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Epipelic Diatom Communities as Bioindicators of Environmental Conditions in Karangjahe Coastal Sediments, Central Java

Mirza Hanif Al Falah[a,d], Muhammad Ilham Jasir[b,d], Tri Retnaningsih Soeprobowati[b,d*], Jumari Jumari [b,d], Łukasz Kruszewski [c,d]

[a] Faculty of Biology, Universitas Gadjah Mada, Yogyakarta, Indonesia
[b] Department of Biology, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Indonesia
[c] Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland
[d] Cluster for Paleolimnology, Universitas Diponegoro, Semarang, Indonesia

*Corresponding author: mirzahanif@ugm.ac.id

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Abstract
Coastal ecosystems at Karangjahe Beach, Rembang, are under increasing pressure from tourism activities and terrestrial runoff. This study aims to analyze epipelic diatom communities as bioindicators of the local environmental health. Sampling was conducted on September 12, 2024, across four stations with distinct environmental characteristics. The results identified a diatom composition comprising 24 families, 45 genera, and 79 species, with a total cumulative abundance of 20,535 ind.gr^{-1}. Station KJ.1, located at an old pier, recorded the highest abundance, while station KJ.2, a recreational playground area, exhibited the lowest. The Shannon-Wiener Diversity Index (H') ranged from 1.5 to 3, indicating moderate community stability. Physicochemical analysis revealed that dissolved oxygen (DO) levels at all sites (2.8–3.6 mg/L) fell below the regulatory minimum of 5 mg/L, indicating environmental stress. This study concludes that the structure of the epipelic diatom community at Karangjahe Beach is significantly shaped by a combination of natural factors, including salinity and substrate type, as well as anthropogenic influences from tourism and aquaculture, with the bioindicator signal primarily driven by key taxa such as *Pseudoplanothidium delicatulum* and *Cyclotella meneghiniana*.

Keywords: Benthic diatoms, Bioindicator, Central Java, Epipelic diatom, Water quality.

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1. Introduction

Coastal ecosystems serve as a critical estuarine-limnological transition zone receiving freshwater terrestrial inputs, playing a pivotal role in global nutrient cycling and carbon sequestration processes (Anu *et al.,* 2024). These regions are increasingly vulnerable to anthropogenic pressures, including industrial discharge and intensive agricultural runoff, which introduce high concentrations of nitrogen and phosphorus into nearshore waters (Tan *et al.,* 2017). In Indonesia, the North Coast of Central Java is particularly susceptible to these stressors due to high population density and rapid land-use changes. Traditional chemical monitoring often fails to capture the long-term ecological shifts driven by these pollutants, as it provides only a snapshot of the water column's condition at the time of sampling (Facca *et al.,* 2014). Consequently,

biological indicators such as diatoms are increasingly utilized to provide a time-integrated reflection of environmental health (Choirul *et al.,* 2025).

Diatoms (Bacillariophyceae) are uniquely suited for environmental assessment due to their ubiquity and rapid response to changes in water chemistry, including salinity, pH, and nutrient availability (Rodríguez-Miret *et al.,* 2025). Their silicified cell walls, or frustules, allow for precise taxonomic identification and can be preserved in sediments for long-term ecological studies (Facca *et al.,* 2014). Benthic diatoms, particularly the epipelic community inhabiting surface sediments, are effective bioindicators in coastal systems (Facca *et al.,* 2014). Unlike planktonic species, which are dispersed by tides and currents, epipelic diatoms are relatively sedentary and remain in direct contact with the substrate, where pollutants often accumulate (Tan *et al.,* 2017). This close association with the benthos allows them to reflect the cumulative effects of environmental stressors over several weeks, providing a more robust measure of ecosystem stability than transient chemical measurements (Anu *et al.,* 2024).

Anthropogenic eutrophication is a primary driver of change in coastal diatom assemblages, often resulting in significant shifts in species composition and diversity (Xu *et al.,* 2022). In river basins influenced by agricultural runoff, nitrogen and phosphorus gradients have been shown to favor pollution-tolerant taxa over sensitive species, thereby altering the functional structure of the aquatic food web (Carpenter, 2005). Recent research has also demonstrated that diatoms can serve as reliable indicators even in highly variable or ephemeral environments, detecting subtle ecological shifts that other biological proxies might miss (Rühland *et al.,* 2003). However, the successful application of these indices in tropical environments requires careful calibration, as tropical coastal taxa may exhibit different environmental optima and tolerance ranges compared to those documented in temperate European or North American waters (Chevalier *et al.,* 2020).

Despite the recognized value of diatoms in global biomonitoring, a significant research gap persists regarding coastal ecosystems in Indonesia, particularly the North Coast of Central Java. Historical limnological studies in this region have focused predominantly on inland freshwater systems, such as the high-altitude lakes of the Dieng Plateau (Sari *et al.,* 2021) or major river systems like the Tuntang River (Al Falah *et al.,* 2025), often emphasizing planktonic or subfossil assemblages. While these studies have advanced our understanding of paleolimnology and riverine water quality, the epipelic diatom communities in coastal surface sediments along the "Pantura" (North Coast) line remain largely undocumented. Current environmental assessments in the Rembang area typically rely on physico-chemical parameters or macro-biota, which lack the high-resolution sensitivity needed to identify early-stage ecological degradation.

Karangjahe Beach in Rembang represents a critical ecological and economic zone, facing simultaneous pressures from tourism and land-based runoff. Establishing a biological baseline through the study of epipelic diatoms is essential for the sustainable management of this coastal ecosystem. This research aims to address the gap by analyzing the community structure of epipelic diatoms in relation to local environmental variables. By documenting the species diversity and abundance in these surface sediments, the study provides the necessary data to calibrate diatom-based indices for tropical coastal monitoring (Facca *et al.,* 2014). Ultimately, this work contributes to a more precise, biology-based framework for environmental management in Indonesia, facilitating climate resilience and long-term ecosystem health. Therefore, the primary objective of this original research is to explicitly analyze the community structure and abundance of epipelic diatoms as bioindicators of environmental conditions along the Karangjahe coastal sediments.

2. Methods

2.1 Field work

The sampling was carried out on September 12, 2024, to capture environmental variables during the dry season. Site selection utilized a purposive sampling technique based on local environmental characteristics and proximity to anthropogenic activities. Four distinct sampling stations were established:

a. Station K.J.1 was situated on the western shoreline at an old pier, near marine waters.

b. Station K.J.2 was positioned on the eastern shoreline, specifically within a children's playground area near the coastal waters.
c. Station K.J.3 was located to the west, outside the main beach zone, characterized by salt and milkfish (Chanos chanos) ponds; this site was distant from the open sea but adjacent to brackish water channels.
d. Station K.J.4 was situated to the east, outside the beach area, within a pond environment (Figure 1).

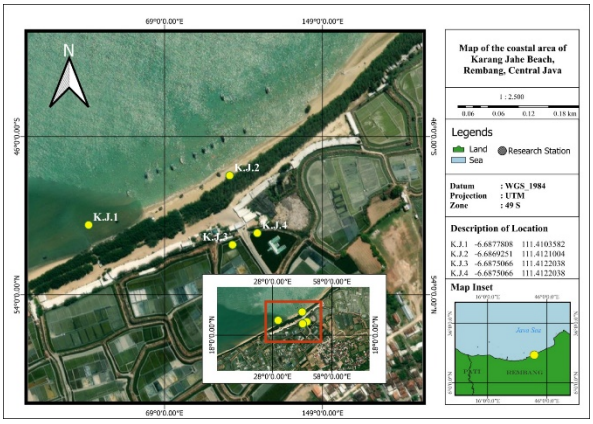


Figure 1. Sampling point location

Surface sediment samples representing recent, active epipelic communities (specifically the top 5 cm of the surface sediment) were collected using a shovel and subsequently stored in sterile zip-lock plastic bags for further analysis. Substrate classification at each station was determined based on direct visual observations in the field. The physicochemical parameters of the water were measured in situ using a Horiba U-50 multiparameter water quality checker. To ensure data precision and accuracy, all measurements were performed in triplicate. While periphytic diatoms are strongly influenced by the availability of light and nutrients, these parameters were not measured during this study, representing a limitation that should be addressed in future ecological assessments.

2.2 Sediment Analysis

A 10-g sediment sample was weighed and then digested. This involved heating the sediment with 50 mL of 10% HCl and 50 mL of 10% H_2O_2, following the procedure described by Soeprobowati *et al.* (2017). The treated samples were allowed to settle for 6–8 hours, after which the supernatant was replaced with distilled water. This washing process was repeated eight times until the samples reached a clear appearance.

For slide preparation, a 400 µL aliquot of the residue was transferred onto a coverslip using a micropipette and permanently mounted with Naphrax®. The prepared slides were examined under a light microscope at 1000× magnification. Observed diatom valves were documented using a digital camera and identified based on taxonomic guides, including Gell *et al.* (1999), Sonneman *et al.* (2000), Krammer & Lange-Bertalot (2004), and Taylor *et al.* (2007), as well as online databases such as Diatoms of North America (diatoms.org), AlgaeBase, and DiatomBase.

2.3 Data Analysis

Diatom community metrics, including diversity, dominance, and evenness indices, were calculated using PAST software version 5.3. In addition to the biological data, physicochemical water quality parameters were recorded, including temperature, pH, electrical conductivity (EC), salinity, dissolved oxygen (DO), and total dissolved solids (TDS).

3. Results and Discussion

3.1 Water Quality Measurement

The water quality assessment in the Karangjahe coastal area included measurements of pH, temperature, conductivity, dissolved oxygen (DO), salinity, and total dissolved solids (TDS). The results obtained from stations K.J.1 through KJ.4 varied, as summarized in Table 1.

Table 1. Water Quality Parameters in the Karangjahe Coastal Area

No	Parameter	Unit	Station			
			KJ.1	KJ.2	KJ.3	KJ.4
1	Temp.	°C	31.4	33.1	31.9	32.1
2	pH	-	6.8	7.4	7.8	7.4
3	Conductivity	mS/cm	36.7	32.2	24.2	31.0
4	Salinity	ppt	23.3	25.8	14.0	21.0
5	DO	mg/L	3.6	2.8	3.4	3.3
6	TDS	g/L	21.8	24.6	13.1	19.8

The physicochemical characteristics of the Karangjahe coastal waters exhibit significant spatial variations across the four sampling stations, influenced by both natural marine dynamics and localized anthropogenic activities. Based on the in-situ measurements, the surface water temperature ranged from 31.4°C to 33.1°C, with the highest recorded value at Station K.J.2, likely due to its shallow nature in a recreational playground area where solar heating is more intense. These thermal conditions generally align with previous observations by Murhandini *et al.* (2022), who noted that stable weather patterns in Karangjahe often result in uniform temperature distributions within the optimal range for supporting diatom life cycles. However, the acidity levels fluctuated between pH 6.8 at K.J.1 and 7.8 at K.J.3, indicating a transition from slightly acidic to alkaline conditions. While pH values between 7 and 8.5 are typically considered optimal for aquatic organisms (Astrini *et al.,* 2014), the lower pH at the old pier (K.J.1) suggests the presence of organic decomposition or terrestrial runoff that slightly acidifies the immediate environment.

Salinity and dissolved solids also displayed distinct patterns, with salinity peaking at 25.8 ppt at K.J.2 and reaching a minimum of 14.0 ppt at K.J.3. The significant drop in salinity at K.J.3 is a direct consequence of its location near salt and milkfish (*Chanos chanos*) ponds, where brackish water inflow dilutes the marine salts. In contrast, higher salinity at the shoreline stations (K.J.1 and K.J.2) is driven by high evaporation rates, as elevated temperatures concentrate dissolved salts in the surface water (Nontji, 2007). Total Dissolved Solids (TDS) followed a nearly identical trend, peaking at 24.6 g/L at K.J.2, which confirms the strong influence of seawater chemical compounds and evaporation on the coastal sediment-water interface. These variations in salinity and depth are known to be primary drivers of habitat heterogeneity in coastal ecosystems, as described by Sidabutar *et al.* (2019).

The most critical indicators of environmental stress in Karangjahe were dissolved oxygen (DO) and conductivity levels. DO concentrations ranged from 2.8 to 3.6 mg/L, consistently failing to meet the minimum regulatory threshold established by Government Regulation (PP) No. 22 of 2021, Appendix VIII, specifying seawater quality standards for marine biota. The lowest DO was recorded at K.J.2, suggesting that high visitor activity in the playground area may increase organic loading and biological oxygen demand. Conductivity reached its maximum of 36.7 mS/cm at K.J.1,

indicating a high concentration of dissolved ions potentially originating from both marine salts and anthropogenic runoff near the pier infrastructure.

As noted by Yu *et al.* (2017), high conductivity can shift pH toward more acidic levels, potentially reducing the abundance of sensitive aquatic taxa. Overall, while parameters such as temperature and TDS remain within acceptable limits for ecotourism (Muhammad *et al.*, 2020), suppressed DO levels and localized conductivity spikes suggest that a combination of tourism-related waste, aquaculture runoff, and coastal infrastructure is impacting Karangjahe's coastal health.

3.2 Diatom Composition and Community Structure

Based on the research findings, the diatom composition in the study area comprises 24 families, 45 genera, and 79 species. These specimens were collected from four sampling stations (K.J.1, K.J.2, K.J.3, and K.J.4) within a single location, each characterized by distinct substrate conditions and varying levels of anthropogenic Diatom abundance revealed the presence of several genera, including *Achnanthes, Achnanthidium, Amphipleura, Amphora, Biremis, Caloneis, Cavinula, Chamaepinnularia, Cocconeis, Coscinodiscus, Cyclostephanos, Cyclotella, Cymbella, Diadesmis, Diatoma, Diploneis, Encyonema, Encyonopsis, Eolimna, Epithemia, Eunotia, Fallacia, Fragilaria, Frustulia, Geissleria, Halamphora, Haslea, Mastogloia, Navicula, Neidium, Nitzschia, Nupela, Oricymba, Pinnularia, Planothodium, Platessa, Psammodictyon, Rhoicosphenia, Rossithidium, Sellaphora, Seminavis, Stauroforma, Stephanocyclus, Stephanodiscus, Surirella, Synedra, Tabellaria,* and *Ulnaria*. Among these, the most taxonomically diverse genera observed were *Cocconeis, Diploneis, Encyonema, Fragilaria, Frustulia, Halamphora,* and *Navicula*.

The relative abundance values across the Karangjahe coastal area exhibited significant variation. Analysis of family distribution showed percentages ranging from 4% to 19% (figure 2). These families were consistently identified across all sampling stations. The presence of these taxa is characteristic of marine environments; however, this study also identified a mixture of freshwater and marine species at all sites. This co-occurrence is likely attributed to brackish water currents flowing from west to east between the sampling points. As noted by Sudinno *et al.* (2015), brackish water pond areas experience continuous fluctuations throughout the year due to varying salinity levels and environmental inputs.

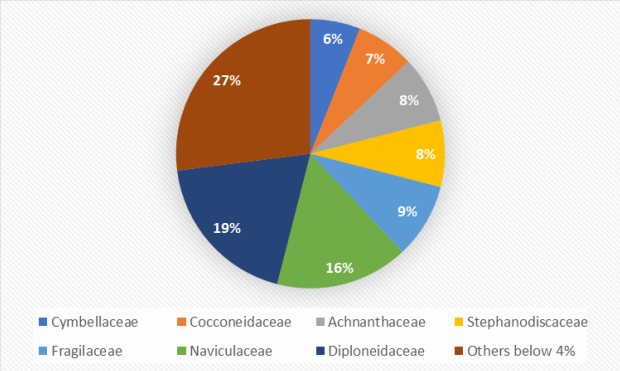


Figure 2. Relative abundance of diatom families found in Karangjahe Beach

The abundance of diatom species varied considerably, ranging from 139 to 1,526 ind.gr^{-1}, with a cumulative abundance of 20,535 ind.gr^{-1}. Station K.J.1 recorded the highest abundance (5,828 ind.gr^{-1} with 29 species), followed by K.J.4 (5,689 ind.gr^{-1} with 18 species) and K.J.3 (5,550 ind.gr^{-1} with 31 species). The lowest abundance was observed at station K.J.2 (3,469 ind.gr^{-1} with 12 species).

These fluctuations are likely driven by the distinct anthropogenic functions and substrate types at each site. Stations K.J.1 (an old pier) and K.J.2 (a tourist recreation area) consist of wet sandy

substrates near the open sea. In contrast, K.J.3 (salt ponds) and K.J.4 (fishponds and floating restaurants) feature silty-sand substrates further from the coastline but adjacent to brackish flows. Rozalina (2020) suggests that ocean currents significantly influence the distribution of silicate, a vital nutrient for diatom frustule development. Furthermore, Sitindoan (2020) emphasizes that sediment types serve as critical habitats for benthic organisms, such as epipelic diatoms, thereby directly affecting organic matter content.

Environmental parameters, particularly salinity, play a crucial role in shaping these communities. At Karangjahe, salinity levels fluctuated across sampling sites, indicating that the diatoms were euryhaline or polyhaline organisms. According to Kordi (1996), water salinity can be classified into oligohaline (0–5 ppt), mesohaline (6–29 ppt), and polyhaline (30–40 ppt). Fitriyah et al. (2016) noted that marine diatoms are prevalent in coastal areas and ponds near the sea, where they adapt to high salinity by maintaining osmotic balance. This adaptability is supported by Barsanti and Gualtieri (2006), who define euryhaline types as those capable of surviving within wide salinity ranges, which is essential for growth and distribution.

Species-specific dominance also varied by station. At K.J.1, *Pseudoplanothidium delicatulum* (1,526 ind.gr^{-1}) was dominant, thriving in the coastal habitat with a pH of 6.8 and salinity of 23.3 ppt. The high salinity at this site is likely intensified by high evaporation rates driven by temperatures reaching 31.4°C, a phenomenon described by Nontji (2007). Zong and Hasan (2004) and Van de Vijver *et al.* (2018) confirm that *P. delitcatulum* (the former name was *Achnanthes delicatula*) is a widespread species in brackish and marine environments, often associated with sandy substrates.

At K.J.2, *Cyclotella meneghiniana* (971 ind.gr-1) and *Cocconeis fluviatilis* (555 ind.gr^{-1}) were most prevalent. Kulikovsky *et al.* (2022) and Hevia *et al.* (2016) note that *C. meneghiniana* can tolerate a wide range of salinity (up to 30 ppt) and pH levels. Pienitz *et al.* (2000) further classify it as a species that favors oligotrophic to eutrophic conditions. *Cocconeis fluviatilis* is similarly recognized for its salt tolerance and preference for warm, shallow, brackish waters (Zalat *et al.*, 2010; Costa *et al.*, 2020).

Stations K.J.3 and K.J.4 were dominated by *Stauroforma exiguiformis* (555 ind.gr^{-1}) and *Nupela neglecta* (1,110 ind.gr^{-1}), respectively. Although these are typically freshwater species, their presence in these brackish pond areas indicates high tolerance to varying conductivity and salinity.

Potapova (2014) and Talgatti *et al.* (2014) report that *S. exiguiformis* can survive in salinities up to 30 ppt and a wide range of conductivity. Similarly, *N. neglecta* is known for its resilience to fluctuations in pH and conductivity (Potapova *et al.*, 2003; Blanco *et al.*, 2020). The substrate further influences the abundance of these species; silty-sand substrates at these sites tend to accumulate higher organic matter compared to the fine sand at K.J.1 and K.J.2 (Handayani *et al.*, 2016).

When compared to established broad-scale diatom biological metrics, these epipelic diatom assemblages mirror the degradation signals often captured by indices such as the OMNIDIA SLA (Sládeček's index) and DESCY, pointing to a functional shift toward pollution-tolerant euryhaline taxa due to regional eutrophication.

Community structure was further evaluated using diversity indices. The Shannon-Wiener Diversity Index (H'') at all stations ranged between 1.5 and 3, indicating moderate community stability and diversity (figure 3). Supono (2016) suggest that moderate H'' values reflect a balanced distribution where no single species completely dominates, though environmental stressors can shift this balance. The Evenness Index (e) ranged from 0.7 to 0.9, approaching 1.0, indicating that species were distributed relatively uniformly across the stations and that competition for resources was minimal (Choirun *et al.*, 2015) (figure 3). Conversely, the Dominance Index (C) remained low, ranging from 0.04 to 0.14 ($0 < C < 0.5$), confirming the absence of strong dominance by any single taxon across the Karangjahe coastal area (figure 3). In summary, the principal findings

underscore that while diatom diversity remains moderately stable, the prominence of specific stress-tolerant taxa vividly illustrates the compounding impacts of aquatic deoxygenation and varied salinities along the transition zone.

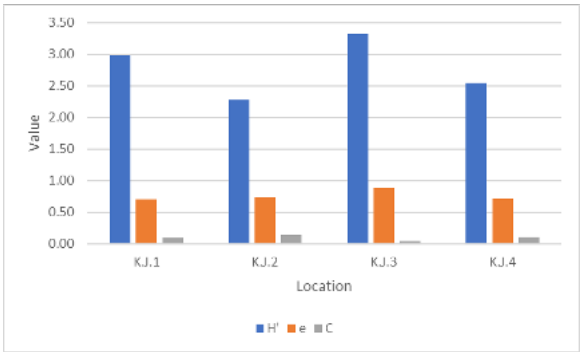


Figure 3. Community structure of diatom in Karangjahe Beach represent ecosystem condition.

4. Conclusion

This research demonstrates that epipelic diatoms, particularly euryhaline taxa like *Pseudoplanothidium delicatulum* and *Cyclotella meneghiniana*, serve as robust and highly sensitive bioindicators of environmental stress along tropical estuarine-limnological transition zones. The significant spatial variations in community structure and abundance across Karangjahe Beach highlight the profound ecological implications of overlapping natural marine dynamics and anthropogenic nutrient loading from coastal tourism and aquaculture. Although parameters like temperature and pH remained within acceptable ranges, the chronic suppression of dissolved oxygen (DO) below regulatory thresholds signals an urgent need for intervention. For the sustainable management of tropical coastal interfaces, future research should prioritize seasonal tracking to account for monsoon variations, direct nutrient flux analysis, and the rigorous calibration of ecological optima specifically for Indonesian coastal taxa. Incorporating these standardized, biology-based monitoring frameworks will be crucial for preserving long-term climate resilience and mitigating ecological degradation in the region.

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6. Conflict of Interest Declaration

The authors declare that there is no conflict of interest regarding the publication of this article. The Authors confirmed that the paper was free of plagiarism.

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Muhammad Ilham Jasir			✓		✓	✓		✓	✓		✓			

Tri Retnaningsih Soeprobowati	✓	✓		✓	✓		✓		✓		✓	✓
Jumari Jumari				✓		✓			✓		✓	
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About Author(s)

Dr. Mirza Hanif Al Falah, S.Si., M.Ling, is a lecturer at the Faculty of Biology, Universitas Gadjah Mada, Yogyakarta, Indonesia, where he focuses on limnology, diatom bioindicators, and aquatic ecosystem conservation. Scopus ID: 58111720600

Muhammad Ilham Jasir, S.Si., is a biology researcher and graduate from the Faculty of Science and Mathematics, Universitas Diponegoro, specializing in biological analysis, environmental sampling, and aquatic ecosystem dynamics.

Prof. Dr. Tri Retnaningsih Soeprobowati, M.App.Sc., is a Professor in the Department of Biology

and Founder of the Cluster for Paleolimnology (CPalim) at Universitas Diponegoro, Semarang, Indonesia. Scopus ID: 55339731500

Dr. Jumari, S.Si., M.Si., is a lecturer and researcher in the Department of Biology, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Indonesia, specializing in ethnobotany, plant ecology, plant taxonomy, and biodiversity conservation. Scopus ID: 59973541600

Assoc. Prof. Łukasz Kruszewski, Ph.D. is an Associate Professor at the Institute of Geological Sciences of the Polish Academy of Sciences (ING PAN), Warsaw, Poland, specializing in mineralogy, trace-element geochemistry, crystallochemistry, and secondary processes associated with coal fires in burning mining waste heaps. Scopus ID: 35113509300