

Copper and Lead Contamination in Sediment and Benthic Ecosystems of Sembilang National Park's Coastal Region, South Sumatra

Rozirwan^{1*}, Dio Alif Ananta¹, Nadila Nur Khotimah², Wike Ayu Eka Putri¹, Fauziyah¹, Gusti Diansyah¹, Yusni Ikhwan Siregar³, Ramses⁴, Isnaini¹, Melki¹, Riris Aryawati¹, Fitri Agustriani¹, Redho Yoga Nugroho¹

¹Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indralaya, 30862, Indonesia

²Doctoral Program of Environmental Science, Postgraduate Program, Universitas Sriwijaya, Palembang, 30139, Indonesia

³Department of Marine Science, Faculty of Fisheries and Marine Science, Universitas Riau, Pekanbaru, 28293, Indonesia

⁴Department of Biology Education, Teacher Training and Education Faculty, Riau Kepulauan University, Batam, 29422, Indonesia

*Corresponding author: rozirwan@unsri.ac.id

Abstract

Littoral zone often face environmental pressure due to anthropogenic activities, which can impact the quality of their ecosystem. This study analyzes the concentrations of copper (Cu) and lead (Pb) in sediments and benthic (*Anadara granosa* and *Cerithidea cingulata*). Sampling procedures were implemented during September 2022 across the aquatic habitats of Sembilang National Park, in South Sumatra Province, using the purposive sampling method. Sediment grain size and substrate type were analyzed using Shepard's triangle. Metal detection using a spectrophotometric method based on atomic absorption. The results showed that the sediment fraction mostly consisted of clay, ranging from 92.03% to 94%. Cu concentrations in the sediment ranged from 5.01 ± 0.017 to 5.71 ± 0 mg/kg, while Pb concentrations ranged from 10.5 ± 0.195 to 11.51 ± 0.395 mg/kg. In the benthic, Cu concentrations ranged from 0.0037 ± 0.00005773 to 0.0147 ± 0.00000346 mg/kg, and Pb concentrations ranged from 0.0001 ± 0.000227 to 0.005 ± 0 mg/kg. According to the statistical evaluation testing via independent sample t-test showed that heavy metals differed significantly ($p < 0.05$) between sediment and benthic compartments. These results show that the environmental quality in Sembilang National Park is still comparatively well maintained and within current quality requirements, despite certain activities that have the potential to pollute the environment. To guarantee the long-term viability of this area, it is advised that environmental quality be frequently monitored as a mitigation action.

Keywords

Benthic, Bioaccumulation, Heavy Metals, Sediment, National Sembilang Park

Received: 10 February 2025, Accepted: 25 May 2025

<https://doi.org/10.26554/sti.2025.10.3.866-876>

1. INTRODUCTION

The sustained presence of human-induced activities in nearshore environments results in pollutant production (Rozirwan et al., 2024b; Elliott and Kennish, 2024). Heavy metals, microplastics, pesticides, and other harmful organic compounds are frequently found as pollutants (Carvalho Ferreira and Lôbo-Hajdu, 2023; Khotimah et al., 2024; Charlena et al., 2025). Heavy metals are a type of pollutant with toxic and non-degradable properties that can cause negative effects on species inhabiting water bodies and humans throughout the organismal feeding sequence (Briffa et al., 2020; Mitra et al., 2022; Zaynab et al., 2022). Metals suspended in the water column are gradually deposited into the underlying sediments (Sankhla et al., 2019). Sediment then become the main accumulation place for heavy metals that can persist for a long time and potentially

disrupt the balance of coastal ecosystems (Lv et al., 2021; Han et al., 2024). The incorporation of heavy metals into sediments primarily occurs through a range of physicochemical mechanisms, such as adsorption and desorption dynamics, redox reactions, and precipitation–dissolution (Dan et al., 2022; Miranda et al., 2022). As species adapted to life on or within the substrate of aquatic ecosystems, benthic communities are very vulnerable to contamination of these heavy metals (Dong et al., 2021; Li et al., 2024). Benthic fauna are capable of assimilating and bioaccumulating heavy metals originating from sediment deposits (Liu et al., 2017). Elevated levels of heavy metals detected in benthic organisms not only impacts their health but also leads to alterations in the ecological framework of benthic populations, ultimately disrupting the aggregate function of the coastal ecosystem (Oron et al., 2021; Korejwo et al., 2022).

Quantification of heavy metal presence and their impact

in littoral zones have shown significant impacts on environmental health and aquatic organisms. Previous studies have demonstrated that heavy metals like Cu and Pb can accumulate in sediments and benthic organisms, altering ecosystem structure and functionality (Roziwan et al., 2023b; Angon et al., 2024). Previous studies have demonstrated that contamination by heavy metals can alter the structure of benthic communities and lead to the degradation of critical mangrove habitats (Roziwan et al., 2023d). Anthropogenic activities can cause pollutant accumulation in the northeast and threaten benthic foraminifera growth and reproduction to reach the lowest level (Cong et al., 2022). Previous studies in the Taihu Basin, China, revealed that certain environmental variables play a dominant role in shaping benthic communities are the presence of arsenic (As) and copper (Cu). The study found that the abundance and biomass of *Oligochaeta* serve as potential indicators to appraise the ecological impact associated with heavy metal presence in the local environment (Bian et al., 2016). Similar to urbanization, the construction of land-based and marine aquaculture operations in Laoshan Bay (Yellow Sea, China) also produces heavy metal pollutants that impact commercially valuable species such as fish, shellfish, and seaweed (Dong et al., 2023). Studies on the bioaccumulation of heavy metals in various coastal areas show that benthic organisms are often early indicators of pollution (Lukhabi et al., 2024). In agreement with the perspective of Jayachandran et al. (2022), benthic communities are in a strategic position to absorb pollutants from sediments and transfer them to higher trophic levels.

Existing literature addressing the presence of heavy metals in coastal ecosystems have primarily focused on pollution levels, sources, and general ecological impacts (Chormare and Kumar, 2022; Chahouri et al., 2023). However, limited research has specifically examined the bioaccumulation of Cu and Pb in both sediments and benthic organisms within a designated conservation area such as Sembilang National Park. This study provides a novel contribution by integrating bioaccumulation analysis with an ecological risk assessment, offering a thorough evaluation of how heavy metal pollution affects the structural complexity and ecosystem functions of benthic assemblages in a protected shoreline habitat (Liu et al., 2020; Fadlillah et al., 2023). The Sembilang National Park Coast is included as a conservation area (Silvius et al., 2016; Fauziyah et al., 2023). Sembilang National Park is a protected area with the main objective of conserving biodiversity and maintaining important ecosystem functions (Roziwan et al., 2022, 2023b). Protected zones frequently serve as habitats for numerous endangered species and have ecosystems that are very vulnerable to disturbance (Pulido-Chadid et al., 2023; Wu et al., 2023). Furthermore, this research highlights the potential threats posed by anthropogenic activities near conservation areas (Holenstein et al., 2021; Le et al., 2023). This study aimed to analyze the level of bioaccumulation of Pb and Cu in sediments and benthic organisms on the coast of Sembilang National Park, identify potential sources of pollution, and assess its impact

on the configuration of benthic biota and the sustainability of coastal ecosystems as a whole.

2. EXPERIMENTAL SECTION

2.1 Materials

Sediment and two benthic species (*Anadara granosa* and *Cerithi dea cingulata*) served as the main materials in this investigation. Wet destruction of samples using HNO₃, HCl, H₂SO₄, distilled water, and filter paper. Supporting tools include hotplates, fume hoods, sieve shakers, and atomic absorption spectrophotometers. Identification, preparation, and sample destruction were accomplished at the Marine Bioecology Laboratory; heavy metal content tests were undertaken at the Integrated Service Unit of the Palembang City Environmental Service.

2.2 Instrumentation

Supporting tools include hotplates (C-MAG HS7), fume hood (BFSD-202), sieve shakers (AS 200 basic), and atomic absorption spectrophotometers (Shimadzu AA-7000).

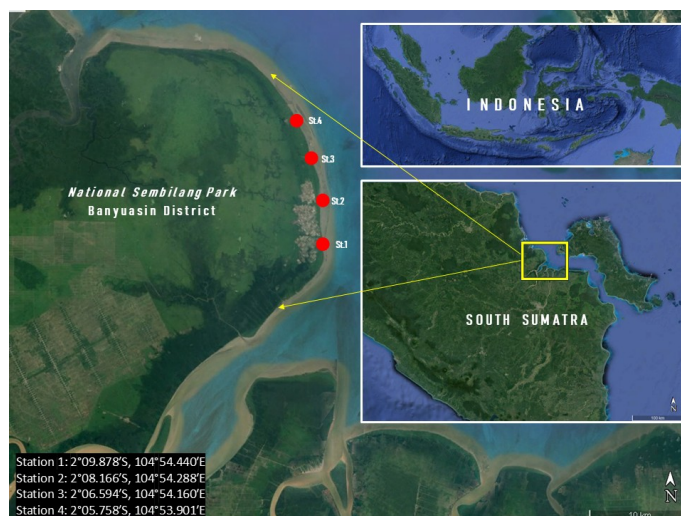


Figure 1. Study Area and Sampling

2.3 Location

This research was conducted around the Sembilang National Park site within Banyuasin, South Sumatra province, Indonesia, at four sampling stations (Figure 1). Sampling was carried out at four stations, each representing different estuarine and coastal environments within the park: Station 1 (2°09.878'S, 104°54.440'E), Station 2 (2°08.166'S, 104°54.288'E), Station 3 (2°06.594'S, 104°54.160'E), and Station 4 (2°05.758'S, 104°53.901'E). Located along the western coast of the Bangka Strait, Sembilang National Park serves as a conservation area. This estuarine region is created by the mixing of freshwater from the Sumatran mainland and seawater sourced from both the Malacca Strait and South China Sea (Sarno et al., 2017;

Rozirwan et al., 2019). Several previous research reports, although included in conservation areas, are also influenced by Various human-related activities including aquaculture, agricultural practices, vessel traffic corridors, and fisheries (Rozirwan et al., 2022; Fitria et al., 2023). Sediment and benthic sampling for species *Cerithidea cingulata* (stations 1 and 2) and *Anadara Granosa* (stations 3 and 4) were conducted in the mangrove ecosystem around Sembilang National Park. These two benthic species were selected due to their ecological roles, availability, and their capacity to bioaccumulate heavy metals, making them appropriate bioindicators. The choice of only two species was based on their dominance and abundance in the observation area during the period of sampling.

The Laboratory of Oceanography and Marine Instrumentation at Sriwijaya University was used for sample preparation and digestion. Meanwhile, laboratory analysis was conducted at the Laboratory of the Environmental and Land Service, Palembang, using the method of the atomic absorption spectrophotometer (AAS). Sediment sampling is referred to in (Abdel Gawad, 2018; Rozirwan et al., 2024a), collection of sediment samples was performed employing a grab sampler, then put into a 1 kg plastic clip. Sampling of benthic organisms was conducted From the top layer of sediment down through the first 30 cm. The samples were placed in a filtered through a 1 cm mesh and washed using seawater. After collection, the samples were immediately labeled, packed in zip-lock bags, and stored in a cooler box to maintain preservation. The samples obtained were then identified in the laboratory, referring to the book (Carpenter and Niem, 1998).



Figure 2. Benthic Species. A). *C. cingulata* and B). *A. granosa*

2.4 Procedure

2.4.1 Environmental Quality Measurement

Direct field measurements of water quality indicators (pH, dissolved oxygen, salinity, and temperature) were conducted in

triplicate (Rozirwan et al., 2021).

2.4.2 Sediment Grain Measurment

Grain size distribution was analyzed using both the sieve and pipette techniques (Romano et al., 2017). The sediment substrate classification was identified through triangular diagram analysis based on Shepard’s method, performed using Microsoft Excel version 202 (Poppe and Eliason, 2008; Anggraini et al., 2020). The type of sediment grain fraction identified was assigned according to the component with the highest percentage in the dataset.

2.4.3 Preparation and Destruction Sample

Preparation of sediment samples is cleaned from foreign items such as fragments of plastic, leaves, etc, followed by drying under room temperature conditions, then grind the sample until homogeneous and stored in a bottle polyethylene covered. Next, the benthic samples were cleaned and separated between the body organs and meat and then ground. Heavy metal samples are destroyed. Quantification of Cu and Pb in sediment and benthic samples utilizing wet digestion refers to Gao et al. (2021); Rizk et al. (2022).

2.4.4 Atomic Absorption Spectroscopic Measurmments

Copper and lead concentrations were analyzed with the aid of an AAS at wavelengths of 324.7 nm for copper and 283.3 nm for lead. The analysis was carried out using a Shimadzu AA-7000, which was calibrated with standard solutions of known concentrations. The detection limits for detection system were 0.007 mg/L for Cu and 0.01 mg/L for Pb, while its sensitivity was 0.003 mg/L for Cu and 0.005 mg/L for Pb. Instrument precision was evaluated based on the relative standard deviation (RSD) obtained from triplicate analyses, was maintained below 5% for both metals, ensuring the reliability and reproducibility of the results (Zhong et al., 2016).

2.5 Data Analysis

2.5.1 Reference Standards

Measured levels of heavy metals in sediments and benthic organisms were assessed in relation to recognized regulatory standards (Table 1).

Table 1. Heavy Metal Quality Standards (mg/kg)

Object	Pb	Cu	References
Sediment	50	65	(ANZECC and ARMCANZ, 2000)
Benthic	1.5	10	(FAO, 1983)

2.5.2 Statistical Analysis

An independent sample t-test was used to evaluate the concentrations of heavy metals differed significantly between sediment and benthic organisms (Rozirwan et al., 2024b). PCA was employed to identify patterns and correlations among various water parameters (dissolved oxygen, salinity, temperature, and

pH) and Amounts of heavy metals accumulated in sediment and benthic organisms. PCA analysis was executed through XLSTAT (v16.16.27), and qualitative variables were quantified in terms of percentages (Colot et al., 2022).

3. RESULTS AND DISCUSSION

3.1 Environmental Parameter Overview

The parameters related to environmental conditions that were measured from stations 1-4 are pH, DO, temperature and salinity (Table 2). The pH value at all stations tends to be homogeneous, with a range of values 6.5 ± 0.53 to 8.2 ± 0.26 . DO has varying values, ranging from 7 ± 0.26 to 11.7 ± 0.20 mg/L. Temperature and salinity at all stations tend to be homogeneous, with a temperature range of 26 ± 0.50 - $30.7\pm1.41^{\circ}\text{C}$ and salinity of 5 ± 0.26 - 21 ± 0.56 PSU.

Table 2. Environmental Parameters

Station	pH	DO (mg/L)	Temperature ($^{\circ}\text{C}$)	Salinity (PSU)
1	6.5 ± 0.53	11.7 ± 0.20	26 ± 0.50	5 ± 0.26
2	6.7 ± 0.62	9.5 ± 0.60	28.7 ± 1.30	10 ± 5.02
3	8.2 ± 0.26	7 ± 0.26	30.7 ± 1.41	21 ± 0.56
4	7.6 ± 0.30	9.8 ± 0.46	29.6 ± 0.62	20 ± 0.46

Based on the measurement results, the waters of Sembilang National Park are influenced by seawater inflow from the Bangka Strait and freshwater inflow from the Banyuasin River during tidal ebb and flow. Changes in water quality parameters can result from the mixing of different water masses (Rozirwan et al., 2021, 2023a). Based on the research results, the pH, temperature, and salinity values tend to be constant, but the DO values vary. The high and low DO values are susceptible to contamination from waste substances present in the aquatic environment. The quality of the water parameters pH, DO, temperature, and salinity show excellent values for growth. *C. cingulata* and *A. granosa*. The concentration of heavy metals is affected by environmental factors like pH, temperature, oxygen availability, and salinity. The presence, mobility, and toxicity of these metals are commonly affected by variations in physicochemical factors (Ramses et al., 2020; Luo et al., 2022). Water quality parameters can be used as indicators of pollution (Dolbeth et al., 2007).

3.2 Description of Benthic

Benthic species observed in the study area comprised *C. cingulata* and *A. granosa* (Figure 2). *C. cingulata* and *A. granosa* are benthic which are generally found in estuary or estuary waters. The *C. cingulata* species found in the waters of Sembilang National Park belongs to the cerithidae family, which is about 2-2.5 cm long and has a long and narrow shell; the opening of the shell is oval, and the operculum is brown. Meanwhile, *A. granosa* has a slightly brownish white to somewhat dark shell color with a size of 4-6 mm. The benthic species *C. cingulata* and *A. granosa* are two types of organisms commonly found in

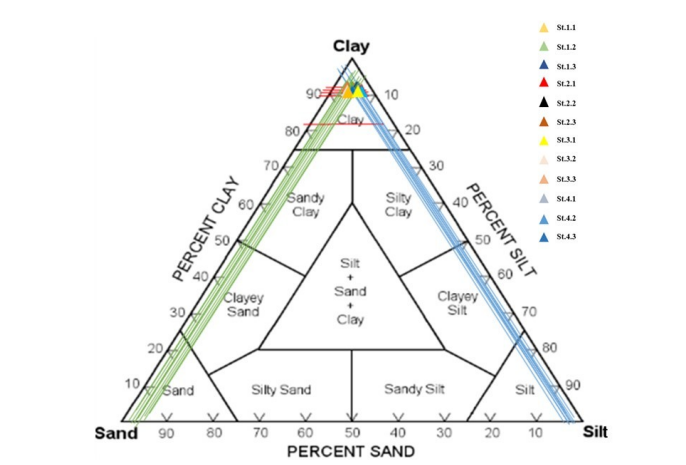


Figure 3. Grain Size Analysis with Triangles Shepard

estuarine waters (Kalat-Meimari et al., 2018; Rahmatin et al., 2024). *C. cingulata* is a gastropod with a cone-shaped shell that has spiral grooves, is dark in color, and is relatively small in size. It is often found in large numbers in muddy or sandy habitats in estuary areas (Kalat-Meimari et al., 2018; Li and Dong, 2020). *C. cingulata*, which is often found in muddy or sandy habitats, has the potential to absorb heavy metals accumulated in sediment through direct contact and feeding activities at the sediment-water interface (Vahidi et al., 2020).

On the other hand, *A. granosa* has a round shell with thick stripes containing thick, reddish flesh, which is often consumed by humans as seafood (Rozirwan et al., 2023c,e). As a filter feeder, *A. granosa* has the ability to filter food particles from water that may contain heavy metals (Mohan et al., 2024). These heavy metals then accumulate in their body tissues, especially in their reddish flesh. Because of its ability to filter water and accumulate heavy metals, *A. granosa* is an important bioindicator in monitoring water quality (Yona et al., 2020). Therefore, analyzing the heavy metal content in these two species can offer valuable insights concerning the concentration of heavy metals in estuarine areas.

Table 3. Sediment Grain Size Analysis.

Station	Sediment Fraction Percentage %				Substrate Type
	Gravel	Sand	Mud	Clay	
1	0.00	6.45	1.5	92.03	Clay
2	0.00	2.38	3.6	93.99	Clay
3	0.00	2.33	3.74	93.91	Clay
4	0.00	1.34	4.09	94.55	Clay

3.3 Size Classification of Sediment Grains

Results of substrate type identification at the study area were derived through the Shepard triangular method (Figure 3). Four types of sediment substrates (mud, gravel, clay, and sand) were

identified in the area surrounding Sembilang National Park. The study's results indicated that clay was the predominant substrate type across all sampling stations. The sediment substrate in the waters surrounding Sembilang National Park is predominantly clay. The clay content across all stations ranges from 92.03% to 94.55%. Station 4 recorded the highest percentage of clay, while station 1 had the lowest percentage (Table 3).

The sediment substrate, which is dominated by clay in Sembilang National Park Waters, provides some important insights into the local ecosystem conditions. The high percentage of clay at all stations, ranging from 92.03% to 94.55%, indicates that this area has environmental characteristics that tend to be calm and stable. The dominance of clay also indicates that the sedimentation process in this area may be influenced by the supply of fine material from the mainland, such as from river flow or surface runoff (Rozirwan et al., 2020; Cao et al., 2024; Ling et al., 2024). This is relevant considering that the mangrove ecosystems around this area are often the site of fine material deposition, consequently altering the spatial structure and community composition of benthic biota. Soegianto et al. (2022) stated that *C. cingulata* and *A. granosa* have a smooth substrate (clay) as a habitat. This is because the clay substrate type makes it easier for *C. cingulata* and *A. granosa* in to make holes to hide from predators. Sediments were predominantly clay, indicating stable environmental conditions conducive to heavy metal accumulation. High clay content supports the adsorption of heavy metals due to its fine particle size and large surface area (Song et al., 2014).

3.4 Heavy Metals Concentration

The data revealed that the levels of heavy metals, Cu and Pb were predominantly concentrated within the sediment than in the *C. cingulata* and *A. granosa* at all sampling stations (Table 4). The highest Cu concentration in sediment was recorded at Station 2 (5.71 ± 0 mg/kg) and the lowest at Station 1 (5.01 ± 0.017 mg/kg). Meanwhile, the highest recorded level of Pb in sediment was recorded at Station 1 (11.5 ± 0.395 mg/kg) and the lowest at Station 3 (10.5 ± 0.195 mg/kg).

Pb reached its highest concentration in *C. cingulata* at Station 2 (0.005 ± 0 mg/kg) and the lowest at *A. granosa* at Station 3 (0.0001 ± 0.000227 mg/kg). In contrast, the highest concentration of Cu was detected in *C. cingulata* at Station 2, with a value of 0.0147 ± 0.0000346 mg/kg and the lowest at *A. granosa* at Station 3 (0.0037 ± 0.00005773 mg/kg). These results indicate variations in heavy metal bioaccumulation between different types of benthic, with *C. cingulata* showing a tendency to accumulate higher Cu compared to *A. granosa*, while Pb accumulation in both biota was relatively low.

Analysis outcomes demonstrated that the levels of Cu and Pb were greater in sediments compared to those in biota. *C. cingulata* and *A. granosa* at all sampling stations. This is in line with the general understanding that sediment functions as the main storage of heavy metals in aquatic ecosystems (Das et al., 2023). Heavy metals progressively settle and concentrate in sediments through adsorption and precipitation processes,

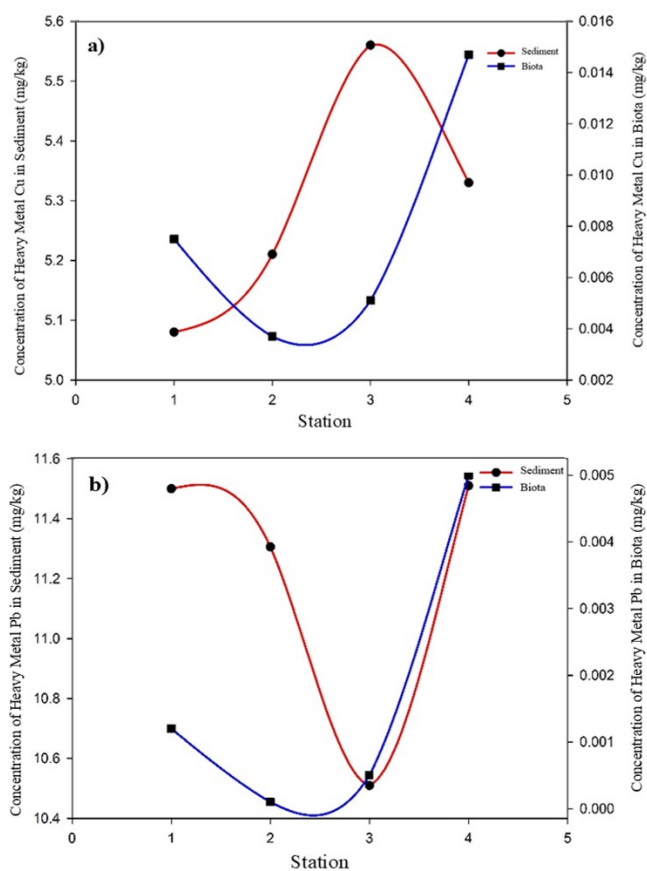
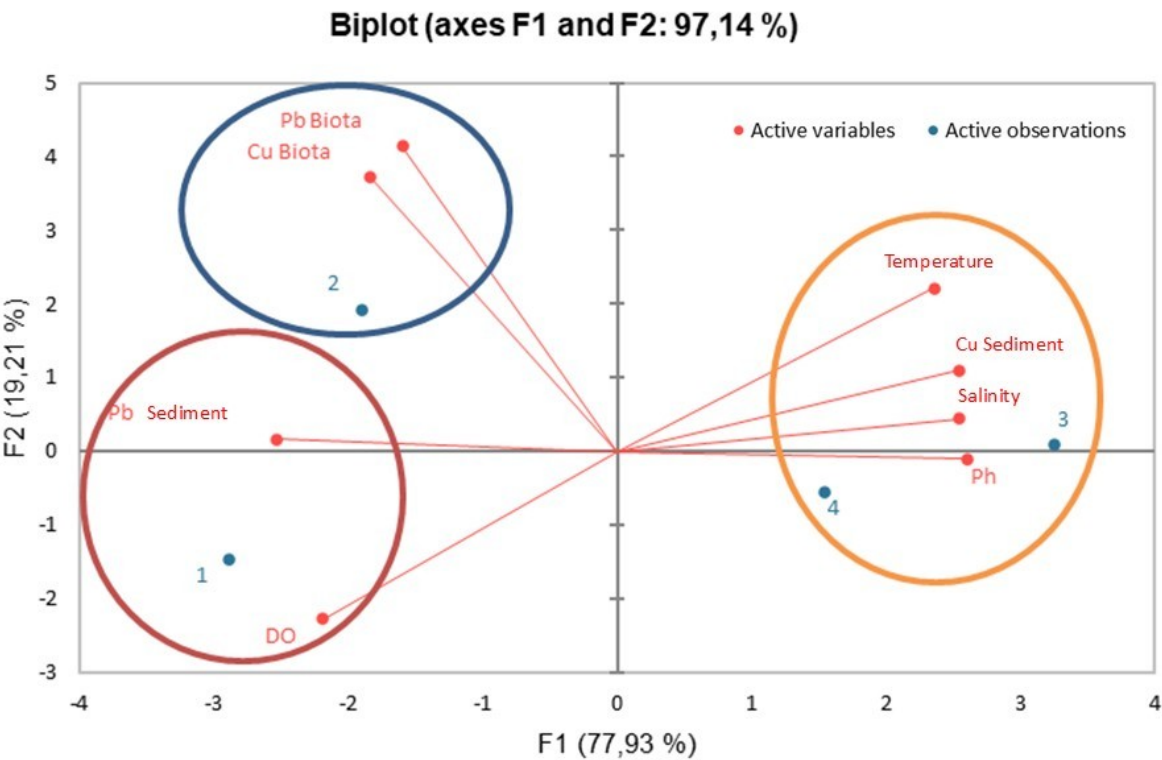


Figure 4. Distribution of Heavy Metals Cu and Pb

causing metal concentrations in sediments to be higher than in organism tissue (Sankhla et al., 2019; Dan et al., 2022). The variation in heavy metal concentrations between sediments and biota indicates that *C. cingulata* and *A. granosa* have different bioaccumulation capabilities. *C. cingulata* showed a tendency to accumulate more Cu compared to *A. granosa*, which may be reflect interspecific differences in physiology, foraging behavior, and ecological niches. *C. cingulata* more on the substrate surface, which allows for more direct exposure to heavy metals bound to sediment particles (Raj and Das, 2023). Mean while, *A. granosa* located in deeper substrate layers (Rozirwan et al., 2023f, 2024c). Pb accumulation in both species was relatively low, which may indicate that Pb may be less bioavailable for accumulation by benthic organisms (Espejo et al., 2019; Raj and Das, 2023). These differences in heavy metal bioaccumulation suggest that the risk of heavy metal toxicity may vary between species and between different heavy metals. The statistical analysis with an independent t-test showed that the significance values for both Cu and Pb levels were below 0.05, meaning there were important differences in the amount of heavy metals found in sediments compared to the organisms living on the bottom.

Table 4. Heavy Metal Concentrations in Sediment and Benthic (mg/kg).

Station	Cu		Pb	
	Sediment	Biota	Sediment	Biota
1 (<i>C. cingulata</i>)	5.01±0.017	0.0075±0.000003191	11.5±0.395	0.0012±0.00000732
2 (<i>C. cingulata</i>)	5.71±0	0.0147±0.00000346	11.3±0.114	0.005±0
3 (<i>A. granosa</i>)	5.66±0.042	0.0037±0.000005773	10.5±0.195	0.0001±0.000227
4 (<i>A. granosa</i>)	5.32±0.017	0.0051±0.000001249	10.51±0	0.0005±0



3.5 Heavy Metal Contamination Profiles in Sediment and Benthic Ecosystem

Visualization of Cu and Pb heavy metal distribution across sediment and organisms was performed with Sigma Plot (Figure 4). The results indicated that the concentration of Cu logan had varying patterns. Meanwhile, Pb concentrations in sediment and biota fluctuate.

Dispersion of Cu and Pb contaminants in sediment and biota revealed variations across research stations. The distribution graph of Cu metal concentration showed fluctuations between stations, with a significant increase in concentration at stations 2 and 3 in sediment, while the concentration of Cu in biota decreased at station 2. In contrast, the distribution of Pb showed a sharp decrease pattern at station 3 in sediment, followed by an upward trend in Pb in biota at the same station. An elevated level of lead was observed in sediment and biota collected from Station 4. This distribution pattern reflects variations in the accumulation and transport mechanisms of

Cu and Pb, within the sediment ecosystem and biota at the research site. The distribution of Cu is significantly determined by a range of factors, including anthropogenic activities, the physicochemical properties of sediment, hydrodynamic conditions, and the interactions between sediment and biota (Hu et al., 2022; Bao et al., 2024). Higher concentrations of Cu in sediment at certain stations may be related to pollution sources originating from agricultural activities, passenger and fishing ship transportation, and the use of antifouling paint on ships and coastal buildings (Rozirwan et al., 2023d; Khotimah et al., 2024).

3.6 Principal Component Analysis (PCA)

PCA evaluating the relationship between water quality parameters and heavy metal pollution indices in sediment and benthic organisms yielded a cumulative Eigenvalue of 97.14%, identifying three primary component groups. Eigenvalue Variability, respectively, namely F1 (77.933%) and F2 (19.210%) (Figure

5).

PCA results revealed significant relationships between water quality parameters and heavy metal distribution. Stations 3 and 4 showed higher Cu sediment concentrations, while Pb bioaccumulation was prominent at Station 2. (Fatmi et al., 2024; Rozirwan et al., 2023f). In contrast, station 1 has higher DO and Pb values in sediment, indicating that the high DO at this station plays a role in the oxidation process that increases Pb concentration (Kutlu et al., 2024). The F2 axis separates station 2 as the third main group, with higher Cu and Pb concentrations in benthic biota, indicating a higher bioaccumulation ability at this station.

The relationship between copper (Cu) and lead (Pb) in the natural environment is often influenced by their similar sources and geochemical behaviors (Suheryanto and Ismarti, 2018; Zhang et al., 2025). Both metals can originate from anthropogenic inputs such as agricultural runoff, industrial discharges, port activities, and they tend to co-accumulate in sediments and benthic organisms due to their affinity for particulate matter (Zhang et al., 2019; Rozirwan et al., 2025). In aquatic environments, Cu and Pb often exhibit positive correlations, particularly in estuarine and coastal areas where fine sediments with high organic content act as sinks for heavy metals (Miranda et al., 2021; Bao et al., 2024).

The observed distribution patterns of Cu and Pb in both sediment and benthic organisms suggest a shared source and similar environmental fate, supporting the notion that these metals are likely transported and deposited together under similar physicochemical conditions. This correlation may also indicate a cumulative impact of pollution in the area, especially in stations 3 and 4, which show higher concentrations of Cu in sediment and a similar distribution pattern of Pb in both sediment and benthic biota. Similarity analysis also shows a significant relationship between stations 3 and 4, which have similar physicochemical conditions and heavy metal distribution. The results contribute substantially to the understanding of heavy metal distribution patterns within aquatic environments and may inform the development of more targeted management approaches to mitigate heavy metal contamination in the region (Rozirwan et al., 2023f; Plaß et al., 2024).

4. CONCLUSIONS

The concentrations of Pb and Cu in sediments and biota within Sembilang National Park remain below established quality standards, suggesting that contamination levels in this area do not pose an immediate environmental risk. However, the presence of potential pollution sources from anthropogenic activities highlights the need for continued vigilance. Maintaining the environmental quality of Sembilang National Park requires periodic monitoring to recognize early contamination symptoms and undertake immediate corrective actions. This proactive approach will help safeguard the ecosystem's health and ensure its long-term sustainability.

5. ACKNOWLEDGMENT

The research/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2024. Nomor SP DIPA 023.17.2.677515/2024, On November 24, 2023. In accordance with the Rector's Degree Number: 0013/UN9/LP2M.PT/2024, On May 20, 2024.

REFERENCES

- Abdel Gawad, S. S. (2018). Concentrations of Heavy Metals in Water, Sediment and Mollusk Gastropod, *Lanistes Carinatus* from Lake Manzala, Egypt. *The Egyptian Journal of Aquatic Research*, 44(2); 77–82
- Anggraini, R. R., U. Yanuhar, and Y. Risjani (2020). Characteristic of Sediment at Lekok Coastal Waters, Pasuruan Regency, East Java. *Jurnal Ilmu Dan Teknologi Kelautan Tropis*, 12(1); 235–246
- Angon, P. B., M. S. Islam, S. KC, A. Das, N. Anjum, A. Poudel, and S. A. Suchi (2024). Sources, Effects and Present Perspectives of Heavy Metals Contamination: Soil, Plants and Human Food Chain. *Heliyon*, 10(7); e28357
- ANZECC and ARMCANZ (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*, volume 1 of *National Water Quality Management Strategy*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand
- Bao, T., P. Wang, B. Hu, Q. Jin, T. Zheng, and D. Li (2024). Adsorption and Distribution of Heavy Metals in Aquatic Environments: The Role of Colloids and Effects of Environmental Factors. *Journal of Hazardous Materials*, 474; 134725
- Bian, B., Y. Zhou, and B. B. Fang (2016). Distribution of Heavy Metals and Benthic Macroinvertebrates: Impacts from Typical Inflow River Sediments in the Taihu Basin, China. *Ecological Indicators*, 69; 348–359
- Briffa, J., E. Sinagra, and R. Blundell (2020). Heavy Metal Pollution in the Environment and Their Toxicological Effects on Humans. *Heliyon*, 6(9); e04691
- Cao, P., S. Liu, X. Fang, H. Zhang, X. Li, G. Yang, S. Khokiatiwong, N. Kornkanitnan, and X. Shi (2024). Spatial and Temporal Distributions of Clay Minerals in the Central Andaman Sea: Provenances and Sedimentary Processes Over the Last 42 Kyr. *Journal of Asian Earth Sciences*, 259; 105895
- Carpenter, K. E. and V. H. Niem (1998). *The Living Marine Resources of the Western Central Pacific*, volume 1. FAO
- Carvalho Ferreira, H. and G. Lôbo-Hajdu (2023). Microplastics in Coastal and Oceanic Surface Waters and Their Role as Carriers of Pollutants of Emerging Concern in Marine Organisms. *Marine Environmental Research*, 188; 106021
- Chahouri, A., I. Lamine, H. Ouchene, B. Yacoubi, A. Moukrim, and A. Banaoui (2023). Assessment of Heavy Metal Contamination and Ecological Risk in Morocco's Marine and Estuarine Ecosystems Through a Combined Analysis of Surface Sediment and Bioindicator Species: Donax

- Trunculus and Scrobicularia Plana. *Marine Pollution Bulletin*, **192**; 115076
- Charlena, Nazriati, B. M. Soebrata, and M. D. Iswara (2025). Synthesis and Characterization of Hydroxyapatite Composites Based on Tutut (Belamya Javanica) and Magnetite by Coprecipitation as Adsorbents of Pb Metals Ion. *Science and Technology Indonesia*, **10**(1); 111–122
- Chormare, R. and M. A. Kumar (2022). Environmental Health and Risk Assessment Metrics With Special Mention to Bio-transfer, Bioaccumulation and Biomagnification of Environmental Pollutants. *Chemosphere*, **302**; 134836
- Colot, J., C. Fouquet, F. Ducrocq, S. Chevalier, C. Le Provost, C. Cazorla, C. Cheval, C. Fijalkowski, A. C. Gourinat, A. Biron, C. Goarant, A. Bourles, B. Marot, and P. Saliou (2022). Prevention and Control of Highly Antibiotic-Resistant Bacteria in a Pacific Territory: Feedback From New Caledonia Between 2004 and 2020. *Infectious Diseases Now*, **52**(1); 7–12
- Cong, J., H. Long, Y. Zhang, and N. Wang (2022). Ecological Environment Response of Benthic Foraminifera to Heavy Metals and Human Engineering: A Case Study From Jiaozhou Bay, China. *China Geology*, **5**(1); 12–25
- Dan, S. F., E. C. Udoh, J. Zhou, B. Wijesiri, S. Ding, B. Yang, D. Lu, and Q. Wang (2022). Heavy Metals Speciation in Surface Sediments of the Cross River Estuary, Gulf of Guinea, South East Nigeria. *Marine Pollution Bulletin*, **185**; 114257
- Das, M., A. Das, and A. Mandal (2023). Exploring the Factors Affecting Urban Ecological Risk: A Case From an Indian Mega Metropolitan Region. *Geoscience Frontiers*, **14**(1); 101488
- Dolbeth, M., P. G. Cardoso, S. M. Ferreira, T. Verdelhos, D. Raffaelli, and M. A. Pardal (2007). Anthropogenic and Natural Disturbance Effects on a Macrobenthic Estuarine Community Over a 10-Year Period. *Marine Pollution Bulletin*, **54**(5); 576–585
- Dong, J.-Y., X. Wang, X. Zhang, G. Bidegain, and L. Zhao (2023). Integrating Multiple Indices Based on Heavy Metals and Macrobenthos to Evaluate the Benthic Ecological Quality Status of Laoshan Bay, Shandong Peninsula, China. *Ecological Indicators*, **153**; 110367
- Dong, J.-Y., L. Zhao, X. Sun, C. Hu, Y. Wang, W.-T. Li, P.-D. Zhang, and X. Zhang (2021). Response of Macrobenthic Communities to Heavy Metal Pollution in Laoshan Bay, China: A Trait-Based Method. *Marine Pollution Bulletin*, **167**; 112292
- Elliott, M. and M. J. Kennish (2024). A Synthesis of Anthropogenic Impacts and Solutions in Estuarine and Coastal Environments. In D. Baird and M. Elliott, editors, *Treatise on Estuarine and Coastal Science (Second Edition)*, chapter 6.1. Academic Press, second edition edition, pages 1–56
- Espejo, W., J. d. A. Padilha, R. A. Gonçalves, P. R. Dorneles, R. Barra, D. Oliveira, O. Malm, G. Chiang, and J. E. Celis (2019). Accumulation and Potential Sources of Lead in Marine Organisms From Coastal Ecosystems of the Chilean Patagonia and Antarctic Peninsula Area. *Marine Pollution Bulletin*, **140**; 60–64
- Fadlillah, L. N., S. Utami, A. A. Rachmawati, G. D. Jayanto, and M. Widyastuti (2023). Ecological Risk and Source Identifications of Heavy Metals Contamination in the Water and Surface Sediments From Anthropogenic Impacts of Urban River, Indonesia. *Heliyon*, **9**(4); e15485
- FAO (1983). Compilation of Legal Limits for Hazardous Substances in Fish and Fishery Products. FAO Fisheries Circular 764. FAO Fisheries Circular No. 764
- Fatmi, B., A. Hazzab, A. Rahmani, and A. Ghenaïm (2024). Examining Temporal Trends in Heavy Metal Levels to Analyze Sediment Pollution Dynamics in the Saida Urban Watershed (N-W Algeria). *Water Environment Research*, **96**(8); e11084
- Fauziyah, F. Agustriani, R. E. Oktavianis, T. Z. Ulqodry, N. Aprianti, and Ardani (2023). Willingness to Pay for Mangrove Conservation in Sembilang National Park, South Sumatra, Indonesia. *Ocean & Coastal Management*, **243**; 106756
- Fitria, Y., Rozirwan, M. Fitriani, R. Y. Nugroho, Fauziyah, and W. A. E. Putri (2023). Gastropods as Bioindicators of Heavy Metal Pollution in the Banyuasin Estuary Shrimp Pond Area, South Sumatra, Indonesia. *Acta Ecologica Sinica*
- Gao, Y., Y. Qiao, Y. Xu, L. Zhu, and J. Feng (2021). Assessment of the Transfer of Heavy Metals in Seawater, Sediment, Biota Samples and Determination of the Baseline Tissue Concentrations of Metals in Marine Organisms. *Environmental Science and Pollution Research International*, **28**(22); 28764–28776
- Han, X., H. Wu, Q. Li, W. Cai, and S. Hu (2024). Assessment of Heavy Metal Accumulation and Potential Risks in Surface Sediment of Estuary Area: A Case Study of Dagou River. *Marine Environmental Research*, **196**; 106416
- Holstein, K., W. D. Simonson, K. G. Smith, T. M. Blackburn, and A. Charpentier (2021). Non-native Species Surrounding Protected Areas Influence the Community of Non-native Species Within Them. *Frontiers in Ecology and Evolution*, **8**; 1–12
- Hu, R., Y. Wang, X. Zhang, L. Zhu, M. Luo, B. Liu, and X. Yuan (2022). Sources and Factors Controlling the Distribution of Heavy Metals in Coastal Sediments of Haiyang, China. *Marine Pollution Bulletin*, **175**; 113152
- Jayachandran, P. R., S. Bijoy Nandan, M. Jima, J. Philomina, and N. K. Vishnudattan (2022). Benthic Organisms as an Ecological Tool for Monitoring Coastal and Marine Ecosystem Health. In P. S. Godson, S. G. T. Vincent, and S. Krishnakumar, editors, *Ecology and Biodiversity of Benthos*, chapter 10. Elsevier, pages 337–362
- Kalat-Meimari, M., J. Shamseddin, and A. Salahi-Moghaddam (2018). Ecological and Parasitological Study on Cerithidea Cingulata (Gastropoda) in Hormoz Strait Littoral, South of Iran. *Iranian Journal of Parasitology*, **13**(2); 285–292
- Khotimah, N. N., Rozirwan, W. A. E. Putri, F. Fauziyah, R. Aryawati, I. Isnaini, and R. Y. Nugroho (2024). Bioaccumulation and Ecological Risk Assessment of Heavy Metal

- Contamination (Lead and Copper) Build Up in the Roots of *Avicennia Alba* and *Excoecaria Agallocha*. *Journal of Ecological Engineering*, **25**(5); 101–113
- Korejwo, E., D. Saniewska, J. Beldowski, P. Balazy, and M. Saniewski (2022). Mercury Concentration and Speciation in Benthic Organisms from Isfjorden, Svalbard. *Marine Pollution Bulletin*, **184**; 114115
- Kutlu, B., F. Çevik, and S. Çetindağ (2024). Assessments of Heavy Metal Contaminations of Surface Water and Sediment of Pülümür Stream (Türkiye). *Environmental Forensics*. Accessed via Semantic Scholar, CorpusID: 268989904
- Le, H., C. Zhao, W. Xu, Y. Deng, and Z. Xie (2023). Anthropogenic Activities Explained the Difference in Exotic Plants Invasion Between Protected and Non-Protected Areas at a Northern Subtropics Biodiversity Hotspot. *Journal of Environmental Management*, **345**; 118939
- Li, A., J. Li, F. Liu, L. Zhu, L. Liu, S. Xue, M. Zhang, Y. Tang, and Y. Mao (2024). Assessment of Benthic Ecological Status and Heavy Metal Contamination in an Estuarine Intertidal Mudflat in the Northern Bohai Sea. *Marine Pollution Bulletin*, **203**; 116501
- Li, X. and Y. Dong (2020). Living on the Upper Intertidal Mudflat: Different Behavioral and Physiological Responses to High Temperature Between Two Sympatric Cerithidea Snails with Divergent Habitat-Use Strategies. *Marine Environmental Research*, **159**; 105015
- Ling, C., Z. Liu, X. Yu, Y. Zhao, F. P. Siringan, K. P. Le, E. Sathiamurthy, C.-F. You, and K. Chen (2024). Clay Minerals Control Silicon Isotope Variations of Fine-Grained River Sediments: Implication for the Trade-Off Between Physical Erosion and Chemical Weathering. *Chemical Geology*, **662**; 122249
- Liu, J., L. Cao, and S. Dou (2017). Bioaccumulation of Heavy Metals and Health Risk Assessment in Three Benthic Bivalves Along the Coast of Laizhou Bay, China. *Marine Pollution Bulletin*, **117**(1); 98–110
- Liu, Y., Y. Zhou, and J. Lu (2020). Exploring the Relationship Between Air Pollution and Meteorological Conditions in China Under Environmental Governance. *Scientific Reports*, **10**(1); 14518
- Lukhabi, D. K., P. K. Mensah, N. K. Asare, M. F. A. Akwetey, and C. A. Faseyi (2024). Benthic Macroinvertebrates as Indicators of Water Quality: A Case Study of Estuarine Ecosystems Along the Coast of Ghana. *Heliyon*, **10**(7); e28018
- Luo, M., Y. Zhang, H. Li, W. Hu, K. Xiao, S. Yu, C. Zheng, and X. Wang (2022). Pollution Assessment and Sources of Dissolved Heavy Metals in Coastal Water of a Highly Urbanized Coastal Area: The Role of Groundwater Discharge. *Science of The Total Environment*, **807**; 151070
- Lv, J., R. Hu, N. Wang, L. Zhu, X. Zhang, X. Yuan, and B. Liu (2021). Distribution and Movement of Heavy Metals in Sediments Around the Coastal Areas Under the Influence of Multiple Factors: A Case Study from the Junction of the Bohai Sea and the Yellow Sea. *Chemosphere*, **278**; 130352
- Miranda, L. S., G. A. Ayoko, P. Egodawatta, and A. Goonetilleke (2022). Adsorption-Desorption Behavior of Heavy Metals in Aquatic Environments: Influence of Sediment, Water and Metal Ionic Properties. *Journal of Hazardous Materials*, **421**; 126743
- Miranda, L. S., B. Wijesiri, G. A. Ayoko, P. Egodawatta, and A. Goonetilleke (2021). Water-Sediment Interactions and Mobility of Heavy Metals in Aquatic Environments. *Water Research*, **202**; 117386
- Mitra, S., A. J. Chakraborty, A. M. Tareq, T. B. Emran, F. Nainu, A. Khusro, A. M. Idris, M. U. Khandaker, H. Osman, F. A. Alhumaydhi, and J. Simal-Gandara (2022). Impact of Heavy Metals on the Environment and Human Health: Novel Therapeutic Insights to Counter the Toxicity. *Journal of King Saud University - Science*, **34**(3); 101865
- Mohan, P., F. Shahul Hamid, H. Furumai, and K. Nishikawa (2024). Beneath the Surface: Exploring Microplastic Intricacies in *Anadara granosa*. *Marine Environmental Research*, **199**; 106581
- Oron, S., A. Sadekov, T. Katz, and B. Goodman-Tchernov (2021). Benthic Foraminifera Geochemistry as a Monitoring Tool for Heavy Metal and Phosphorus Pollution — A Post Fish-Farm Removal Case Study. *Marine Pollution Bulletin*, **168**; 112443
- Plaß, L., F. Heid, and U. Windisch (2024). Comparison of Heavy Metal Contamination in Sediment, Water and *Gammarus* spp. (Crustacea: Amphipoda) in Small Streams with Respect to Anthropogenic Discharges. Research Square
- Poppe, L. J. and A. H. Eliason (2008). A Visual Basic Program to Plot Sediment Grain-Size Data on Ternary Diagrams. *Computers & Geosciences*, **34**; 561–565
- Pulido-Chadid, K., E. Virtanen, and J. Geldmann (2023). How Effective Are Protected Areas for Reducing Threats to Biodiversity? A Systematic Review Protocol. *Environmental Evidence*, **12**(1); 1–10
- Rahmatin, N. M., A. Soegianto, B. Irawan, C. M. Payus, K. N. Indriyasar, A. Marchellina, W. Mukholladun, and Y. Irmidayanti (2024). The Spatial Distribution and Physico-Chemical Characteristic of Microplastics in the Sediment and Cockle (*Anadara granosa*) from the Coastal Waters of East Java, Indonesia, and the Health Hazards Associated with Cockle Consumption. *Marine Pollution Bulletin*, **198**; 115906
- Raj, K. and A. P. Das (2023). Lead Pollution: Impact on Environment and Human Health and Approach for a Sustainable Solution. *Environmental Chemistry and Ecotoxicology*, **5**; 79–85
- Ramses, Ismarti, F. Amelia, Rozirwan, and Suheryanto (2020). Diversity and Abundance of Polychaetes in the West Coast Waters of Batam Island, Kepulauan Riau Province-Indonesia. *AACL Bioflux*, **13**(1); 381–391
- Rizk, R., T. Juzsakova, M. B. Ali, M. A. Rawash, E. Domokos, A. Hedfi, M. Almalki, F. Boufahja, H. M. Shafik, and Á. Rédey (2022). Comprehensive Environmental Assessment of Heavy Metal Contamination of Surface Water, Sed-

- iments and Nile Tilapia in Lake Nasser, Egypt. *Journal of King Saud University-Science*, **34**(1); 101748
- Romano, E., M. C. Magno, and L. Bergamin (2017). Grain Size Data Analysis of Marine Sediments, from Sampling to Measuring and Classifying: A Critical Review. In *IMEKO TC19 Workshop on Metrology for the Sea, MetroSea 2017: Learning to Measure Sea Health Parameters*. pages 173–178
- Roziirwan, S. A. F. Az-zahrah, N. N. Khotimah, R. Y. Nugroho, W. Ayu, and E. Putri (2024a). Ecological Risk Assessment of Heavy Metal Contamination in Water, Sediment, and Polychaeta (*Neoleanira tetragona*) from Coastal Areas Affected by Aquaculture, Urban Rivers, and Ports in South Sumatra. *Biodiversitas*, **25**(1); 303–319
- Roziirwan, F. Fauziyah, R. Y. Nugroho, M. Melki, T. Z. Ulqodry, F. Agustriani, E. N. Ningsih, W. A. E. Putri, A. Absori, and M. Iqbal (2022). An Ecological Assessment of Crab's Diversity Among Habitats of Migratory Birds at Berbak-Sembilang National Park, Indonesia. *International Journal of Conservation Science*, **13**(3); 961–972
- Roziirwan, H. Hananda, R. Y. Nugroho, R. Apri, N. N. Khotimah, F. Fauziyah, W. A. E. Putri, and R. Aryawati (2023a). Antioxidant Activity, Total Phenolic, Phytochemical Content, and HPLC Profile of Selected Mangrove Species from Tanjung Api-Api Port Area, South Sumatra, Indonesia. *Tropical Journal of Natural Product Research*, **7**(7); 3482–3489
- Roziirwan, I. Iskandar, M. Hendri, R. Apri, Supardi, N. Azhar, and W. Mardiansyah (2019). Distribution of Phytoplankton Diversity and Abundance in Maspari Island Waters, South Sumatera, Indonesia. *Journal of Physics: Conference Series*, **1282**(1); 012021
- Roziirwan, N. N. Khotimah, W. A. E. Putri, Fauziyah, R. Apri, Isnaini, and R. Y. Nugroho (2024b). Investigating the Antioxidant Activity, Total Phenolics and Phytochemical Profile in *Avicennia alba* and *Excoecaria agallocha* Root Extracts as a Defence Mechanism Against Pollutants. *Farmacia*, **72**(5); 1216–1226
- Roziirwan, N. N. Khotimah, W. A. E. Putri, Fauziyah, R. Aryawati, N. Damiri, Isnaini, and Nigr (2023b). Environmental Risk Assessment of Pb, Cu, Zn, and Cd Concentrations Accumulated in Selected Mangrove Roots and Surrounding Their Sediment. *Biodiversitas*, **24**(12); 6733–6742
- Roziirwan, N. N. Khotimah, W. A. E. Putri, Fauziyah, R. Aryawati, G. Diansyah, and R. Y. Nugroho (2025). Biomarkers of Heavy Metals Pollution in Mangrove Ecosystems: Comparative Assessment in Industrial Impact and Conservation Zones. *Toxicology Reports*, **14**; 102011
- Roziirwan, Melki, R. Apri, Fauziyah, A. Agussalim, Hartoni, and I. Iskandar (2021). Assessment the Macrobenthic Diversity and Community Structure in the Musi Estuary, South Sumatra, Indonesia. *Acta Ecologica Sinica*, **41**(4); 346–350
- Roziirwan, H. I. Muda, and T. Z. Ulqodry (2020). Short Communication: Antibacterial Potential of Actinomycetes Isolated from Mangrove Sediment in Tanjung Api-Api, South Sumatra, Indonesia. *Biodiversitas Journal of Biological Diversity*, **21**(12); 5723–5728
- Roziirwan, M. Muhtadi, T. Z. Ulqodry, R. Y. Nugroho, N. N. Khotimah, F. Fauziyah, W. A. E. Putri, R. Aryawati, and C. A. R. Mohamed (2023c). Insecticidal Activity and Phytochemical Profiles of *Avicennia marina* and *Excoecaria agallocha* Leaves Extracts. *Ilmu Kelautan: Indonesian Journal of Marine Sciences*, **28**(2); 148–160
- Roziirwan, Nanda, R. Y. Nugroho, G. Diansyah, Muhtadi, Fauziyah, W. A. E. Putri, and A. Agusallim (2023d). Phytochemical Composition, Total Phenolic Content and Antioxidant Activity of *Anadara granosa* (Linnaeus, 1758) Collected from the East Coast of South Sumatra, Indonesia. *Baghdad Science Journal*; 1–8
- Roziirwan, S. Ramadani, W. Ayu, E. Putri, N. Nur, and R. Y. Nugroho (2023e). Evaluation of Calcium and Phosphorus Content in Scallop Shells (*Placuna placenta*) and Blood Cockle Shells (*Anadara granosa*) from Banyuasin Waters, South Sumatra. *Egyptian Journal of Aquatic Biology & Fisheries*, **27**(3); 1053–1068
- Roziirwan, A. C. Rosadi, W. A. Eka Putri, Fauziyah, and R. Y. Nugroho (2024c). Ecological Study of Macrozoobenthos in the Mudflat Zone of Sembilang National Park, South Sumatra. In *BIO Web of Conferences*, volume 112. page 04004
- Roziirwan, A. P. Saputri, R. Y. Nugroho, N. N. Khotimah, W. A. E. Putri, Fauziyah, and A. I. S. Purwiyanto (2023f). An Assessment of Pb and Cu in Waters, Sediments, and Mud Crabs (*Scylla serrata*) from Mangrove Ecosystem Near Tanjung Api-Api Port Area, South Sumatra, Indonesia. *Science and Technology Indonesia*, **8**(4); 675–683
- Sankhla, M. S., R. Kumar, and A. Biswas (2019). Dynamic Nature of Heavy Metal Toxicity in Water and Sediments of Ayad River with Climatic Change. *International Journal of Hydrology*, **3**(5); 345–349
- Sarno, R. A. Suwignyo, Z. Dahlan, Munandar, M. R. Ridho, N. Aminasih, Harmida, M. E. Armanto, and E. Wildayana (2017). Short Communication: The Phenology of *Sonneratia alba* J. Smith in Berbak and Sembilang National Park, South Sumatra, Indonesia. *Biodiversitas*, **18**(3); 909–915
- Silvius, M. J., Y. R. Noor, I. R. Lubis, W. Giesen, and D. Rais (2016). Sembilang National Park - Mangrove Reserves of Indonesia. In *The Wetland Book*. pages 1–11
- Soegianto, A., H. I. Wahyuni, B. Yulianto, and L. A. Manaf (2022). Health Risk Assessment of Metals in Mud Crab (*Scylla serrata*) from the East Java Estuaries of Indonesia. *Environmental Toxicology and Pharmacology*, **90**; 103810
- Song, Y., M. S. Choi, J. Y. Lee, and D. J. Jang (2014). Regional Background Concentrations of Heavy Metals (Cr, Co, Ni, Cu, Zn, Pb) in Coastal Sediments of the South Sea of Korea. *Science of The Total Environment*, **482–483**(1); 80–91
- Suheryanto, S. and I. Ismarti (2018). Bio-concentration Factors of Copper (Cu) and Lead (Pb) in Seagrass and Some Fish from Coast Batam, Riau Islands, Indonesia. *Journal of Physics: Conference Series*, **1095**(1); 012038
- Vahidi, F., S. M. R. Fatemi, A. Danehkar, A. Mashinchian, and R. Musavi Nadushan (2020). Benthic Macrofaunal

- Dispersion Within Different Mangrove Habitats in Hara Biosphere Reserve, Persian Gulf. *International Journal of Environmental Science and Technology*, **17**(3); 1295–1306
- Wu, H., L. Yu, X. Shen, F. Hua, and K. Ma (2023). Maximizing the Potential of Protected Areas for Biodiversity Conservation, Climate Refuge and Carbon Storage in the Face of Climate Change: A case study of Southwest China. *Biological Conservation*, **284**; 110213
- Yona, D., S. H. J. Sari, F. Iranawati, M. Fathur Rayyan, and N. M. Rini (2020). Heavy Metals Accumulation and Risk Assessment of *Anadara granosa* from Eastern Water of Java Sea, Indonesia. *IOP Conference Series: Earth and Environmental Science*, **416**(1); 012007
- Zaynab, M., R. Al-Yahyai, A. Ameen, Y. Sharif, L. Ali, M. Fatima, K. A. Khan, and S. Li (2022). Health and Environmental Effects of Heavy Metals. *Journal of King Saud University - Science*, **34**(1); 101653
- Zhang, J., M. Wang, and K. Yang (2025). Identification of Copper and Lead Pollution Elements Based on Spectra of Corn Leaves in Different Leaf Layers. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, **329**; 125516
- Zhang, Z., D. Zheng, Z. Xue, H. Wu, and M. Jiang (2019). Identification of Anthropogenic Contributions to Heavy Metals in Wetland Soils of the Karuola Glacier in the Qinghai-Tibetan Plateau. *Ecological Indicators*, **98**; 678–685
- Zhong, W. S., T. Ren, and L. J. Zhao (2016). Determination of Pb (Lead), Cd (Cadmium), Cr (Chromium), Cu (Copper), and Ni (Nickel) in Chinese Tea with High-Resolution Continuum Source Graphite Furnace Atomic Absorption Spectrometry. *Journal of Food and Drug Analysis*, **24**(1); 46–55