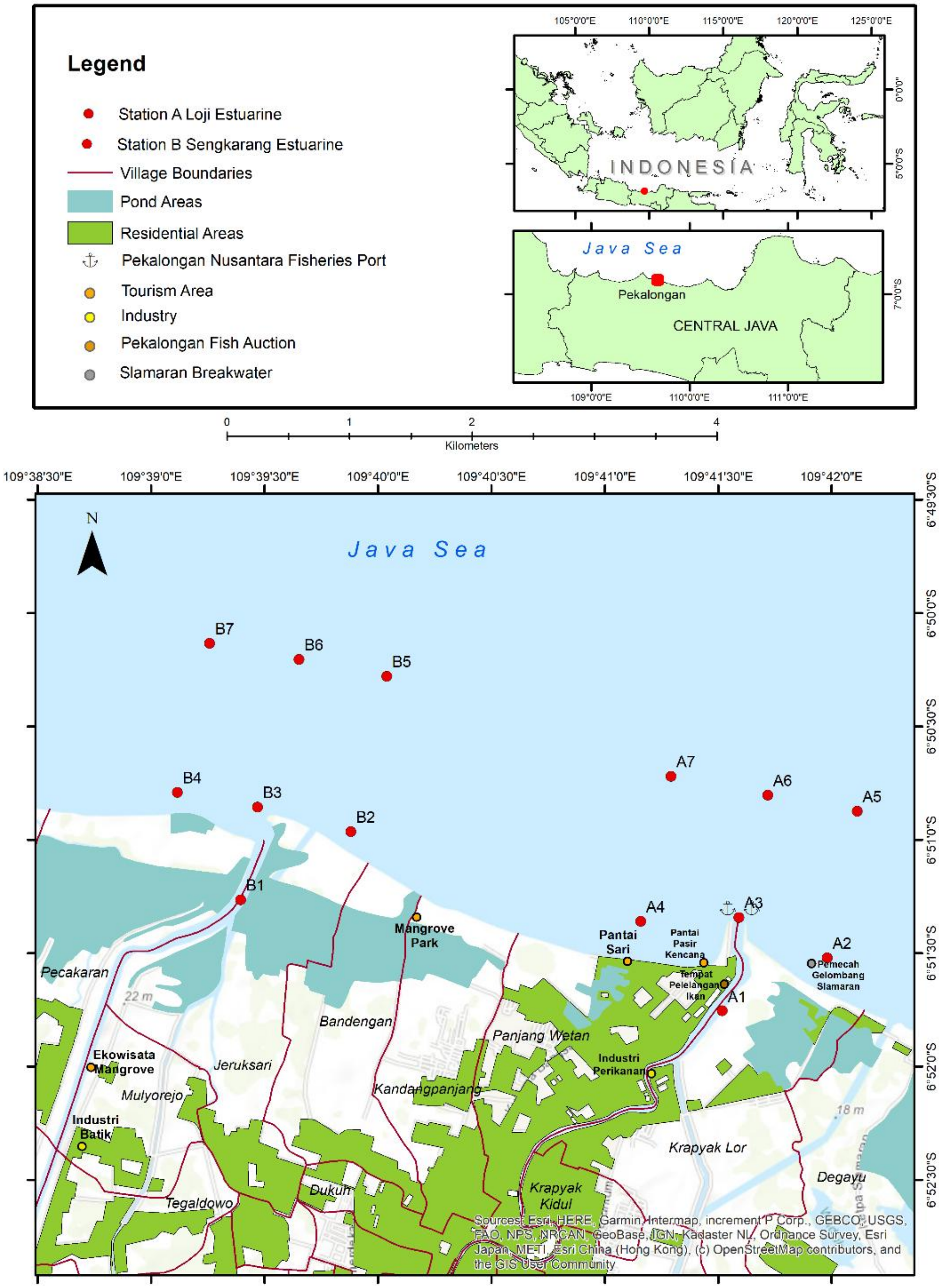

Fig. 1. Sampling location.

Table 1.
Characteristics of the sampling sites (spatial approach).

Location	Station	Characteristics	Ordinate	
			Longitude	Latitude
Loji Estuarine	A1	Loji River, near Pekalongan Fish Auction, settlements, ponds, fish industry	109°41'31.09"E	6°51'45.25"S
	A2	Coastal, near Slamaran Beach and pond areas	109°41'58.85"E	6°51'31.25"S
	A3	River mouth, near Pekalongan Nusantara Fisheries Port	109°41'35.52"E	6°51'20.56"S
	A4	Coastal, near Sari Beach and settlement areas	109°41'9.56"E	6°51'21.56"S
	A5	Open sea area	109°42'6.80"E	6°50'52.44"S
	A6		109°41'43.15"E	6°50'48.16"S
	A7		109°41'17.56"E	6°50'43.15"S
Sengkarang Estuarine	B1	Sengkarang river	109°39'23.69"E	6°51'15.84"S
	B2	Coastal, near Pekalongan Mangrove Park	109°39'52.85"E	6°50'57.80"S
	B3	River mouth, near mangrove forest	109°39'28.19"E	6°50'51.32"S
	B4	Coastal, near mangrove forest	109°39'6.98"E	6°50'47.47"S
	B5	Open sea area	109°40'2.35"E	6°50'16.69"S
	B6		109°39'39.17"E	6°50'12.23"S
	B7		109°39'15.52"E	6°50'7.98"S

3. DATA AND METHODS

3.1. Data Collection and Laboratory Analysis

Water samples were collected from the sea surface at each sampling coordinate and stored in sample containers for laboratory analysis. Temperature and pH were measured in situ using a pH meter, while dissolved oxygen (DO) and salinity were measured using a DO meter and a refractometer, respectively. Water quality parameters were assessed using both in situ and ex-situ approaches. In situ measurements, conducted directly at the sampling sites, were used to evaluate parameters that change rapidly, such as pH, temperature, salinity, and DO. Ex-situ analysis, conducted in the laboratory, measured Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), nitrate (NO_3^-), phosphate (PO_4^-), and total coliforms. The results of ex-situ tests and laboratory evaluations were compiled in tabular format and analyzed descriptively, supported by a review of relevant literature.

TSS and total coliforms were the primary physical and biological parameters analyzed in the laboratory. TSS was evaluated using the gravimetric method, which involves weighing the sample before and after isolating suspended solids (Alaerts & Santika, 1987). Total coliform analysis employed the Most Probable Number (MPN) method. The presence of fecal coliforms is indicated by metallic green colonies on Eosin Methylene Blue Agar (EMBA) media, while pink colonies indicate non-fecal coliform bacteria (APHA 9221 B.C., 2022) The analysis in this study included laboratory testing of nitrate, phosphate, BOD, and COD parameters. Nitrate concentrations were determined using the cadmium reduction method, where nitrate compounds are reduced to nitrite by cadmium (Cd) coated with copper in a column. The sample was then analyzed using a UV-Vis spectrophotometer at a wavelength of 543 nm (Parsons et al., 1984). Phosphate concentrations were analyzed using the molybdenum blue method, with absorbance measured at 885 nm using a UV-Vis spectrophotometer (Strickland & Parsons, 1968). BOD_5 was measured using the 5-day BOD method, which quantifies the oxygen consumed during a 5-day incubation period. This includes the oxygen required for the biochemical decomposition of organic substances (carbonaceous demand), oxidation of inorganic compounds such as sulfides and ferrous iron, and oxidation of reduced nitrogen compounds (nitrogenous demand) (APHA 5210 B, 2022a). COD was determined using the closed reflux colorimetric method for water and wastewater samples. In this method, most organic matter in the sample is oxidized by a boiling mixture of chromic and sulfuric acids in the presence of excess potassium dichromate ($K_2Cr_2O_7$). After refluxing, the remaining dichromate is titrated with ferrous ammonium sulfate (FAS), and the color change indicates the end of the reaction (APHA 5220 D, 2022).

3.2. Pollution Index Calculation

The Pollution Index (PI) calculation involved several steps. First, water quality data from each sampling point were entered into a spreadsheet. For each parameter, the ratio between the measured concentration (Ci) and the corresponding water quality standard (Lij) was calculated. For parameters that have an inverse relationship with water quality, such as DO, the ratio was calculated using a special calculation. The maximum ratio was defined as the highest individual parameter ratio between Ci and Lij at each station, while the average ratio was calculated as the arithmetic mean of all parameter ratios. These two values were then combined using Equation (1) to obtain the final PI value for each sampling location. All parameters were given equal weight, and no additional normalization was applied beyond the regulatory formulation. This index can inform decision-makers when water quality declines due to pollutant presence and prompt necessary actions. The overall water quality index for coastal Pekalongan was calculated based on the Ministry of Environment and Forestry Regulation No. 27 of 2021 (Appendix I: Environmental Quality Index), which provides the basis for the PI method. The formula used is shown in Equation (1). A GIS desktop software was employed to visualize the spatial distribution of PI scores and land use in the study area.

The pollution index (PI) was calculated separately for river and coastal waters using parameter sets and reference standards appropriate to each environment. Although several physicochemical parameters were standard to both calculations, the final parameter selection was guided by the respective regulatory water quality criteria. As a result, the type of parameters included in the PI calculation was not identical for river and coastal stations. Instead, PI values were used to evaluate pollution status relative to the designated water quality standards within each aquatic system. In contrast, spatial patterns and qualitative trends were used to infer land–sea interactions. This approach ensures regulatory consistency while avoiding misleading cross-system quantitative comparisons.

$$PI = \sqrt{\frac{\left(\frac{Ci}{Lij}\right)^2 Max + \left(\frac{Ci}{Lij}\right)^2 Avg}{2}} \quad (1)$$

where:
L_{ij}: Standard concentration for water usage (j)
C_i: Sample concentration of water quality parameter (i)
PI: Pollution Index for specific usage
(C_i/L_{ij}) *Max*: Maximum value of C_i/L_{ij}
(C_i/L_{ij}) *Avg*: Average value of C_i/L_{ij}

The interpretation of the PI is as follows:

$0 \leq PI \leq 1$ = meets the standard (good condition)
$1 < PI < 5$ = slightly polluted
$5 < PI \leq 10$ = moderately polluted
$PI > 10$ = heavily polluted

4. RESULTS AND DISCUSSIONS

4.1. Assessment of Water Quality at Loji Estuary

This study evaluates river water quality based on temperature, TSS, COD, pH, BOD, DO, phosphate, nitrate, and total coliform levels. The assessment follows Government Regulation No. 22 of 2021, Appendix VI, which provides water quality standards for rivers. **Table 2** presents the results of water quality testing at the Loji and Sengkarang Rivers, based on the standards for class 2 river water. This classification includes activities such as recreation, freshwater aquaculture, livestock, and irrigation—uses consistent with those of the Loji River. Based on the analysis, the PI for the Loji River was 12.2604, categorizing it as heavily polluted.

Table 2.

Water Quality Measurements in the Loji and Sengkarang Rivers.

Water Quality Variable	Unit	Sampling Station (River)		Permitted Level
		A1 (Loji)	B1 (Sengkarang)	
Physical				
Temperature	C	**31.6**	28.85	Dev 3 (23-29)
TSS	mg/L	**73.9**	34.4	50
Chemical				
COD	mg/L	**38.02**	23.15	25
pH		7.93	7.65	6 - 9
BOD	mg/L	2.881	**7.317**	3
DO	mg/L	**0.61**	6.44	4
Phosphate	mg/L	**3.419**	**0.515**	0.2
Nitrate	mg/L	0.420	0.412	10
Biological				
Total Coliform	MPN/ 100 mL	240	49	5000
PI Score		**12.2604**	**2.18113**	
Water Quality Status		**Heavily Polluted**	**Slightly Polluted**	

Permitted level source: National Regulation of the Republic of Indonesia No. 22/2021, Appendix VI.

Based on tests conducted in the Loji River area (A1), all physical parameters, including temperature and total suspended solids (TSS), exceeded the class II river water quality standards. Elevated TSS levels may result from the densely populated settlements surrounding the river, which reduce groundwater absorption. This disrupts the natural soil layer, leading to erosion, runoff, and sedimentation in the river (Istomi et al., 2025). In addition to residential areas, the Loji River is located near the fishing industry, a known source of domestic waste (**Table 1**). The discharge of solid and liquid waste into the river contributes to increased TSS concentrations (Ciupa et al., 2021).

High water temperatures in the Loji River are likely caused by limited vegetation along the riverbanks, allowing direct sunlight to reach the water surface (Pandiangan et al., 2023). Elevated temperatures stimulate microbial activity that breaks down organic matter, increasing oxygen consumption. As a result, DO levels decrease (Anh et al., 2023). The DO value in the Loji River was recorded at 0.61, below the minimum acceptable threshold. Low DO levels can harm aquatic organisms, as oxygen is essential for respiration and metabolic processes. A drop in DO can also increase the toxicity in the water.

In addition to dissolved oxygen (DO), other chemical parameters that exceed designated quality standards include Chemical Oxygen Demand (COD) and phosphate levels in Loji River (A1). These elevated COD and phosphate values are suspected to stem from the careless disposal of Batik dye waste into the river. Based on data from the Pekalongan City Environmental Agency, there are approximately 600 active Batik industries, of which 75% of Batik waste is not adequately processed (Dinas Lingkungan Hidup Kota Pekalongan, 2025). High COD levels in Batik wastewater are typically attributed to the considerable amount of organic compounds generated during fabric processing, such as starch, oils, and residues from the wax rolling process. Consequently, the river water often appears black and emits an unpleasant odor. Additional organic compounds arise from detergents and caustic soda used during the washing of Batik cloth, contributing to increased phosphate content, which further degrades water quality (Agustina et al., 2025; Safamaura & Afany, 2025). Meanwhile, other parameters—such as pH, BOD, nitrate, and total coliform—remained within the acceptable limits. However, total coliform levels in the Loji River were significantly higher than those in the Sengkarang River, indicating substantial waste contamination, particularly from human or warm-blooded animal sources (Ismanto et al., 2024).

Estuary water quality assessment using the PI method at six sampling points is presented in **Table 3.** Parameters include temperature, TSS, salinity, pH, BOD, DO, phosphate, nitrate, and total coliform. Based on these results, the Loji estuary was categorized as moderately polluted at points A2 and A3 and lightly polluted at other points, with PI values varying at each station (**Fig. 2**). Pollution levels in the coastal area (stations A2, A3, and A4) were higher, with PI scores ranging from 4.89 to 6.88, compared to the offshore stations (A5, A6, and A7), which ranged from 1.72 to 4.69. This pattern is likely due to the coastal area's proximity to human activities on land, which increase pollutant discharge into the estuary via river flow (Indrayanti et al., 2022).

Table 3.

Water Quality Measurements in the Loji Estuary.

Water Quality Variable	Unit	Sampling Station (Loji Estuary)						Permitted Level
		A2	A3	A4	A5	A6	A7	
Physical								
Temperature	C	31.3	31.3	31.1	30.8	31	31	28-32
TSS	mg/L	**80.9**	72.9	**88.7**	60.6	73.4	77.8	80
Chemical								
Salinity	‰	30	23	31	19	30	30	34
pH		8.26	8.18	**8.53**	8.295	8.175	8.27	7-8.5
BOD	mg/L	2.301	2.02	1.778	1.746	1.201	5.21	20
DO	mg/L	6.315	5.435	6.4	6.735	7.025	6.915	5
Phosphate	mg/L	**0.258**	**0.756**	**0.206**	**0.137**	**0.189**	**0.017**	0.015
Nitrate	mg/L	**0.419**	**0.415**	**0.410**	**0.254**	**0.140**	**0.110**	0.06
Biological								
Total Coliform	MPN/ 100 mL	17	49	23	49	14	33	1000
PI Score		***5.231365***	***6.881005***	***4.8943966***	***4.22408***	***4.69812***	***1.72791***	
Water Quality Status		***Moderately Polluted***	***Moderately Polluted***	***Slightly Polluted***	***Slightly Polluted***	***Slightly Polluted***	***Slightly Polluted***	

Permitted level source: National Regulation of the Republic of Indonesia No. 22/2021, Appendix VIII.

Based on the assessment of the coastal areas (A2-A4), several parameters—namely TSS, nitrate, and phosphate—exceeded the quality standards, as shown in **Table 3**. The increase in TSS levels is believed to be influenced by nearby artificial structures. At sampling point A2, the Slamaran breakwater traps sediment carried by currents, leading to accumulation in that area. At point A4, elevated TSS levels are likely caused by sediment buildup due to the current obstruction from the Pekalongan Nusantara Fisheries Port located to the east. This aligns with the findings of (Senarathna Atapaththu et al., 2025), which stated that coastal construction projects such as ports, seawalls, and breakwaters can disrupt natural water flow and alter tidal patterns. These disruptions can affect water circulation, concentrating pollutants in specific areas and leading to erosion or sediment accumulation that impacts surrounding ecosystems. However, TSS levels at point A2 were lower than those recorded at point A4.

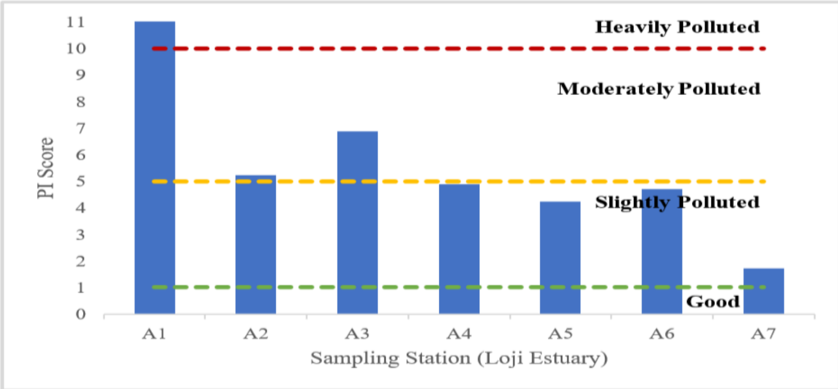

Fig. 2. Classification Ranges of PI Scores at Loji Estuary

In addition, nitrate and phosphate levels in coastal areas exceeded established standards. These nutrients are likely carried by river currents after waste decomposition into organic matter (Maslukah et al., 2023). Beyond river runoff, coastal aquaculture also contributes to nutrient loading. The area of ponds in North Pekalongan sub-district reaches 474.8 hectares (BPS Statistics of Pekalongan Municipality, 2025). Pond activities release organic waste through uneaten or undigested feed and fish excretion, which decomposes and increases nitrogen and phosphorus levels in nearby waters (Edwards et al., 2024). Elevated nitrate and phosphate concentrations were also observed in all open sea locations, likely due to the offshore transport of nutrients by tidal currents.

4.2. Assessment of Water Quality at Sengkarang Estuary

This assessment is based on Government Regulation No. 22 of 2021, Appendix VI, which outlines class II river water quality standards. This classification covers uses such as freshwater aquaculture and irrigation, consistent with the function of the Sengkarang River. Based on the evaluation, the pollution index for the Sengkarang River is 2.18113, indicating a slightly polluted status. Among the tested parameters, only BOD and phosphate exceeded the standard. The BOD value recorded was 7.317 mg/L, while the permissible limit is 3 mg/L (see **Table 2**). BOD refers to the amount of oxygen required by microorganisms to decompose organic matter in water. A high BOD level suggests a significant presence of organic pollutants, likely originating from household waste and decaying vegetation along the river (Anh et al., 2023). This elevated BOD indicates that bacteria are consuming large amounts of oxygen to break down the organic material. Agricultural activities—including the use of pesticides, fertilizers, compost, and manure—also contribute to higher BOD through surface runoff from residential and farming areas (Istomi et al., 2025; Lee et al., 2020). Meanwhile, the recorded phosphate concentration in the Sengkarang River was measured at 0.515 mg/L, which surpasses the permissible limit of 0.2 mg/L (refer to Table 2). This elevation in phosphate levels can be attributed to the multitude of anthropogenic and industrial activities in the vicinity of the river. Furthermore, the Sengkarang River functions as a transit route for local fishermen and is utilized for various activities, including bathing, washing, and recreational white-water rafting. Such practices can significantly contribute to the increased influx of phosphate into the aquatic environment, thereby amplifying concerns regarding water quality and its ecological implications (Damayanti et al., 2022).

Water quality in the Sengkarang estuary was assessed using the PI method at six sampling points, as shown in **Table 4**. Based on the results, the estuary is categorized as slightly to moderately polluted, with varying PI scores at each location (**Fig. 3**). Pollution levels were higher in coastal areas (stations B2, B3, and B4), with PI values ranging from 4.75 to 5.19, compared to the open sea stations (B5, B6, and B7), which ranged from 3.47 to 4.82. Similar to the Loji estuary, this trend is likely due to human activity near coastal areas, which introduces more pollutants into the estuary through river flow.

Table 4.

Water Quality Measurements in the Sengkarang Estuary.

Water Quality Variable	Unit	Sampling Station (Sengkarang Estuary)						Permitted Level
		B2	**B3**	**B4**	**B5**	**B6**	**B7**	
Physical								
Temperature	°C	31.45	29.3	30.4	30.92	30.35	31.35	28-32
TSS	mg/L	**83.3**	40.8	47.9	78.4	53.7	58.4	80
Chemical								
Salinity	‰	26.5	14	25	25	24.5	25	34
pH		8.48	7.915	8.325	8.505	8.435	8.43	7-8.5
BOD	mg/L	1.838	1.206	2.067	1.298	1.672	1.617	20
DO	mg/L	6.86	6.68	6.84	6.995	7.195	7.085	5
Phosphate	mg/L	**0.189**	**0.206**	**0.258**	**0.206**	**0.155**	**0.086**	0.015
Nitrate	mg/L	**0.387**	**0.356**	**0.347**	**0.099**	**0.094**	**0.085**	0.06
Biological								
Total Coliform	MPN/100 mL	13	27	33	7.8	4.5	6.8	1000
PI Score		***4.75334***	***4.84556***	***5.19692***	***4.82457***	***4.37327***	***3.47375***	
Water Quality Status		***Slightly Polluted***	***Slightly Polluted***	***Moderately Polluted***	***Slightly Polluted***	***Slightly Polluted***	***Slightly Polluted***	

Permitted level source: National Regulation of the Republic of Indonesia No. 22/2021, Appendix VIII.

In the coastal area (B2–B4), several parameters exceeded the quality standards, including TSS, nitrate, and phosphate (see **Table 4**). Elevated TSS at station B2 is likely influenced by the nearby lagoon. The lagoon's sedimentary basin traps sediments transported by currents, increasing the solubility of suspended solid pollutants due to contributions from the mainland and estuary, along with current-induced movement (Erfando et al., 2023). This disruption in water circulation can lead to erosion or sediment accumulation, which affects the surrounding ecosystem. Increased nitrate and phosphate levels in coastal stations are likely caused by decomposing waste carried by river flow. The continuous release of organic waste contributes to nutrient buildup in the coastal areas (B2, B3, and B4), with concentrations decreasing toward the open sea (Indrayanti et al., 2022). This is consistent with (Feng et al., 2024), who noted that nutrient levels are typically higher near land due to terrestrial influences such as agricultural runoff, domestic waste, and industrial activity. Agriculture and residential settlements are the primary sources of pollution in the Sengkarang River.

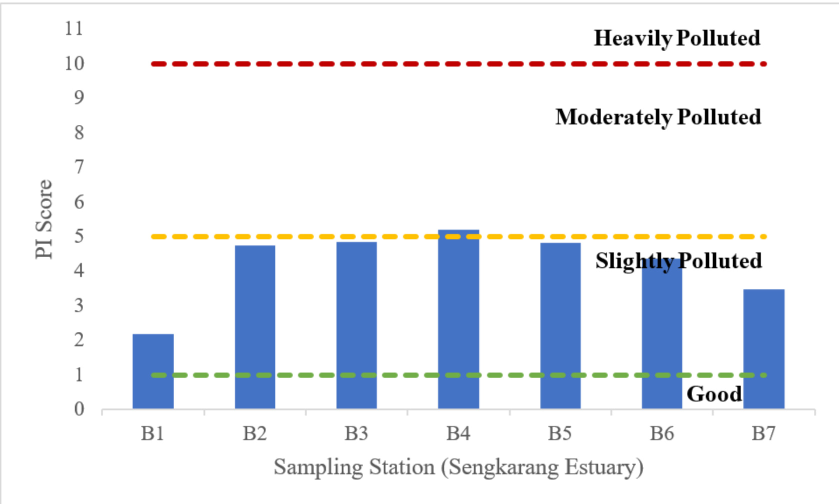

Fig. 3. Classification Ranges of PI Scores at Sengkarang Estuary.

4.3. Characterization and Evaluation of Water Pollution

4.3.1. Comparative Analysis of Pollution Index Between Estuaries

Water quality and pollution profiles were analyzed using several parameters: TSS, COD, BOD, DO, pH, salinity, phosphate, nitrate, and total coliform. The PI provides a single value summarizing water quality by integrating multiple parameters measured at a specific time and location. The coastal water quality assessment using the PI method for the Loji and Sengkarang estuaries is illustrated in **Fig. 4**. The results indicate that both estuaries fall into the "slightly polluted" to "heavily polluted" category, with varying PI scores across sampling points. The Loji Estuary shows higher pollution levels than the Sengkarang Estuary. This is attributed to various anthropogenic activities, including industrial discharge, domestic waste, and port operations, that heavily influence the Loji River mouth. According to data from the Environmental Agency of Pekalongan City, the amount of wastewater generated from domestic activities is 30,549.22 m³/day, corresponding to a population of 318,221 in 2024 (Dinas Lingkungan Hidup Kota Pekalongan, 2025). The estuary is also located near the Pekalongan Nusantara Fisheries Port, which functions as a boat mooring site and fish auction center and receives waste from fish processing activities. Intensive port activities can increase wastewater containing dissolved organic matter, nitrates, and phosphates.

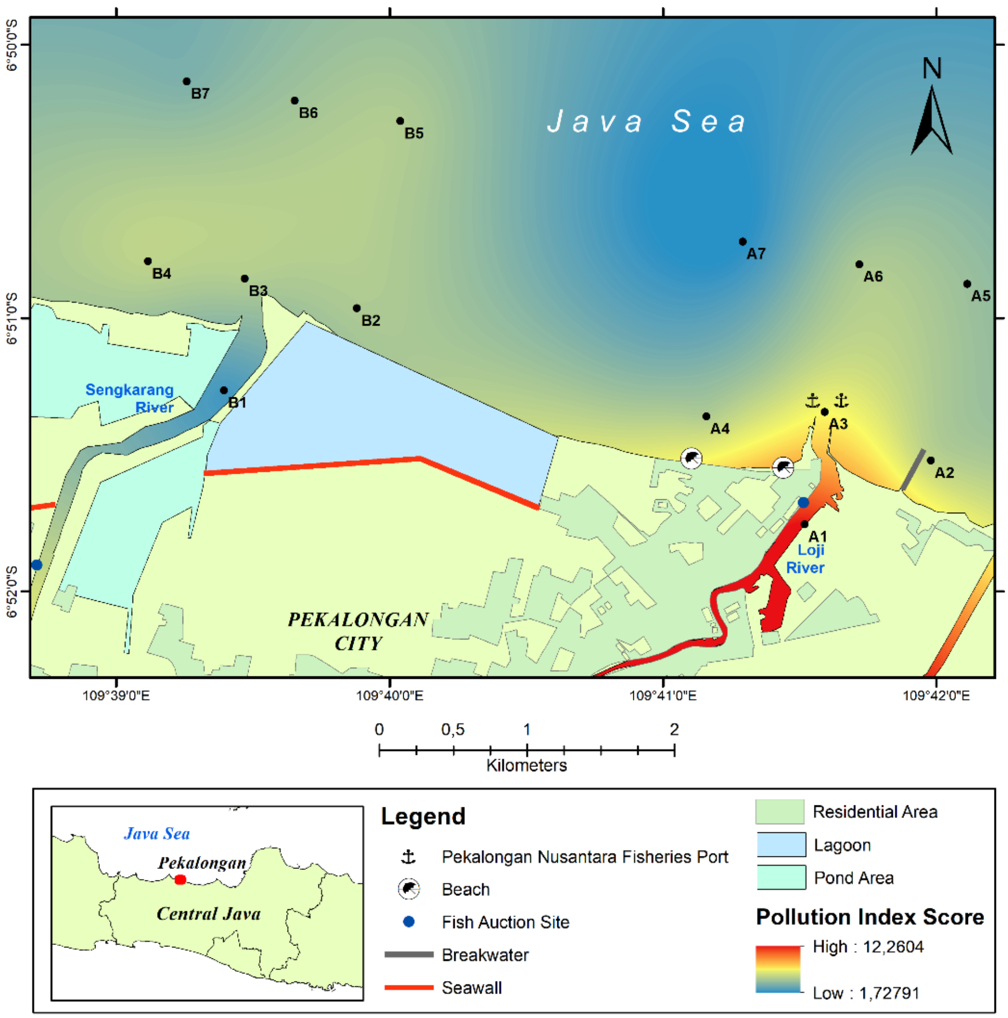

Fig. 4. Spatial distribution of Pollution Index for Loji and Sengkarang Estuaries.

Additionally, pollution input is amplified by household, agricultural, and industrial activities along the river that discharge waste into the estuary (Wardani et al., 2024). According to (I Patty et al., 2019), villages, ports, industrial areas, and river systems significantly contribute to marine waste, making the surrounding waters highly susceptible to pollution and water quality degradation.

4.3.2. Influence of Hydrodinamic Factors on Pollution Distribution

Pollutant distribution is also influenced by tides, which result from differences in gravitational forces arising from the Moon and Sun's changing positions relative to Earth's surface. The coastal area of Pekalongan has a mixed tidal type, consistent with the general tidal pattern on the north coast of Java (Windupranata et al., 2024). The highest high tide was 2.48 m, and the lowest low tide was 1.44 m. The tidal pattern is shown in **Fig. 5,** where the high-tide-to-low-tide transition dominates sampling. Under these conditions, river flow exceeds sea flow, resulting in the accumulation of organic matter in the estuary, which then moves offshore.

Tidal patterns can alter current direction. Based on modeling results, the current direction at the time of sampling was predominantly northwest, southwest, and southeast. Current speeds at high and low tide were lower than those between low and high tide, a phenomenon known as the slack-water effect (Shidqirrohman et al., 2024). As seen in **Fig. 6**, current speeds initially peaked northwestward during low tide to high tide, then decreased at 8:00 a.m. Western Indonesian Time (WIB), when the highest tide occurred, and the current direction turned landward. Subsequently, current speeds increased southeastward, affecting pollutant transport in the waters. This hydrodynamic condition plays a crucial role in shaping the spatial distribution of Pollution Index (PI) values across the study area. Higher PI values observed at coastal stations (A2-A4 and B2-B4) compared to open sea stations (A5-A7 and B5-B7) can be attributed to the proximity of these coastal sites to land-based pollution sources, including river discharge and anthropogenic activities. As the ebb tide progresses, pollutants accumulated in estuarine and nearshore zones are transported offshore by seaward-directed currents, leading to a gradual dilution effect with increasing distance from the coast, which is reflected in the lower PI values at offshore stations. This pattern also influenced pollutant distributions in offshore waters, with elevated levels at eastern stations such as A5, A6, and B5.

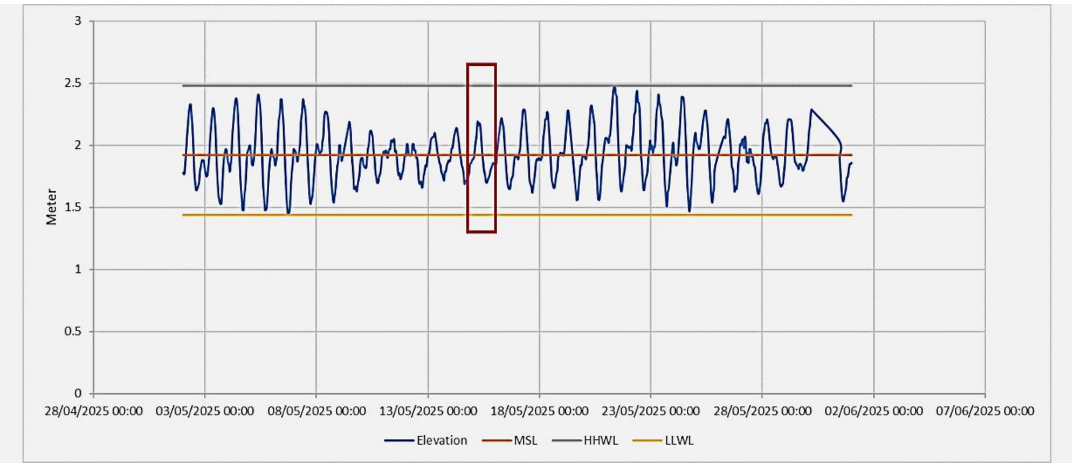

Fig. 5. Tidal Graph of Pekalongan Waters.

In addition to tides and currents, rainfall indirectly affects coastal water pollution through runoff and the transport of materials from upstream areas to estuaries and coastal waters. Stations located near river mouths, particularly A3 and B3, exhibited relatively elevated PI values, which may be influenced by antecedent rainfall prior to sampling. Rainfall can enhance surface runoff and mobilize pollutants from upstream catchments, subsequently increasing pollutant loads entering the estuarine environment. Rainfall levels several days before sampling are shown in **Fig. 7**.

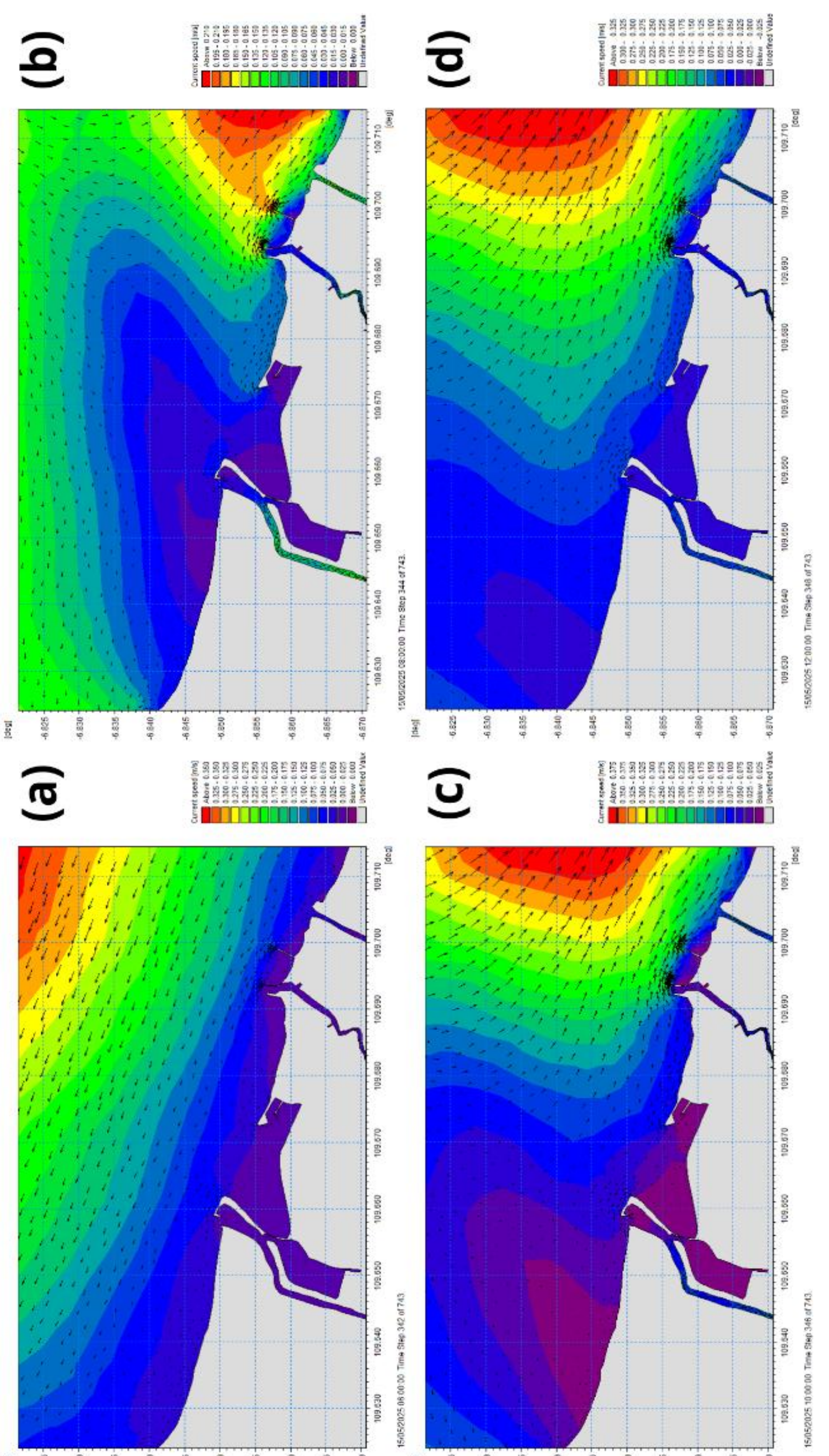

Fig. 6. Surface Current Patterns (a) 06.00 WIB, (b) 08.00 WIB, (c) 10.00 WIB, (d) 12.00 WIB.

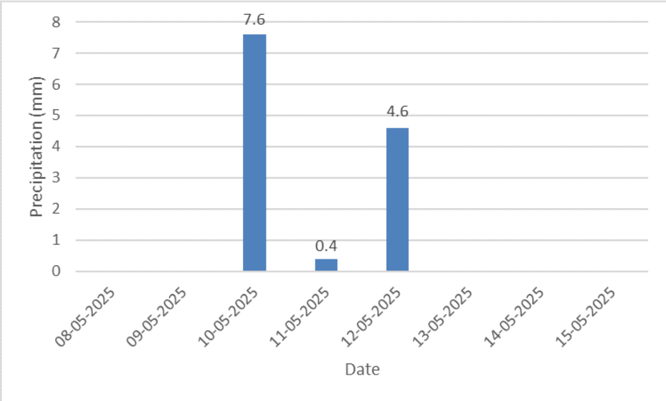

Fig. 7 Rainfall Levels Before the Sampling Period.

Even at relatively low intensities, rainfall events can dissolve and transport pollutants accumulated on land surfaces, in drainage channels, and in river bodies. This process is accumulative and has a time lag, so the impact of rainfall is not always immediately detectable on the day of the incident. Still, it may appear several days later in coastal areas. Furthermore, hydrodynamic conditions, such as relatively weak tides and currents during the transitional season, can slow dispersion, allowing pollutants carried from land to accumulate along the coast and increase pollution levels in that area. The combined effects of rainfall-driven inputs and tidal current transport therefore explain the observed spatial variability in PI values, highlighting the strong coupling between hydrodynamic processes and water quality conditions in the study area.

4.3.3. Key Pollution Parameters and Sources

In this study, the parameters TSS, phosphate, and nitrate exceeded coastal water quality standards. Elevated TSS levels are attributed to coastal development projects, such as ports, embankments, and breakwaters, which disrupt natural water flow and tidal movements, leading to sediment accumulation in nearby areas. Phosphate levels were consistently high across all locations. This increase is primarily caused by river runoff carrying organic waste−including detergents, human waste, and household cleaners−into the sea. These substances are major sources of phosphate and initiate biogeochemical processes involving the breakdown of organic matter. Nitrate levels also rose due to similar processes. The bacterial decomposition of organic matter in wastewater results in the formation of nitrate molecules. This process, referred to as nitrate output, contributes to water quality indices. The presence and activity of bacteria significantly influence nitrate concentrations, which are also linked to organic matter and sediment in the water. While biogeochemical processes are simplified in water quality calculations, they are more complex under natural conditions and vary by location and time.

Across all stations, nitrate concentrations were higher in coastal areas than in the open sea. Typically, nitrate levels are greatest near land and decrease with distance from shore (Adnina et al., 2023). This pattern reflects the influence of tides, currents, and bathymetry, which facilitate nitrate accumulation in coastal zones (Patanda et al., 2024; Zainuri et al., 2022). Nitrate distribution generally mirrors pollution patterns, with coastal areas exhibiting higher levels of both. The pollution pattern is highly concentrated in the coastal area and then decreases in the open sea following the current. In marine environments, nitrate is often the primary limiting nutrient in the nitrogen-to-phosphorus (N:P) ratio, a key indicator of algal bloom potential (Feng et al., 2024). While elevated nutrient levels can enhance phytoplankton growth and fish production, they also pose risks, including oxygen depletion and the proliferation of harmful algal blooms.

4.3.4. Regional Comparison and Study Limitations

The novelty found in this study is the distributions of all variables were concentrated in the coastal area and decreased in the land during the sea level rise (high tidal flood) compared to the (Zainuri et al., 2022) result. These previous studies demonstrated a distribution related to the land elevation which are not limited by the presence of embankment. The limitation of pollution distribution identified by the application of the pollution index and resulting a narrow scale of the pollution values. A significant limitation of this study is the reliance on a single sampling campaign conducted in May 2025. Water quality in estuarine and coastal environments exhibits pronounced seasonal variability, driven by changes in rainfall and hydrodynamic conditions. May represents a transitional period between the wet and dry seasons in Indonesia, which may not fully capture annual water quality conditions. Future studies incorporating multi-seasonal sampling and relevant meteorological and hydrological data, with emphasis on precipitation rate and period, are recommended to improve the robustness of the conclusions. Another limitation of this study is the lack of quantitative data on wastewater discharge volumes and pollutant loads from each source, such as fishing ports, agriculture, and aquaculture. The absence of sector-specific discharge data limits the applicability of quantitative source-identification analyses. Consequently, pollution sources are discussed qualitatively, drawing on land-use information, spatial patterns in water-quality parameters, and supporting evidence from prior research. Future studies that integrate discharge measurements, pollutant load estimation, and source identification modeling are recommended to strengthen causal attribution.

High pollution levels are not unique to the Pekalongan coast but are also observed in various areas surrounding the Java Sea. To place the findings of this study in a broader national context, **Table 5** presents pollution levels reported for several Indonesian coastal regions. It should be noted that the pollution levels presented in Table 5 were derived from different studies that employed varying sets of water quality parameters, pollution index formulations, and reference standards. Differences in study periods, seasonal conditions, sampling times, and spatial coverage may also influence the reported pollution status. Therefore, the comparison in **Table 5** is intended to provide a qualitative overview of pollution conditions in several Indonesian coastal areas rather than a direct quantitative comparison.

Pollution levels are reported using the original methodologies and reference standards employed in each study and are qualitatively compared to illustrate general pollution patterns across Indonesian coastal regions. In general, these areas experience pollution primarily due to human activities such as industrial operations, fishing, port activity, agriculture, and residential development. Inadequate waste management significantly contributes to rising pollution levels (Tosepu & Umu Nasibah, 2025). Additionally, climate change-related factors—such as sea level rise and marine heatwaves—further increase the vulnerability of coastal waters (Senarathna Atapaththu et al., 2025). Pollution in coastal areas endangers both the marine ecosystem and the well-being of the surrounding communities. Without effective mitigation, this ongoing pollution poses serious risks to coastal ecosystems and may lead to long-term environmental degradation. A multidisciplinary approach is recommended to foster effective dialogue among researchers, environmental advocates, and stakeholders for the sustainable management of coastal ecosystems.

Table 5

Pollution Levels in Several Coastal Regions of Indonesia.

Study Sites	Pollution Level	Sources
West Java, North Bekasi, and Indramayu Coasts	Slightly polluted	(Patanda et al., 2024)
Banten, Banten Bay	Slightly to moderately polluted	(Adnina et al., 2023; Dafitri et al., 2025; Rahmania et al., 2024)
Lampung, Ketapang Beach	Moderately polluted	(Delis et al., 2024)
South Kalimantan, Kusan Estuary	Moderately polluted	(Zainudin et al., 2024)

5. CONCLUSIONS

The PI values for the Loji and Sengkarang estuaries indicate that both fall into the polluted category, with varying scores across sampling points. Pollution levels in the Loji Estuary are generally higher than those in the Sengkarang Estuary, primarily due to anthropogenic influences such as industrial discharge, household waste, and port-related activities. Coastal areas also show higher pollution levels compared to open sea zones. Similar patterns are observed in other coastal regions around the Java Sea. Pollution in these areas largely originates from human activities, including industrial operations, fishing, port infrastructure, agriculture, and residential development. The findings of this study provide valuable insights for stakeholders to recognize the environmental impact of industries located near water bodies that discharge waste into rivers and, ultimately, the ocean. This study serves as a baseline assessment, highlighting the need for more extensive future studies to explore additional influencing factors. A comprehensive and cooperative approach is essential for fostering a healthy and sustainable coastal ecosystem.

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