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by Rozirwan Rozirwan

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Implication of microplastic presence in sediment and blood clams *Anadara granosa* (Mollusca: Bivalvia) in the Musi Estuary, Indonesia

M. AKBAR RAHMAN[1], ROZIRWAN[2,♥], WIKE EKA AYU PUTRI[2], GUSTI DIANSYAH[2], MELKI[2], ICA DELYA[2], REDHO YOGA NUGROHO[2]

[1]Department of Environment Management, Graduate School of Environmental Sciences, Universitas Sriwijaya. Jl. Padang Selasa No.524, Palembang 30129, South Sumatra, Indonesia

[2]Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya. Jl. Raya Palembang-Prabumulih Km. 32, Ogan Ilir 30862, South Sumatra, Indonesia. Tel.:+62-711-580056, Fax.:+62-711-580268, ♥email: rozirwan@unsri.ac.id

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Abstract. *Rahman MA, Rozirwan, Putri WEA, Diansyah G, Melki, Delya I, Nugroho RY. 2025. Implication of microplastic presence in sediment and blood clams* Anadara granosa *(Mollusca: Bivalvia) in the Musi Estuary, Indonesia. Biodiversitas 26: 1720-1733.* Microplastic pollution poses a serious risk to estuarine ecosystems, affecting sediments and benthic species. Blood clam *Anadara granosa* represent a significant commercial seafood product in Indonesia, including those from the Musi Estuary. This study investigated the risks associated with microplastic contamination in sediments and *A. granosa* in the Musi Estuary, located in South Sumatra, Indonesia. Sediment samples were extracted using sodium chloride (NaCl, 1.2 g cm^{-3}) and hydrogen peroxide (30% H_2O_2). In contrast, *A. granosa* samples were digested with 10% KOH for microplastic extraction. The abundance and shape of microplastics were analyzed from both samples. Pollution risk assessment was conducted through the calculation of the Pollution Load Index (PLI), Nemerow Pollution Index (NPI), and Bioconcentration Factor (BCF). The results revealed the presence of microplastics in sediments, with a mean abundance of 1.31±0.41 particles/g dw, while in *A. granosa*, it was 21.05±10.31 particles/ind. Both samples exhibited high microplastic bioaccumulation (NPI>2), although the pollution load remained relatively low (minor category, PLI<10). The bioconcentration factor between *A. granosa* and sediment was determined to be 23.28, indicating that the *A. granosa* absorbed microplastics present in the sediment. These findings highlight the significant bioaccumulation potential of microplastics in *A. granosa* within the Musi Estuary. The local community and government need to establish mitigations for future microplastic management efforts.

Keywords: Bioaccumulation, blood clams, microplastics, Musi Estuary, sediment

INTRODUCTION

River estuaries are dynamic ecosystems crucial for ecological balance and socio-economic functions (Boerema and Meire 2017; Hasan et al. 2022, et al. 2023; Retnaningdyah et al. 2022). They support diverse species and serve as hubs for urban, recreation, and commercial use (Islamy and Hasan 2020; Lonsdale et al. 2022; Natsir et al. 2022; Aunurrahman et al. 2023). Among the major estuaries in Sumatra, Indonesia, the Musi Estuary holds significant ecological and economic importance (Surbakti et al. 2023). It provides essential habitat for fish and benthic species that support local livelihoods (Rozirwan et al. 2021, et al. 2022a; Fauziyah et al. 2022, 2023). However, Intensified human activity around the Musi River has caused severe environmental degradation, mainly due to heavy metal and microplastic pollution (Maherlsa et al. 2019; Purwiyanto et al. 2022; Rahutami et al. 2022; Fitria et al. 2023; Rozirwan et al. 2023a, et al. 2024; Diansyah et al. 2024). These pollutants may compromise estuarine stability, with potential impacts on biodiversity and dependent communities.

Macrozoobenthos are considered pivotal components in preserving the equilibrium of estuarine ecosystems (Sari et al. 2022; Isroni et al. 2023). These organisms play a crucial role in the food web and nutrient cycling (Griffiths et al. 2017). Moreover, macrozoobenthos are highly sensitive to environmental changes, making them reliable bioindicators of ecological degradation (Sahidin et al. 2022). Bivalves such as *Anadara granosa* (Linnaeus, 1758) are commonly used as bioindicators due to their ability to accumulate pollutants through filter-feeding (Fitri and Patria 2019; Ward et al. 2019; Ding et al. 2021; Bonifacio et al. 2022; Saleh et al. 2023; Rahmatin et al. 2024). *Anadara granosa* is widely consumed by the general public as a nutrient-rich seafood, particularly among local communities (Rozirwan et al. 2023b, c). Among these, *A. granosa* is an important bivalve that helps maintain ecosystem balance and supports the livelihoods of coastal communities (Yulinda et al. 2020; Prasetiyono et al. 2022; Mahary et al. 2023). *Anadara granosa*'s ecological and economic roles make assessing its pollutant contamination essential to understanding environmental pollution impacts.

Pollutants such as heavy metals, hydrocarbons, pesticides, and microplastics frequently accumulate in estuarine sediments (Zhao et al. 2015; Kılıç et al. 2023; Han et al. 2024; Jacq et al. 2024). Among these, plastic pollution has emerged as a critical concern due to its pervasive impact on aquatic environments (Borrelle et al. 2020; Hecker et al. 2023). Over the last five decades, single-use plastics have accumulated and fragmented widely across ecosystems (Zhang et al. 2021; Walker and

Fequet 2023). As plastics degrade, they break down into microplastics, defined as particles ranging in size from 1 µm to 5 mm (Frias and Nash 2019). Microplastics in aquatic ecosystems originate from plastic fragmentation, synthetic fiber release during washing, and microbeads in personal care products (Napper et al. 2015; Praveena et al. 2018; Belzagui and Gutiérrez-Bouzán 2022; Gan et al. 2023). Microplastics threaten aquatic ecosystems by releasing toxic additives and transporting organic pollutants and heavy metals (Caruso 2019; Fu et al. 2021; Issac and Kandasubramanian 2021; Ta and Babel 2023). These impacts may disrupt food webs, alter nutrient cycles, modify habitats, and potentially cause genetic changes in aquatic organisms (Thacharodi et al. 2024).

Previous studies reported surface water microplastic concentrations in the Musi Estuary at 467.67±127.84 particles/m³ during flood tide and 723.67±112.05 particles/m³ at ebb tide (Diansyah et al. 2024). These microplastics often bind with toxic heavy metals, such as lead (Pb) and copper (Cu), amplifying their environmental harm (Purwiyanto et al. 2022). Microplastics in the water column tend to settle in estuarine sediments, the second-largest global reservoir after fjords (Harris 2020). Microplastic accumulation in estuarine sediments raises ecological concerns, especially due to ingestion by benthic organisms like *A. granosa* (Fitri and Patria 2019; Saleh et al. 2023; Mohan et al. 2024; Rahmatin et al. 2024). While numerous studies have examined microplastic concentrations in the water column, research on their distribution in sediments and bioaccumulation in benthic species, particularly *A. granosa*, remains limited.

This study aims to investigate the bioaccumulation and risks of microplastic pollution in sediments and *A. granosa* in the Musi Estuary, Indonesia. The findings are expected to enhance understanding of benthic organisms, especially *A. granosa*, and its potential health risks for local seafood consumers.

MATERIALS AND METHODS

Study area and sample collection

The Musi Estuary, located on the east coast of South Sumatra, Indonesia is where seawater from the Bangka Strait mixes with freshwater from the Musi River. The Musi Esturay is an important area for fisheries and benthic habitats in South Sumatra, Indonesia (Rozirwan et al. 2021, et al. 2022b). Sampling locations were selected based on hydrodynamic conditions influencing microplastic transport and deposition, considering salinity variations and water mass interactions (Cheng et al. 2024; Diansyah et al. 2024). Locations of the sampling sites are shown in Figure 1 and Table 1. Based on in situ measurements, water parameters include temperature (27.31-31.6°C), pH (6.95-8), dissolved oxygen (3.62-5.21 mg/L), salinity (6-30‰), water brightness (0.1-0.9 m), water current speed (0.1-1.8 m/s). Sediment and *A. granosa* were collected during low tide from the Musi Estuary, South Sumatra, Indonesia. Sediment samples were collected from ten sampling points using a Peterson Grab at each station (Dwiyitno et al. 2024). Samples were placed in glass jars that had been rinsed with pure distilled water and covered using aluminum foil to avoid contamination. Samples were placed in a cool box (±4°C) for further analysis in the laboratory.

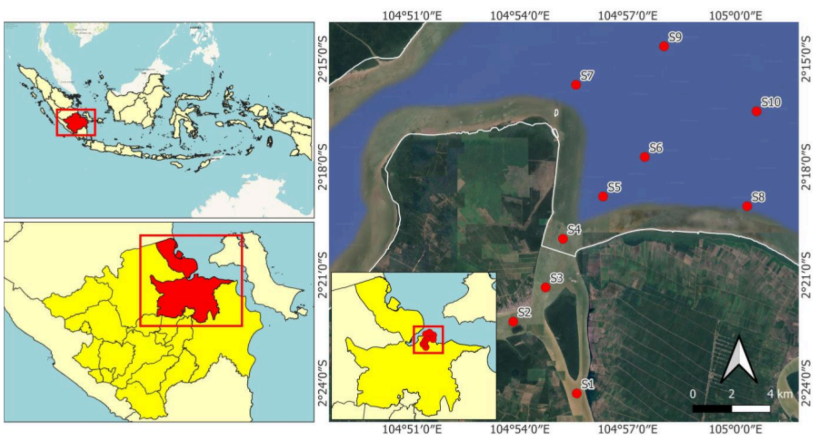

Figure 1. Study site at the Musi Estuary, South Sumatra, Indonesia

Table 1. Coordinates of the sampling location

Estuary zone	Description	Station	Latitude (°S)	Longitude (°E)
Inner zone	closest to the river body and dominated by freshwater	S1	2.40470°S	104.92643°E
	mangrove vegetation and muddy substrate	S2	2.37144°S	104.89695°E
	near densely populated coastal village activities, shipping and fishing activities	S3	2.35558°S	104.91200°E
Middle zone	between the inner zone and the outer zone	S4	2.33316°S	104.92003°E
	mangrove vegetation and muddy substrate	S5	2.31353°S	104.93862°E
	shipping and fishing activities	S6	2.29524°S	104.95794°E
Outer zone	closest to the ocean (at the sea), dominated by seawater,	S7	2.26183°S	104.92603°E
	no vegetation, muddy substrate	S8	2.31807°S	105.00547°E
	shipping and fishing activities	S9	2.24403°S	104.96686°E
		S10	2.27413°S	105.00978°E

Anadara granosa samples were identified based on their morphological traits according to the World Register of Marine Species (WoRMS) (Abelouah et al. 2024). Twenty adult *A. granosa* (7.48-11.44 cm) were collected from fishermen's catch in the Musi Estuary. *Anadara granosa* samples were identified based on their morphological traits according to the World Register of Marine Species (WoRMS) (Abelouah et al. 2024). The mussels were rinsed with pure distilled water to remove any dirt. *Anadara granosa* were wrapped in aluminum foil and stored in a cooler at approximately 4°C to preserve their freshness. After that, they were transported to the laboratory and frozen at -20°C before further analysis (Ding et al. 2021).

Microplastic extraction from sediment

Microplastics in sediments were extracted using the standard method of density separation and organic matter removal with minor modifications (Thompson et al. 2004; Nabezeit and Dubaish 2012). A total of 500 g of wet sediment samples were placed in a beaker glass covered with aluminum foil. The samples were dried in an oven at 60°C for 48 hours, or until they reached a constant mass (Patria et al. 2023). The sediment samples were pulverized and sieved through a 5 mm steel sieve. A portion of 100 g of dried sediment was taken from the sieve, placed into a beaker glass, and covered with aluminum foil to prevent external contamination.

The sample was suspended in 400 mL of saturated NaCl solution (1.2 g cm^{-3}), which is four times the sample weight, using a magnetic stirrer. This NaCl solution was prepared by dissolving pure NaCl crystals (Merck Millipore EMSURE®) in filtered distilled water that was free from contaminants. The selection of a NaCl solution for the separation of microplastics from sediments was based on the premise that this method is cost-effective and environmentally friendly (Perumal and Muthuramalingam 2022).

Stirring was carried out for 5 minutes until completely dissolved, and the mixture was allowed to stand for 1 hour. After one hour, 10 mL of 30% H_2O_2 was added to assist in the breakdown of organic matter, followed by stirring for an additional five minutes. Hydrogen peroxide (H_2O_2) is commonly used in similar studies and is regarded as highly effective for organic matter removal (Lee et al. 2023). The sample was allowed to stand for 24 hours, covered with aluminum foil. The samples were then filtered using the Whatman No. 42 filter paper (mesh size 0.45 µm, Φ = 90 mm), assisted by a vacuum pump at 17 kPa to isolate the microplastics. The collected samples were deposited into petri dishes for identification.

Microplastic extraction from *Anadara granosa*

The previously frozen *A. granosa* samples were defrosted under controlled conditions at room temperature (±25°C) for 1 hour. After the ice melted, the *A. granosa* were washed with pure distilled water to eliminate contamination from other objects, such as sediment. The length and wet weight of the *A. granosa* were measured using an analytical balance (0.01 g). The digestive tract was carefully removed from the *A. granosa* using sterile stainless steel utensils that had been rinsed with distilled water. The extraction of microplastics from the digestive tract of the *A. granosa* was adapted from previous studies with minor modifications (Ding et al. 2018, et al. 2021). The digestive tract was transferred into an Erlenmeyer flask, and 100 mL of KOH solution (10%) was added. The use of KOH is regarded as a more efficacious method for the digestion of biological material, and it has no impact on the integrity of the plastic polymer (Karami et al. 2017). The sample was covered with aluminum foil and stirred for 5 minutes using a 150 rpm magnetic stirrer. The supernatant was incubated at room temperature (±25°C) until complete digestion of organic matter occurred. The sample was then filtered through Whatman 42 filter paper (mesh size 0.45 µm, Φ = 36 mm) to isolate microplastic. The filter paper was dried in an oven at 40°C for 5 hours and stored in petri dishes for subsequent identification of microplastic content.

Microplastic identification and quantification

Identification and quantification of microplastics from sediments and *A. granosa* were performed using the same method. Microplastic identification was performed using an Olympus CX23 microscope with 10 × 10 or 4 × 10 magnification to visually detect microplastics (Diansyah et al. 2024). The filter paper was observed closely and carefully to avoid contaminants that could enter the filter paper. Microplastics were identified based on the number and form of microplastics (fragment, film, fiber, and foam).

The data obtained were recorded by sample type and station/individual for statistical purposes. To prevent contamination, personnel wear cotton lab coats, latex gloves, and cotton masks. Furthermore, access to the detection room is restricted to prevent outside contact during observations.

Procedures for quality assurance and contamination prevention

The quality and contamination control measures were implemented to prevent any alterations to the microplastics in the samples. Before sampling, glass jars and aluminum foil were rinsed with filtered distilled water. Although the samples were in a cool box, they were stored in a place that was not exposed to direct sunlight to keep the samples in good condition. Personnel are also required to wear latex gloves during sampling. During the study, from sampling to laboratory analysis, the use of plastic equipment was minimized to avoid unintentional fragmentation of the microplastics. The distilled water used was filtered with filter paper (0.45 μm,) to prevent microplastics from entering our materials. All equipment was washed with filtered distilled water to remove potential contamination from external particles (Ding et al. 2021). We prepared two controls by filtering each solution we used to avoid contaminants from materials, equipment, and air. No microplastics were found contaminating the instrument. The sterilized equipment was wrapped in aluminum foil to prevent any input of contaminants from outside. Laboratory personnel were required to wear latex gloves, lab coats, and masks throughout the analysis. Access to the laboratory was restricted during the analysis to minimize external interference that could lead to protocol errors.

Data analysis

Pollution Load Index (PLI)

PLI was calculated using a pollutant load approach, which assesses the total concentration of contaminants relative to a baseline level, to evaluate its significance. Equations were utilized to quantify the level of microplastic pollution in both sediments and *A. granosa* in the Musi Estuary, with the method adapted accordingly (Tomlinson et al. 1980; Xu et al. 2018; Wang et al. 2021):

$$CF_i = \frac{C_i}{C_{0i}}$$

This equation shows that the Concentration Factor (CF_i) at a particular sample is obtained by dividing the current Concentration (C_i) by the Initial Concentration (C_{0i}). Ci indicates the quantified presence of microplastics at each sampling location or within each clam (ind), while C_{0i} denotes the background concentration, defined as the lowest value recorded across all sampling locations. Given the lack of previously published research on microplastics in sediments or *A. granosa* in the Musi River Estuary, we determined C_{0i} values from minimum concentrations across sampling stations.

$$PLI = \sqrt{CF_i}$$

This equation shows that the Pollution Load Index (PLI) is generated by calculating the square root of the Concentration Factor (CF). The PLI value of microplastics is derived from the Contaminant Factor (CF_i) calculated for each station/individual.

$$PLI_{zone} = \sqrt[n]{PLI_1 \times PLI_2 \times \ldots\ PLI_n}$$

Pollution Load Index of Zone (PLI_{zone}) is determined by taking the square root of the product of individual PLI values from multiple sites within the zone. This method integrates data from several measurement points, providing a more comprehensive assessment of microplastic contamination within the analyzed. A PLI_{zone} is used to assess pollution based on specific estuary zones as well as the overall estuary area. PLI values are categorized into four predefined categories of pollution load, as shown in Table 2.

Nemerow Pollution Index (NPI)

NPI is designed to assess the bioavailability of microplastics in sediments and *A. granosa*. This index was adapted from equations used in prior studies evaluating heavy metal contamination (Alam et al. 2023).

$$NPI = \sqrt{\frac{\left(\frac{C_i}{S_i}\right) max^2 + \left(\frac{C_i}{S_i}\right) ave^2}{2}}$$

The NPI value is calculated using the square root of the mean squared deviation, incorporating both the maximum and average concentration ratios relative to the background concentration (S_i). The formula includes the sum of the squares of the maximum concentration ratio ($C_{i\ max}/S_i$) and the average concentration ratio ($C_{i\ ave}$). The Ci value represents the concentration of microplastics found in the sediment or clams at a specific station or individual, while the Si value denotes the background level of microplastics, determined as the lowest concentration recorded across all sample types. The NPI provides a measure of microplastic bioavailability in sediments and *A. granosa*, with values below 2 indicating low bioavailability and values above 2 indicating high bioavailability.

Bioconcentration Factor (BCF)

The Bioconcentration Factor (BCF) quantifies the extent to which microplastics accumulate in biota relative to their environmental concentration and is calculated using the following equation (Li et al. 2022a).

Table 2. Microplastic pollution load categories

Definition	Value			
Value of the Pollution Load Index (PLI)	<10	10-20	20-30	>30
Risk category Information	I Minor	II Middle	III High	IV Extreme

$$BCF = \frac{C\ biota_{ave}}{C\ sediment_{ave}}$$

In this equation, BCF represents the bioconcentration factor, which is derived from the calculation of the average concentration of microplastic in biota (*A. granosa*) divided by the average concentration of microplastic in its environment (sediment). This value is intended to assess how much microplastic is concentrated in the biota.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics 27. Descriptive statistics, including total, mean, standard deviation, percentage, minimum, and maximum, were utilized to assess data variation. A One-Way ANOVA was applied to analyze differences in microplastic abundance between estuarine zones when the data met normality assumptions. For non-normal data, the Kruskal-Wallis test was employed to assess the significance of differences between zones. All tests were carried out with a significance level of α = 0.05.

RESULTS AND DISCUSSION

Microplastic presence in sediment from Musi Estuary

The Musi Estuary in South Sumatra, Indonesia, is a dynamic brackish water environment where freshwater from the Musi River meets the saltwater of the Bangka Strait (Figure 2). Characterized by turbid waters and muddy sediments rich in organic matter, the estuary is fringed by mangrove forests that provide habitat for aquatic species, including the *A. granosa*, a key species in local aquaculture (Rozirwan et al. 2023c). Surrounded by urban and industrial areas, including Palembang, the estuary faces pollution from domestic, agricultural, and industrial waste, making it susceptible to microplastic accumulation in sediments and ingestion by benthic organisms like *A. granosa* (Almiza and Patria 2021; Diansyah et al. 2024).

The results of this study indicate that microplastics were detected at all sampling stations, as shown in Figure 4. A total of 1,308 microplastic particles were identified, with concentrations ranging from 66 to 178 particles per 100 g of dry sediment (dry weight, dw). The average abundance of microplastics was 1.31±0.41 particles/g dw, with the highest concentration found at station S1 (1.78 particles/g dw) and the lowest at station S8 (0.66 particles/g dw). High levels of human activity in the upstream area of Musi Estuary, which flows downstream to the estuary and ultimately into the ocean, are responsible for the presence of microplastics (Rozirwan et al. 2021; Diansyah et al. 2024). Urban activities in close proximity to the Musi River Watershed, particularly in Palembang City, significantly contribute to the generation of plastic waste. Increased population density near riverbanks enhances the potential for plastic pollution. Furthermore, population density is a crucial factor in the entry of microplastics into rivers (Eo et al. 2023; Dwiyitno et al. 2024). As a result, plastic pollutants from domestic activities, such as the disposal of food packaging and plastic bags, can be transported through stormwater drains and eventually end up in rivers (Kunz et al. 2023). Fishing activities around Musi Estuary can contribute to microplastic pollution, primarily through fibers released from fishing nets (Li et al. 2022a Fauziyah et al. 2023). This increases anthropogenic pressure at river mouths, which can lead to a greater accumulation of microplastics (Castro-Jiménez et al. 2024). Additionally, tidal fluctuation influences water flow, which facilitates the deposition of microplastics in sediment at these locations (Harris 2020). The findings of this study indicate that anthropogenic activities are responsible for high levels of microplastic deposition in the sediments of Musi Estuary. Microplastic particles that accumulate in sediments serve as a habitat for benthic organisms, which can have long-term implications for ecosystem health and balance (Rahmatin et al. 2024). As vectors for pollutants, microplastics can exacerbate toxicity, potentially endangering various populations (Caruso 2019; Fu et al. 2021; Issac and Kandasubramanian 2021; Ta and Babel 2023). Furthermore, the processes of bioaccumulation and biomagnification in benthic organisms present heightened risks to these animals, potentially leading to human consumption (Unuofin and Igwaran 2023). Therefore, it is crucial for local governments to address the handling and prevention of further microplastic accumulation.

Figure 2. General conditions in the Musi Estuary, South Sumatra, Indonesia: A. Coastal settlements; B. Shipping activities; C. Fisheries; D. Mangrove ecosystem

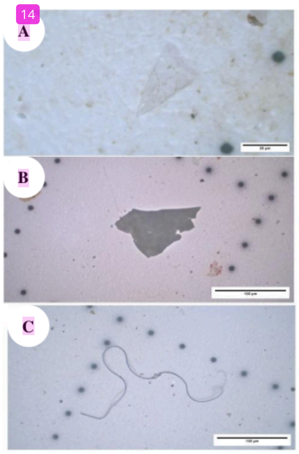

Figure 3. Various forms of microplastics from Musi Estuary, South Sumatra, Indonesia: A. Film; B. Fragment; C. Fiber

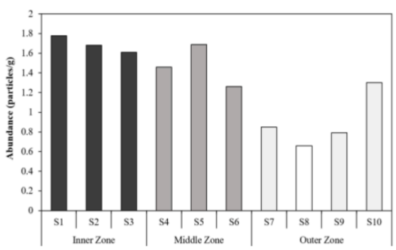

Figure 4. Distribution of microplastics from sediments in Musi Estuary, South Sumatra, Indonesia

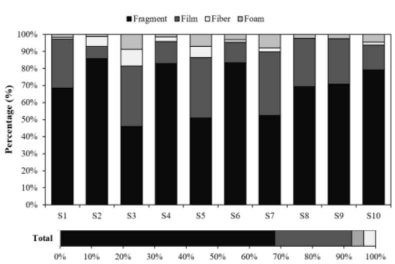

Figure 5. Percentage abundance of microplastic shapes form sediments in Musi Estuary, South Sumatra, Indonesia

The microplastics identified in the sediments were predominantly fragments (68.92%), followed by films (23.86%), fibers (4.05%), and foams (3.17%) (Figure 3 and Figure 5). The dominance of fragments, which are a common form of secondary microplastics, occurs as a result of macroplastic degradation (Barnes et al. 2009). Fragments represented the most common type across all sediment samples analyzed. This dominance of fragments in estuarine sediments aligns with findings from various studies conducted in other estuarine environments. Research indicates that estuarine sediments globally tend to accumulate diverse microplastic forms, particularly fibers (Firdaus et al. 2020; Alam et al. 2023; Samuels et al. 2024; Santucci et al. 2024), with many studies also reporting a predominance of fragment types (Zhou et al. 2021; Suteja et al. 2024). These observations corroborate the literature, which consistently shows that fibers and fragments constitute the majority of microplastic pollution in estuarine ecosystems (Feng et al. 2023a).

This study reveals notable variations in microplastic concentrations compared to similar research in estuaries globally. Our findings indicate that the Musi Estuary has lower microplastic concentrations than those reported in several other Indonesian and international estuaries. For example, the Jakarta Bay Estuary exhibits concentrations nearly ten times higher, ranging from 1,184 to 1,337 particles per 100 grams of river sediment and 804 to 1,055 particles per 100 grams of beach sediment (Dwiyitno et al. 2024). Such elevated levels are likely due to increased anthropogenic activities along Jakarta's rivers, which substantially contribute to plastic waste flow. In another comparison, the Pearl River Estuary in China also shows higher microplastic densities, with concentrations between 2.05×10^3 and 7.75×10^3 particles per kilogram of dry weight sediment (Xu et al. 2024). This estuary's coastal regions experience high human activity, enhancing the potential for microplastic deposition. Similarly, the Meghna Estuary in Bangladesh, which receives sediment from the Ganges River Basin, reports even higher microplastic levels at 4,014.66±1,717.59 particles per kilogram dry weight (Alam et al. 2023). These findings underscore the significant role of anthropogenic influences on microplastic accumulation in global estuarine sediments, including the Musi Estuary. Other environmental factors, like location, sampling period, sediment depth, sediment composition, and local hydrodynamic conditions, may also affect these changes in the amount of microplastics found (Zheng et al. 2020; Feng et al. 2023b; Yuan et al. 2023).

In contrast, the abundance of microplastics in the sediments of the Musi Estuary surpasses levels reported in other regions, both within Indonesia and globally. Concentrations in the Musi Estuary are notably higher than those in the Zandvlei River Watershed and estuarine areas of South Africa (70.23±7.36 particles/kg dw) (Samuels et al. 2024), the Claromecó Estuary in Argentina (299±114 particles/kg dw) (Truchet et al. 2021), and the upper sediment layer (0-5 cm) of the Fuhe River Estuary in Northern China (1049±462 particles/kg dw) (Zhou et al. 2021). These numbers are also higher than those found in coastal Río de la Plata (547.83±620.06 particles/kg dw) (Santucci et al. 2024), Benoa Bay, Bali (31.08±21.53 particles/kg dw) (Suteja et al. 2024), Jagir Estuary in Surabaya (up to 590 particles/kg dw) (Firdaus et al. 2020), and the Pekalongan River Estuary in Java (0.77 to 1.01 particles/g dw) (Ismanto et al. 2023). The high microplastic concentration in the Musi Estuary is likely due to extensive plastic waste disposal in the river basin by the surrounding community. Research supports that plastic debris forms a substantial part of the macro-waste in the Musi River (Maherlsa et al. 2019). Additionally, local communities frequently establish settlements along the river, relying on it for water access and transportation. Consequently, domestic waste, including plastic, often enters the river directly. This local waste management issue reflects a broader trend, with Indonesia identified as the world's second-largest contributor to oceanic plastic pollution, following China (Jambeck et al. 2015).

Spatial distribution microplastic in sediments

The study revealed that the abundance of microplastics was significantly higher in the inner and middle zones when compared to the outer zone. The mean abundances were 1.69±0.08 particles/g dw in the inner zone, 1.47±0.22 particles/g dw in the middle zone, and 0.9±0.28 particles/g dw in the outer zone. Significant differences in mean microplastic abundance between zones were revealed by the one-way ANOVA ($p<0.05$) as illustrated in Figure 6. The Tukey HSD test revealed no significant difference in mean microplastic abundance between the inner and middle zones. However, we observed a significant difference in the outer zone compared to both the middle and outer zones. Our results indicate that the inner and middle estuary regions exhibit greater mean concentrations of microplastics compared to the outer estuary. Natural factors, particularly the effects of currents and wave action in coastal and estuarine environments, significantly influence this phenomenon by altering microplastic distribution. The influx of freshwater promotes the sedimentation and prolonged retention of high-density microplastics within the system (Li et al. 2024a). Furthermore, the sedimentation process is affected by the density and buoyancy of microplastics, with increased salinity in estuarine waters enhancing buoyancy forces and influencing distribution patterns (Cheng et al. 2024). Our findings align with research from the Liaohe Estuary in China, revealing a higher accumulation of microplastics in inner river sediments compared to the outer estuary (Xu et al. 2020). Additionally, sampling depth plays a critical role in accurately measuring microplastics in surface waters, bottom layers, and sediments (Feng et al. 2023a).

The spatial analysis revealed distinct patterns of microplastic accumulation between the two sides of the coast adjacent to the estuary. Notably, Site S7 exhibited higher concentrations compared to Site S8, likely due to its proximity to other pollution sources. Specifically, S7 is located near the Banyuasin Estuary, which is believed to significantly contribute to the deposition of microplastics in the surrounding sediments. Based on da Costa et al. (2023), confirmed that nearby sources of pollution heavily influence microplastic deposition in coastal regions. The accumulation of microplastics at the mouth of the adjacent river further exacerbates this phenomenon, facilitating the settlement of microplastics within the sediment. Additionally, studies suggest that the depth of the sampling locations significantly influences microplastic deposition, revealing a greater abundance of microplastics at deeper water levels (Bayo et al. 2022). The substantial accumulation of microplastics in sediments is attributed to their persistent characteristics as well as the protective conditions offered by deeper environments, which are shielded from UV light, maintain lower temperatures, and exhibit low oxygen levels, thus slowing biodegradation processes (Zhang et al. 2021).

Our findings confirm the presence of microplastics in the sediments of the Musi Estuary, likely originating from suspended microplastics that eventually settle from the water's surface. Previous research has found that there are 467.67±127.84 particles/m³ and 723.67±112.05 particles/m³ of microplastic in surface waters during ebb and flow conditions, respectively (Diansyah et al. 2024). Hydrodynamic conditions in the estuary and processes like aggregation and biofouling, which increase microplastic density, influence the deposition of these particles (Malli et al. 2022). The specific properties of the microplastics and the water dynamics of the estuary strongly influence microplastic deposition. For instance, biofouling can make microplastics denser, accelerating their descent into sediments (Lin et al. 2023). Since microplastics often have higher densities than water, they can remain suspended in the water column before eventually settling (Dai et al. 2022). High Total Suspended Solids (TSS) in the Musi Estuary have the potential to cause aggregation of microplastics (Rahutami et al. 2022). High TSS levels make it easier for sediments and other suspended particles to stick together on microplastic surfaces, which speeds up their deposition (Yang et al. 2022). However, microplastics can also become resuspended in the water column (Tang et al. 2020). Stirring forces in estuarine environments can lift microplastics back into the water, where turbulence and bioturbation may redistribute them (Malli et al. 2022). Therefore, additional studies are required to fully characterize the mechanisms of microplastic deposition in the Musi Estuary. Climate factors also influence microplastic distribution in Musi Estuary sediments. In Indonesia, where regions such as the Musi Estuary experience distinct rainy and dry seasons, seasonal changes affect water dynamics and microplastic transport. During the rainy season, increased river velocity may carry microplastics upward from sediments, while in the dry season, slower flows facilitate microplastic accumulation at the water's surface (Zhao et al. 2020). Currently, there are no studies specifically examining the seasonal impact on microplastic presence in the Musi Estuary, underscoring the need for further research to address this gap.

Bioaccumulation of microplastics in *Anadara granosa*

We extracted 133 microplastic particles from the digestive tracts of twenty samples of *A. granosa* species presented in Figure 7. Each sample from the Musi Estuary had accumulated microplastics, ranging from 6 to 49 particles/ind or 8 to 69.01 particles/g ww, as shown in Figures 8 and 9. The mean abundance of microplastics found in the digestive tracts was 21.05±10.31 particles/ind or 30.46±16.7 particles/g ww. Several factors contribute to the increased microplastic inputs in bivalve species, including human activities, tourism, fishing equipment, freshwater runoff, and wastewater discharges combined with the area's hydrodynamic conditions (Vital et al. 2021). The elevated levels of microplastics found in *A. granosa* from the Musi River Estuary suggest a significant degree of contamination in their habitat, including both water and sediment, which may adversely affect the health of these organisms and disrupt local ecological balances. This observation aligns with existing literature, which indicates a strong correlation between the abundance of microplastics in bivalves, such as mussels, and their sediment environments (Sathish et al. 2020), reinforcing the need for monitoring these pollutants in aquatic ecosystems.

Microplastics were observed in three morphological forms: film, fiber, and fragment. Film accounted for the majority of microplastics (59.38%), followed by fiber (31.59%) and fragments (9.03%), as shown in Figure 10. The digestive tracts of the *A. granosa* studied did not contain any pellets or foam. Statistical analysis using the Kruskal-Wallis test revealed significant differences in the abundance of the three microplastic forms ($p<0.05$). This predominance of film microplastics in *A. granosa* is likely attributable to the extensive use of disposable plastic packaging within the community, which subsequently degrades into microplastics. Although fragments dominate the sediment substrate, *A. granosa* predominantly absorbs film microplastics. The lower density of film microplastics may facilitate their accumulation in the upper sediment layer, making them susceptible to resuspension in the overlying water column. This phenomenon is consistent with the feeding behavior of *A. granosa*, which frequently filters water from the sediment surface, resulting in the accumulation of film microplastics within their digestive tracts.

Our findings indicate a higher abundance of microplastics in *A. granosa* from the Musi Estuary compared to certain other regions globally. For instance, *A. granosa* from the Chanthaburi estuarine ecosystem in eastern Thailand contained 0.40±0.16 particles/g ww (Potipat et al. 2024), while samples from Peninsular Malaysia showed concentrations of 0.20±0.08 particles/g ww and 1.54±0.30 particles/ind ww (Mohan et al. 2024). Additionally, microplastic levels in *A. granosa* from Pao Village, Tarowang Sub-district, Jeneponto District, Indonesia, were measured at 0.0144 particles/g ww (Namira et al. 2023), and those from Likas Bay Beach in North Borneo, Malaysia, at 24.4±0.6 particles/g ww (Abd Rahman et al. 2024). In contrast, the *A. granosa* analyzed in this study accumulated lower microplastic concentrations than those reported in several other studies. For instance, *A. granosa* from the Pangkal Babu mangrove forest area in Tanjung Jabung Barat District, Jambi, exhibited 434±97.05 particles/ind (Fitri and Patria 2019), while those from Lada Bay in Pandeglang, Banten, had concentrations of 618.8±121.4 particles/ind (Ukhrowi et al. 2021). Overall, this study shows that microplastics have contaminated the sediment environment of the Musi Estuary, South Sumatra, indicating that *A. granosa* can serve as effective bioindicators of this pollution.

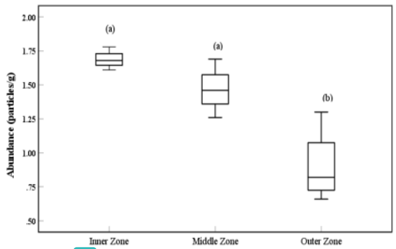

Figure 6. The difference in microplastic abundance between zones in the sediments from Musi Estuary, South Sumatra, Indonesia

Figure 7. Specimens of *Anadara granosa* from Musi Estuary, South Sumatra, Indonesia

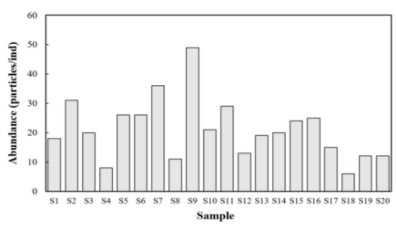

Figure 8. Microplastic abundance of *Anadara granosa* from the Musi Estuary, South Sumatra, Indonesia

Table 3. The microplastic risk factor in sediments of Musi Estuary, South Sumatra, Indonesia

Sediment Station	CF	PLI	PLI zone	PLI sediment	NPI
S1	2.70	1.64	Inner zone 1.60	1.37	2.37
S2	2.55	1.60			
S3	2.44	1.56			
S4	2.21	1.49	Middle zone 1.49		
S5	2.56	1.60			
S6	1.91	1.38			
S7	1.29	1.13	Outer zone 1.20		
S8	1.00	1.00			
S9	1.20	1.09			
S10	1.97	1.40			

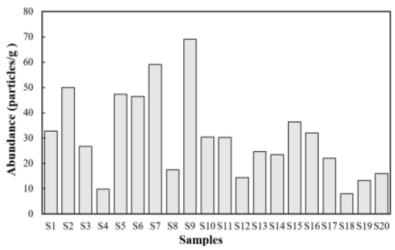

Figure 9. Microplastic abundance (in particles/g) of *Anadara granosa* from the Musi Estuary, South Sumatra, Indonesia

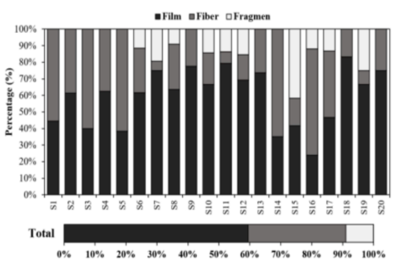

Figure 10. Shape of microplastics in *Anadara granosa* from the Musi Estuary, South Sumatra, Indonesia

Risk assessment of microplastics in sediments and *Anadara granosa*

A risk assessment of microplastic contamination in the Musi River Estuary was carried out by calculating the Pollution Load Index (PLI), the Nemerow Pollution Index (NPI), and the Bioconcentration Factor (BCF). The PLI values across all sediment samples indicate that the estuarine sediment is subject to minor pollution, with values ranging between 1.00 and 1.64, as shown in Table 3. In the three zones of the estuary (inner, middle, and outer), the PLI values were 1.60, 1.49, and 1.20, respectively. We calculated the overall average PLI for the Musi Estuary to be 1.37. All zones reported PLI values below 3.00, which suggests that the area experiences only minor microplastic pollution. The analysis of microplastic presence in sediment samples revealed a significantly high concentration of microplastics, with an NPI value of 2.37. This suggests a substantial bioavailability of microplastics in the estuarine environment. This elevated NPI underscores the ecological risk posed by microplastic contamination, despite the relatively low PLI observed across the study area.

Anadara granosa analyzed in this study exhibited significant risk values associated with microplastic contamination. The PLI for these clams ranged from 1 to 2.86, with an overall mean PLI value of 1.77 for the entire sample, as shown in Table 4. This indicates that the pollution load in *A. granosa* falls within the minor category (PLI<3). Furthermore, the bioavailability of microplastics in *A. granosa* was significantly higher, with an NPI value of 6.29, indicating a high bioavailability. The bioconcentration factor of microplastics from sediment to *A. granosa* was measured at 23.28, suggesting a significant potential for the transfer of microplastics from sediment to *A. granosa* in the Musi Estuary.

Our findings demonstrated that the bioavailability of microplastics in sediments and *A. granosa* was categorized as high (NPI = 2.37; NPI>2). In comparison, the bioavailability of microplastics in *A. granosa* was even higher, with an NPI value of 9.89. The elevated bioavailability in sediments suggests a greater potential for absorption by aquatic organisms, particularly benthic animals. Furthermore, the Bioconcentration Factor (BCF) calculated for *A. granosa* in sediment was 23.28, indicating a significant transfer of microplastics from sediments to these organisms in the Musi Estuary. This high BCF value is attributed to the non-discriminatory feeding process of *A. granosa*, allowing them to ingest microplastics along with other particles. When compared to several benthic species from the Yangtze River Estuary, which exhibited a BCF of 29.48±6.52 (Li et al. 2022c), the BCF of *A. granosa* in the Musi Estuary remains lower. Nonetheless, both sediments and *A. granosa* from the Musi Estuary are classified within the minor pollution risk index category (PLI<10). The bioaccumulation of microplastics by benthic animals like *A. granosa* poses a significant risk to human health for those consuming these clams (Wang et al. 2023; Winiarska et al. 2024). Therefore, periodic assessments are crucial to evaluate the risk of microplastic contamination in sediments and *A. granosa*, providing essential information to understand the ecological and health implications in the Musi Estuary.

The impact of high bioaccumulation extends beyond the toxicity of microplastic materials; it also facilitates the accumulation of other pollutants. Previous research has detected heavy metals, such as lead (Pb) and copper (Cu), adhering to the surfaces of microplastics in the Musi Estuary (Purwiyanto et al. 2020). Additionally, various hazardous heavy metals, including iron (Fe), cadmium (Cd), chromium (Cr), lead (Pb), and zinc (Zn), were identified with high bioavailability in the aquatic environment of the Musi Estuary (Rahutami et al. 2022). This accumulation allows for the deposition of significant quantities of heavy metals on microplastic surfaces, thereby increasing the risk of microplastic toxicity for estuarine ecosystems. Moreover, the involvement of microorganism vectors, misidentification in aquatic organisms' diets, and their harmful toxicological effects on benthic animals heighten the risk associated with microplastics (Gong and Xie 2020). Consequently, the high output of microplastics from the Musi Estuary has the potential to jeopardize the condition of the surrounding aquatic environment, including fisheries and migratory birds, which are critical to the ecosystem (Rozirwan et al. 2019, 2022a).

This study holds significant ecological implications for the Musi Estuary ecosystem, as the presence of microplastics poses a long-term threat to ecosystem stability. Previous studies have shown that microplastics can affect the physicochemical properties of sediments, such as electrical conductivity, organic matter content, and nutrients, and well as impair enzymatic activity in sediment bacteria (Rillig 2012; Li et al. 2022b; Yuan et al. 2023). These changes can lead to structural and functional alterations in aquatic habitats (Li et al. 2022b). Microplastics can also enter various levels of the food chain through bioaccumulation and biomagnification processes. For example, microplastics in plankton can cause a decline in zooplankton populations, which impacts food availability for small fish and predatory species at higher trophic levels (Malinowski et al. 2023). The accumulation of microplastics in *A. granosa* in this study indicates that the pressure of plastic waste in the Musi Estuary is already quite high. Microplastics can act as vectors for other pollutants, such as microorganisms, heavy metals, and other inorganic pollutants can increase the risk of toxicity for aquatic organisms, including *A. granosa* (Purwiyanto et al. 2020; Rafa et al. 2024). Research indicates that exposure to microplastics can lead to behavioral and physiological changes in aquatic organisms, including changes in diet and reproductive success (Guo et al. 2020; Liang et al. 2023). Moreover, microplastics disrupt endocrine functions and metabolic pathways, causing oxidative stress, cell necrosis, and apoptosis, which can ultimately lead to mortality (Pannetier et al. 2020; Jeyavani et al. 2021). Disruption of any component of the food chain can trigger a domino effect, threatening the balance of the Musi Estuary ecosystem. However, this study only examines microplastic pollution in sediment and *A. granosa* as environmental indicators. Additional research is needed to understand microplastic buildup in other species, such as fish, shrimp, and benthic organisms, for a more complete picture of microplastic pollution in the Musi Estuary and its impact on the global marine environment.

Microplastic contamination of *A. granosa* in the Musi Estuary poses a significant threat to local communities, particularly clam fishers. Microplastics that accumulate in *A. granosa* may pose health risks to community members who consume them regularly as a primary source of protein. Long-term exposure to microplastics can potentially disrupt various human body systems, including the digestive, respiratory, reproductive, nervous, and cardiovascular systems (Li et al. 2024b). Furthermore, microplastics may cause both acute and subchronic toxicity and are considered potentially carcinogenic and disruptive to human development (Yuan et al. 2022). Once in the bloodstream, microplastics can be transported to the liver, the primary organ responsible for detoxification. Accumulation in the liver may trigger adverse physiological reactions, including increased oxidative stress, liver fibrosis, and impaired lipid metabolism. In addition to health risks, microplastic contamination in *A. granosa* in the Musi Estuary may reduce consumer confidence and decrease market demand due to food safety concerns (Unuofin and Igwaran 2023). The long-term effect could weaken local economic resilience as marine products in the region are perceived to be contaminated with microplastics (Barrientos et al. 2024). Therefore, it is crucial for governments and communities to recognize these risks and collaborate on mitigation efforts to protect ecosystems, public health, and local economies.

Furthermore, seafood hygiene practices in local communities and fishing industries can help reduce microplastic contamination (Lusher et al. 2017; Smith et al. 2018). For example, *A. granosa* and other seafood, when thoroughly cleaned by repeated washing and clam removal before cooking, may reduce microplastic intake (Li et al. 2022a). The concentration of microplastics in shellfish is significantly lower after boiling and steaming compared to frying, suggesting that cooking methods affect microplastic retention in seafood (Evode et al. 2021). This method can also be applied to shrimp, fish, and other shellfish to lower the risk of microplastic exposure. Implementing these recommendations will help reduce microplastic pollution and provide long-term benefits for public health, ecosystem stability, and the economic resilience of local fisheries (Prata et al. 2019).

Table 4. Risk factors for microplastics in *Anadara granosa* from the Musi Estuary, South Sumatra, Indonesia

A. granosa sample	CF	PLI	PLI A. granosa	NPI	BCF
S1	3.00	1.73	1.77	6.29	23.28
S2	5.17	2.27			
S3	3.33	1.83			
S4	1.33	1.15			
S5	4.33	2.08			
S6	4.33	2.08			
S7	6.00	2.45			
S8	1.83	1.35			
S9	8.17	2.86			
S10	3.50	1.87			
S11	4.83	2.20			
S12	2.17	1.47			
S13	3.17	1.78			
S14	3.33	1.83			
S15	4.00	2.00			
S16	4.17	2.04			
S17	2.50	1.58			
S18	1.00	1.00			
S19	2.00	1.41			
S20	2.00	1.41			

In conclusion, this study demonstrates the significant presence of microplastics in the sediment and *A. granosa* in the Musi Estuary, Indonesia. These findings indicate a serious threat to the aquatic ecosystem and to local public health, as microplastics can enter the food chain and potentially harm organisms across trophic levels, including humans (Ningrum and Patria 2022; Edwin et al. 2023; Patria et al. 2023). This pollution heightens environmental risks, particularly for species integral to both the community's diet and economy (Jeong et al. 2024). The microplastics likely originate from human activities, especially urban waste from upstream areas that flows downstream and accumulates in the estuary (Diansyah et al. 2024). These results highlight the urgent need for routine monitoring and stricter waste management practices, particularly for plastic disposal, to reduce further contamination (Barletta et al. 2019). A comprehensive strategy is essential to controlling plastic waste throughout the river system—from source to estuary. Effective measures should include coordinated waste management practices, public education on the impact of pollution, and cross-sector collaboration to preserve estuarine health (Wakwella et al. 2023; Ihenetu et al. 2024). Such initiatives are crucial to protecting ecosystem health and sustaining local fisheries, ensuring these resources continue to support community well-being.

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Implication of microplastic presence in sediment and blood clams Anadara granosa (Mollusca: Bivalvia) in the Musi Estuary, Indonesia

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