Accumulation of Heavy Metal Mercury (Hg) in Anadara Granosa and its Relationship with Water Physicochemical Parameters in Kayeli Bay, Buru Island

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Abstract

Kayeli Bay, located in Buru Island, Maluku, Indonesia, is subject to mercury (Hg) contamination originating from illegal artisanal gold mining activities at Gunung Botak. Mining effluents are transported via the Waelata and Anahoni Rivers and deposited in bay sediments, creating a significant risk of Hg bioaccumulation in benthic organisms. This study aimed to quantify Hg concentrations in blood cockle Anadara granosa collected from three stations at different distances from the pollution source and also to determine the relationship between water physicochemical parameters (pH, temperature, salinity, and dissolved oxygen) and Hg accumulation levels. Samples were collected during February–March 2025. Mercury analysis was performed using a Mercury Analyzer (Analytic Jena Control AA). The results showed Hg concentrations of 0.41703 mg/kg (Station 1), 0.02539 mg/kg (Station 2), and 0.09531 mg/kg (Station 3). The highest concentration was found at the station closest to the river mouth, characterized by muddy substrate and weak currents. Measured physicochemical parameters included pH (6.4–7.0), temperature (29–38 °C), salinity (27.5–33.7 ‰), and dissolved oxygen (3.2–4.8 mg/L). Correlation analysis revealed that changes in pH, temperature, salinity, and dissolved oxygen played a very significant role in regulating the solubility, mobility, and bioavailability of Hg. Decreased pH and salinity, along with increased temperature and low dissolved oxygen levels, significantly enhanced the absorption and accumulation of Hg in tissues. Generally, Hg levels were below the national threshold (SNI 1.0 mg/kg), as well as the USA-FDA and Australian standards. However, levels at Station 1 exceeded the stricter limits set by Japan and Canada (0.3–0.4 mg/kg). Anadara granosa proved to be an effective bioindicator of heavy metal pollution, highly sensitive to changes in environmental quality.

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1. Introduction

Kayeli Bay is a strategically important aquatic ecosystem in Buru Island, Maluku Province, Indonesia. The bay serves as a productive fishing ground and critical habitat for diverse marine biota, particularly benthic filter-feeding organisms. The livelihood of coastal communities in the area depends heavily on the harvesting of shellfish and fish from this bay. However, since the early 2010s, illegal artisanal and small-scale gold mining (ASGM) activities in the Gunung Botak area have introduced significant quantities of mercury into the terrestrial and aquatic environment. Elemental mercury used in gold amalgamation is discharged into the Waelata and Anahoni Rivers, which ultimately drain into Kayeli Bay. Once in the aquatic environment, inorganic mercury undergoes microbial methylation to form methylmercury (MeHg), a highly neurotoxic compound that bioaccumulates in aquatic organisms and biomagnifies through food chains (Rodríguez, 2023; Thiraviyam et al., 2026).

Blood cockle (Anadara granosa) is a benthic mollusk widely distributed in Indonesian coastal waters. This species is a filter-feeder, living buried in muddy substrates, and possesses a high capacity to accumulate contaminants from the surrounding water and sediment. These biological characteristics make A. granosa an ideal bioindicator species for monitoring heavy metal pollution, as it effectively reflects the quality of its ambient environment (Sami Abdalla, 2024; Wu et al., 2024).

The accumulation of heavy metals in aquatic organisms is not only determined by the concentration of pollutants but is also strongly influenced by environmental conditions. Physicochemical parameters such as pH, temperature, salinity, and dissolved oxygen control the chemical speciation, solubility, and mobility of metals in water, thereby affecting their bioavailability and uptake rate by organisms (dos Santos et al., 2024; Miedico et al., 2020; Swetha et al., 2025; Yusuf & Handooyo, 2004).

Despite the ecological and economic importance of Kayeli Bay and the documented threat from ASGM-derived mercury, there is a critical lack of scientific data on metal contamination levels in commercially exploited bivalves from this bay. Previous ecological studies of Indonesian coastal waters have primarily focused on Java and Sumatra (Arifin et al., 2012; Ismanto et al., 2024; Maslukah, 2010; Rositasari & Puspitasari, 2021; Soegianto et al., 2020; Suryono, 2006), leaving eastern Indonesian waters, including Maluku, significantly understudied. This data gap impedes evidence-based environmental management and the formulation of food safety advisories for local communities.

Therefore, this study aimed to: (1) determine the concentration of Hg in A. granosa at three stations in Kayeli Bay representing different levels of exposure to mining effluents; (2) characterise the water physicochemical parameters at each station; and (3) analyse the statistical relationship between physicochemical parameters and Hg bioaccumulation. The food safety implications of measured Hg levels were also assessed against national and international standards.

2. MATERIALS AND METHODS

2.1. Study Area and Sampling Design

This research was conducted in Kayeli Bay, Buru Island, from February to March 2025. Sampling was carried out at three stations selected based on their distance from the estuaries of the Waelata and Anahoni Rivers and hydrological conditions:

Station 1: Located near the river mouth (closest to the pollution source), characterized by weak currents and muddy substrate.
Station 2: Located in the middle part of the bay, with moderate water current and mixed sediment.
Station 3: Located at the outer part of the bay, influenced by direct mixing with open seawater.

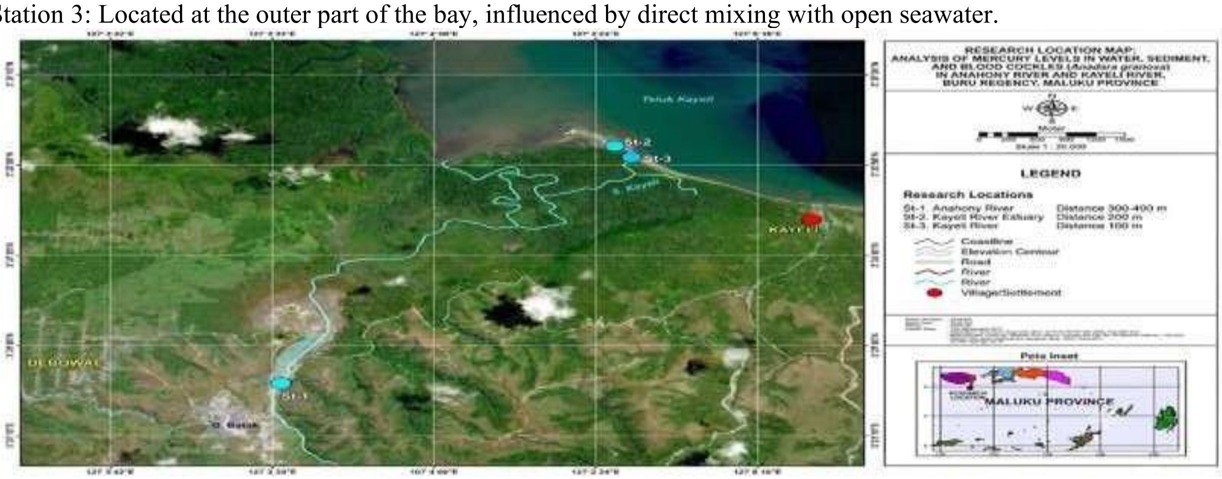

Figure 1. Map of sampling locations in Kayeli Bay, Buru Regency.

2.2. Sample Collection and Analysis

Samples of Anadara granosa were collected randomly from each station. The specimens were cleaned, labeled, and transported to the laboratory for analysis. Mercury concentration was determined using a Mercury Analyzer (Analytic Jena Control AA) following standard procedures for heavy metal analysis in biological tissues. The results were expressed in milligrams per kilogram (mg/kg) wet weight.

Simultaneously, in-situ measurements of water quality parameters were conducted. Parameters measured included pH, water temperature (°C), salinity (‰), and dissolved oxygen (DO, mg/L), using standard water quality meters.

2.3. Data Analysis

The distribution pattern of Hg concentration was analyzed descriptively. Correlation analysis was performed to determine the relationship between physicochemical parameters and Hg accumulation levels. To evaluate food safety, the obtained data were compared against safety thresholds established by (Garofalo et al., 2025; Miedico et al., 2020; Nauen & Fisheries and Aquaculture Management Division, 1983):

Indonesia (SNI 7387:2009): 1.0 mg/kg
USA-FDA / Australia: 1.0 mg/kg
Italy: 0.7 mg/kg
Japan / Canada: 0.3 – 0.4 mg/kg (BSN, 2009; FAO, 1983)

3. Results And Discussion

3.1. Mercury Concentration in Anadara granosa

The concentrations of Mercury found in Anadara granosa at the three stations are presented in Table 1.

Table 1. Mercury concentration in Anadara granosa at Kayeli Bay.

Station	Hg Concentration (mg/kg)	Location Characteristics	Comparison with SNI 7387:2009
1	0.41703	Near the river mouth, weak current, muddy substrate	Below limit (safe, under SNI); Exceeds Japan/Canada limit
2	0.02539	Middle bay, moderate current	Well below all limits (safe)
3	0.09531	Outer bay, high seawater mixing	Below all international limits (safe)

(Source: Authors)

Figure 2. Mercury concentration in Anadara granosa at Kayeli Bay

The highest Hg concentration (0.41703 mg/kg) was recorded at Station 1, the area closest to the river estuary. This location receives direct discharge from the Waelata and Anahoni Rivers, which carry mining runoff. The strongly reducing conditions associated with the muddy substrate at Station 1 are likely to promote mercury methylation, increasing MeHg bioavailability for uptake by benthic organisms (Jonsson et al., 2022; Rainbow, 1995; Talpur et al., 2026). This value exceeds the threshold recommended by Japan and Canada (0.3–0.4 mg/kg) but remains below the

Indonesian national standard (1.0 mg/kg; BSN, 2009), the USA-FDA standard (1.0 mg/kg), and the Italian standard (0.7 mg/kg).
In contrast, the lowest concentration (0.02539 mg/kg) was found at Station 2. This area has stronger water currents, leading to greater dilution of pollutants and reduced accumulation in sediments. Station 3 showed moderate levels (0.09531 mg/kg) due to the influence of open seawater, which dilutes the concentration of terrestrial pollutants. This spatial gradient confirms that the rivers originating from the Gunung Botak mining area are the primary source of Hg pollution in Kayeli Bay.

These results are consistent with spatial patterns reported in other Indonesian coastal studies. Soegianto et al. (2020) documented Hg concentrations in A. granosa from the East Java Coast ranging from 0.003 to 0.12 mg/kg wet weight, with higher values near industrial river estuaries (Soegianto et al., 2020). Similarly, Dinulislam et al. (2021) reported detectable Hg levels in blood cockles from Banten Bay near industrial discharge points (Dinulislam et al., 2021). The values obtained in Kayeli Bay at Station 1 are notably higher than those reported from East Java, which can be attributed to the specific impact of ASGM mercury, which is known to produce concentrated and localised Hg pulses distinct from industrial diffuse sources (Thiraviyam et al., 2026).

Globally, comparable studies in other tropical coastal regions also report elevated Hg in bivalves near mining or industrial zones. The systematic review by Fioravanti et al. (2025) on European seafood confirms that Hg concentrations in bivalves typically remain below regulatory limits in open coastal areas but may approach or exceed stricter standards near pollution hotspots—a pattern clearly mirrored in the Kayeli Bay data (Fioravanti et al., 2025).

3.2. Influence of Physicochemical Parameters on Hg Accumulation

The water quality parameters measured during the study period are summarised in Table 2.

Table 2. Water physicochemical parameters measured at three stations in Kayeli Bay.

Station	pH	Temperature (°C)	Salinity (‰)	DO (mg/L)
1	6.4	38	27.5	3.2
2	7.0	29	33.7	4.8
3	6.8	31	31.2	4.1
r (Pearson)	−0.94*	+0.87*	−0.81*	−0.76*

Note: * indicates significant correlation at $p < 0.05$; r = Pearson correlation coefficient with Hg concentration in A. granosa.
(Source: Authors)

Pearson correlation analysis revealed that all four physicochemical parameters were significantly correlated with Hg accumulation in A. granosa (Table 2). The strongest negative correlation was observed for pH (r = −0.94), indicating that more acidic conditions are associated with higher Hg accumulation. This is mechanistically consistent with the finding that at lower pH values, the ionic form of mercury (Hg^{2+}) predominates over particulate-bound forms, increasing the proportion of dissolved, bioavailable Hg in the water column (Garofalo et al., 2025). The acidic conditions at Station 1 (pH 6.4), attributable to the direct input of acid mine drainage components from ASGM activities, thus directly augment the bioavailability of Hg at the estuary.
Water temperature showed a significant positive correlation with Hg accumulation (r = +0.87). The high temperature recorded at Station 1 (38 °C) reflects the shallow, low-circulation character of the inner estuary. Elevated temperatures increase the metabolic rate and filtration activity of bivalves, thereby accelerating the rate of contaminant uptake from the water column (Ochoa-Esteso et al., 2024). Additionally, higher temperatures promote mercury methylation by sulphate-reducing bacteria in sediments, increasing the production of the more bioavailable MeHg form (Rodríguez, 2023). The interaction between high temperature and low pH at Station 1 thus creates a compound effect that maximises Hg bioavailability and uptake.
Salinity was negatively correlated with Hg accumulation (r = −0.81). Station 1, which receives substantial freshwater discharge from the rivers, had the lowest salinity (27.5‰). In low-salinity conditions, the ionic strength of water decreases, promoting the desorption of Hg ions from suspended particles and sediments, releasing them into the dissolved phase where they are more readily absorbed through the gills and digestive system of bivalves (Jonsson et al., 2022). Conversely, Station 3, with the highest salinity (33.7‰) from open ocean mixing, showed lower Hg accumulation, consistent with the dilution and particle-binding of Hg in higher-salinity seawater.
Dissolved oxygen (DO) showed a significant negative correlation with Hg accumulation (r = −0.76). The lowest DO (3.2 mg/L) was recorded at Station 1. Hypoxic and sub-oxic conditions create anaerobic microenvironments in bottom sediments that are conducive to the activity of sulphate-reducing bacteria (SRB), which are the primary mediators of mercury methylation in coastal environments (Jonsson et al., 2022). Under low-oxygen conditions, MeHg production rates in sediments are enhanced, and the reducing chemical environment also promotes the partitioning of Hg into the dissolved aqueous phase, increasing its bioavailability to benthic organisms. These findings are consistent with the broader literature indicating that DO is one of the most important modulating factors for Hg cycling in estuarine environments (Thiraviyam et al., 2026).

Overall, these results demonstrate that the accumulation of Hg in A. granosa in Kayeli Bay is not simply proportional to the total Hg input but is critically mediated by the interplay of physicochemical conditions. The simultaneous occurrence of low pH, high temperature, low salinity, and low DO at Station 1 creates optimal conditions for Hg bioavailability and uptake, a compounding effect that must be considered in environmental risk assessments.

3.3. Anadara granosa as a Bioindicator

The distinct and systematic variation in Hg concentrations across the three stations—closely corresponding to the pollution gradient from the river estuary outward—strongly supports the utility of A. granosa as a bioindicator for heavy metal pollution in Kayeli Bay. As a sedentary, filter-feeding benthic organism with a high metal-accumulation capacity relative to surrounding water, A. granosa integrates pollutant exposure over time and reflects localised contamination patterns that are not detectable through single-point water sampling (Ochoa-Esteso et al., 2024).

The bioindicator value of A. granosa is further corroborated by studies across Southeast Asian coastal waters. Soegianto et al. (2020) confirmed that cockle tissue metal concentrations reliably reflected anthropogenic gradients along the East Java coastline (Soegianto et al., 2020). In Indonesia more broadly, Saleh et al. (2021) demonstrated that green mussels (Perna viridis) and related bivalves can serve as effective biomonitors for multiple metals, including Hg, Pb, and Cd (Saleh et al., 2021). Kunda et al. (2024) further documented the histopathological sensitivity of bivalve gill tissue to heavy metal exposure, emphasising the ecological relevance of such bioaccumulation data (Kunda et al., 2024). The results from Kayeli Bay add to this body of evidence by demonstrating the applicability of A. granosa biomonitoring in an eastern Indonesian context where anthropogenic Hg sources are spatially discrete and intense.

Globally, the use of bivalves in Mussel Watch programmes has been validated as a cost-effective and ecologically meaningful monitoring strategy (Cao et al., 2023). The significant concentration gradients observed across just three stations in Kayeli Bay illustrate how even a minimal spatial sampling design can yield meaningful information when the bioindicator organism is well chosen.

3.4. Food Safety Assessment

The measured Hg concentrations in A. granosa were compared against multiple regulatory standards for mercury in seafood (Table 3).

Table 3. Comparison of Hg concentration in A. granosa from Kayeli Bay with international food safety standards.

Station	Hg (mg/kg)	Indonesia/USA (1.0 mg/kg)	Italy (0.7 mg/kg)	Japan/Canada (0.3–0.4 mg/kg)
1	0.41703	safe ✓	safe ✓	exceeds limit ✗
2	0.02539	safe ✓	safe ✓	safe ✓
3	0.09531	safe ✓	safe ✓	safe ✓

(Source: Authors)

All stations fall below the Indonesian national standard of 1.0 mg/kg (BSN, 2009) and the USA-FDA and Australian limit of 1.0 mg/kg. Similarly, all stations are below the Italian threshold of 0.7 mg/kg. However, Station 1exceeds the more stringent limits recommended by Japan and Canada (Garofalo et al., 2025; Nauen & Fisheries and Aquaculture Management Division, 1983). This has particular significance for communities that consume A. granosa harvested near the estuary on a frequent basis, as chronic low-level MeHg exposure can accumulate in the human body over time.

The monitoring study by Garofalo et al. (2025) of heavy metals in European seafood demonstrated that even concentrations below regulatory thresholds can pose cumulative health risks to vulnerable populations, including pregnant women and children, particularly when the dominant form is MeHg (Garofalo et al., 2025). In the context of Kayeli Bay, where local communities are likely to have few alternative protein sources and may consume cockles frequently, the exceedance of the Japan/Canada standard at Station 1 warrants precautionary advisory measures.

These results underscore the importance of applying multiple regulatory benchmarks in food safety assessments, rather than relying solely on the national standard. The national SNI 7387:2009 limit of 1.0 mg/kg provides a legally enforceable threshold for market access, but stricter international standards provide an additional safety margin for human health protection, especially for regular consumers of locally harvested shellfish.

4. Conclusion

This study provides the first documented assessment of mercury accumulation in Anadara granosa from Kayeli Bay, Buru Island, and its relationship with water physicochemical parameters. The following key conclusions are drawn:

1. Mercury concentrations in A. granosa from Kayeli Bay ranged from 0.026 to 0.417 mg/kg wet weight across three stations, with the highest levels occurring near the river estuaries receiving ASGM runoff. All values were below the Indonesian national food safety threshold (SNI 7387:2009: 1.0 mg/kg). However, the Station 1 value exceeded the stricter Japan/Canada threshold of 0.3–0.4 mg/kg, indicating a potential risk for frequent consumers of cockles harvested near the estuary.

2. Anadara granosa is confirmed as a sensitive and reliable bioindicator for Hg contamination in tropical coastal ecosystems, capable of reflecting spatial gradients in pollution exposure.
3. The compound effect of low pH, high temperature, low salinity, and low DO at Station 1 demonstrates the synergistic role of physicochemical stressors in amplifying heavy metal bioaccumulation risk in ASGM-affected estuarine environments.

5. References

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