Water quality and heavy metal contents in sediments and sea cucumbers from the Sangihe Islands, North Sulawesi, Indonesia

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Abstract. This study aims to determine the impact of mining activities on seawater quality and the heavy metal content found in sediments and sea cucumbers in Binebas and Bowone villages, Sangihe Islands, Indonesia. Sampling was conducted in each village, in April, 2026, with three repetitions for water quality measurements, including temperature, pH, turbidity, dissolved oxygen, total dissolved solids, salinity, and sea depth. Sediment and sea cucumber sampling was only conducted once at each location. Analysis of heavy metal content (As, Cd, Hg, and Pb) in sediments and biota (sea cucumbers) was carried out *ex situ* using the atomic absorption spectrometry (AAS) method. The compliance of the values obtained with environmental quality standards was evaluated. The indications of bioaccumulation and potential ecological risks in the waters around the Sangihe mining sites were examined. The results of this study indicate that all water quality parameters in the waters around the Sangihe mining site are in a tolerable range for marine organisms, including sea cucumbers. Heavy metals, which do not meet quality standards for almost all uses, indicate serious environmental and health risks.
Keywords: arsenic, cadmium, lead, mercury, mining.

Introduction. Metals occur naturally in aquatic environments through geological and biogeochemical processes, but their concentrations can increase substantially due to anthropogenic activities (França et al., 2005). Rapid industrialization, urbanization, land-use changes, and increased terrestrial runoff are among the major contributors to elevated metal levels in aquatic ecosystems (Rahman et al., 2012). Heavy metal pollution has become a major environmental concern because heavy metals are persistent, toxic, and capable of accumulating in organisms and sediments, potentially causing neurological disorders, reduced cognitive function, and carcinogenic effects in humans (Hu et al., 2013; Wang et al., 2015). Contamination by heavy metals in marine and coastal environments has become a global issue (Nindyapuspa & Ni'am, 2018; Mwatsahu et al., 2020; Rozirwan et al., 2024) due to its adverse effects on ecosystem health (Yuan et al., 2020), marine organisms (Dan et al., 2022; Shimod et al., 2022; Melake et al., 2023), and human health through environmental exposure and the food chain (Wang et al., 2020).

Heavy metals are toxic, persistent, non-biodegradable elements that can bioaccumulate and biomagnify in aquatic ecosystems (Oluwagbemiga et al., 2019; Taslima et al., 2022). Although some metals such as Fe, Cu, Co, Cr, Mn, Se, Ni, and Zn are essential in trace amounts, most heavy metals are non-essential to organisms (Najamuddin et al., 2023). Naturally occurring at low concentrations, these metals may reach toxic levels in aquatic environments due to their persistence and accumulation in sediments and aquatic organisms (Suvarapu & Baek, 2017; Zhu et al., 2020; Shirdel et al., 2020; Esmaeilbeigi et al., 2021). Sediments, which serve as habitats for various macrobenthic organisms, can function both as reservoirs and secondary sources of heavy metals depending on environmental conditions such as pH and redox potential (Eggleton & Thomas, 2004; Bendary et al., 2023; Singh et al., 2023; Rozirwan et al., 2024). The distribution and mobility of heavy metals are influenced by physicochemical and hydrodynamic factors including temperature, salinity, dissolved oxygen, currents, tides, and water mixing processes (Najamuddin et al., 2016). Coastal ecosystems are particularly vulnerable to anthropogenic inputs, especially mining activities, which can release heavy metals such as As, Cd, Hg, and Pb into marine environments through runoff, erosion, and waste disposal (Alloway, 2012; Förstner & Wittmann, 2012).

Previous studies have shown that sea cucumbers can accumulate heavy metals such as Hg, Pb, and Cd from both seawater and sediments (Riani et al., 2022). Several species, including *Eupentacta fraudatrix*, *Holothuria mammata*, *H. polii*, *H. tubulosa*, and *H. atra*, have been reported to contain high arsenic concentrations, while *Stichopus herrmanni* has shown elevated mercury levels (Bhuyan et al., 2024). Similarly, arsenic concentrations exceeding safe thresholds were detected in *Theletona ananas*, although Cu, Zn, and Fe remained within acceptable limits (Yap et al., 2025). As benthic deposit feeders, sea cucumbers ingest sediment and organic matter, making them effective bioindicators of marine pollution and potential pathways for biomagnification in the food chain (Purcell et al., 2013). In addition to their ecological roles in sediment bioturbation and nutrient recycling, sea cucumbers are also important seafood commodities in Asian markets, highlighting potential food safety concerns. Previous studies have further demonstrated that mining activities contribute significantly to heavy metal contamination in coastal waters, including elevated Hg levels near gold mining areas and increased Pb and As concentrations in coastal environments exposed to mining waste (Tarras-Wahlberg et al., 2000; Islam & Tanaka, 2004).

The Sangihe Islands Regency is one of the areas with potential mineral resources and developing mining activities. However, scientific information regarding the impact of these activities on aquatic environmental quality is still limited. Therefore, this study aims to analyse seawater quality and heavy metal concentrations (As, Cd, Hg, Pb) in sediments and biota (sea cucumber), evaluate their compliance with environmental quality standards, and examine indications of bioaccumulation and potential ecological risks in the waters around the Sangihe mining sites.

Material and Method

Sea water sampling. This study was conducted in coastal waters surrounding the mining area in the Sangihe Islands Regency, Indonesia. Sampling was carried out at two main sites, namely Binebas and Bowone, each consisting of three water quality sampling points. The coordinates for the Binebas site were N 03°29'26.72" E 125°38'32.84", N 03°29'27.68" E 125°38'32.21", and N 03°29'28.34" E 125°38'30.84", while the Bowone site included N 03°29'37.80" E 125°39'01.08", N 03°29'38.88" E 125°39'01.3", and N 03°29'41.52" E 125°39'02.72" (Figure 1).

Water quality parameters measured at each sampling point included temperature, pH, turbidity, dissolved oxygen, total dissolved solids (TDS), salinity, and water depth using a Horiba multiparameter instrument (Model U-5000G, Horiba Advanced Techno Co., Japan). Measurements for each water quality parameter for each body of water with 3 sampling points were conducted 3 times (Table 1).

Sediment and sea cucumber sampling. Sediment and sea cucumber samples were collected once at each site. This study used primary data obtained from sediment and marine biota (sea cucumber) samples to analyse heavy metal concentrations of arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb).

Sampling was conducted using purposive sampling based on the proximity of the sites to mining activities. Sediment samples were collected from the surface layer of the seabed using an Ekman grab, while sea cucumbers were collected directly from the same locations. Specimens of *Holothuria atra* and *H. leucospilota* (Figure 2) were collected from the coastal waters of Binebas and Bowone, respectively, in April 2026. All samples were placed in plastic bags, stored in cool boxes under cold conditions, and transported to the laboratory (Testing Laboratory, Manado Industrial Standardization and Service Agency) for further analysis.

For measuring heavy metal content in sediments, 850 g of sample were used, with 2 repetitions at each location (Binebas and Bowone), while for sea cucumbers, 200 g were used with no repetitions.

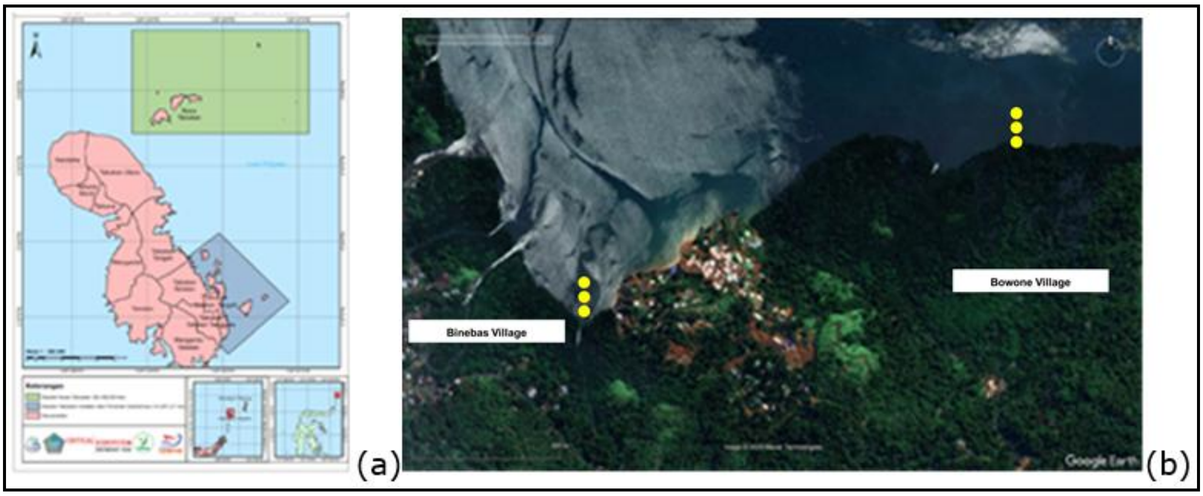

Figure 1. Map of conservation areas for the Nusa Tabukan cluster, South Tabukan and surrounding coasts, Sangihe Islands Regency, North Sulawesi (a); research sites in Binebas village and Bowone village (b).


Figure 2. Sea cucumbers, *Holothuria atra* (above), and *Holothuria leucospilota* (below) from coastal waters of Sangihe Islands (source: authors' personal archive and photos taken by authors, 2026).

Heavy metal content analysis. Heavy metal concentrations of arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) in sediment, water and sea cucumber samples were analysed in the laboratory using atomic absorption spectrometry (AAS). Prior to analysis, samples underwent acid digestion to determine metal concentrations expressed in mg kg^{-1}. The data were analysed descriptively and comparatively by determining the concentration ranges of heavy metals in each medium and comparing the results with seawater quality standards for ports, marine tourism, and marine biota.

Standard quality reference. Sea water quality evaluation refers to the national standard for heavy metal quality in seawaters based on environmental use (ports, tourism, and marine life) (Indonesian Government Regulation No. 22 Year 2021).

Comparison with quality standards (exceedance ratio analysis). Evaluating the level of pollution, the exceedance ratio (ER) approach is used, which is the comparison between the measured concentration and the quality standard for marine biota:

$ER = C_{measured}/C_{standard}$

Where C represents the concentration.

Simple pollution index. The contamination factor (CF) is used to calculated the simple pollution index:

$CF = C_{sample}/ C_{background/standard}$

A CF <1 shows a low pollution, a CF of 1-3 shows a medium pollution, a CF of 3-6 shows high pollution, and a CF higher than 6 shows a very high pollution.

Results and Discussion. The results of water quality measurements in the Binebas coastal waters at three sampling points are presented in Tables 1, 2, and 3. The results of repetitions for each parameter from each sampling point were averaged.

Table 1

Water quality of Binebas coastal waters at geographical coordinates N 03°29'26.72" E 125°38'32.84" (first sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	28.60	28.52	28.57	28.60±0.04
pH	-	7.23	7.35	7.43	7.34±0.10
Turbidity	(NTU)	3.50	4.00	3.50	3.67±0.29
Dissolved oxygen	(mg L^{-1})	7.01	6.56	6.61	6.73±0.25
Total dissolved solids	(g L^{-1})	24.60	24.60	24.60	24.60±0.00
Salinity	ppt	25.73	25.82	25.76	25.77±0.05
Water depth	m	0.65	0.65	0.65	0.65±0.00

Table 2

Water quality of Binebas coastal waters at geographical coordinates N 03°29'27.68" E 125°38'32.21" (second sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	28.72	28.73	28.70	28.72±0.02
pH	-	7.60	7.65	7.70	7.65±0.05
Turbidity	(NTU)	4.70	4.00	4.00	4.23±0.40
Dissolved oxygen	(mg L^{-1})	6.11	6.04	6.02	6.06±0.05
Total dissolved solids	(g L^{-1})	25.10	25.20	25.20	25.17±0.06
Salinity	ppt	26.39	26.44	25.44	26.42±0.56
Tool depth	m	1.00	1.05	1.00	1.02±0.03

Table 3

Water quality of Binebas coastal waters at geographical coordinates N 03°29'28.34" E 125°38'30.84" (third sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	28.64	28.63	28.62	28.63±0.01
pH	-	7.70	7.72	7.73	7.72±0.02
Turbidity	(NTU)	2.70	2.40	2.10	2.40±0.30
Dissolved oxygen	(mg L^{-1})	6.02	5.80	5.85	5.89±0.12
Total dissolved solids	(g L^{-1})	25.30	25.20	25.30	25.27±0.06
Salinity	ppt	26.54	26.51	25.56	26.54±0.51
Tool depth	m	1.00	1.00	1.00	1.00±0.00

The results of water quality measurements in the Bowone coastal waters at three sampling points are presented in Tables 4, 5, and 6. The results of repetitions for each parameter from each sampling point were averaged.

Table 4

Water quality of Bowone coastal waters at geographical coordinates N 03°29'37.80" E 125°39'01.08" (first sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	28.81	28.81	28.82	28.81±0.01
pH	-	7.27	7.47	7.57	7.44±0.15
Turbidity	(NTU)	3.10	2.40	3.30	2.93±0.47
Dissolved oxygen	(mg L^{-1})	7.35	6.77	6.23	6.78±0.56
Total dissolved solids	(g L^{-1})	26.30	26.20	26.30	26.27±0.06
Salinity	ppt	27.69	27.68	27.70	27.69±0.01
Tool depth	m	1.35	1.35	1.30	1.33±0.03

Table 5

Water quality of Bowone coastal waters at geographical coordinates N 03°29'38.88" E 125°39'01.3" (second sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	28.84	28.84	28.81	28.83±0.02
pH	-	7.79	7.80	7.82	7.80±0.02
Turbidity	(NTU)	1.90	1.70	1.60	1.73±0.15
Dissolved oxygen	(mg L^{-1})	6.36	6.27	6.22	6.28±0.07
Total dissolved solids	(g L^{-1})	26.40	32.40	26.30	28.37±3.49
Salinity	ppt	27.88	27.84	27.80	27.84±0.04
Tool depth	m	0.70	0.70	0.75	0.72±0.03

Table 6

Water quality of Bowone coastal waters at geographical coordinates N 03°29'41.52" E 125°39'02.72" (third sampling point)

Parameter	*Unit*	*Measurement results*			*Average and standard deviation*
		Repetition 1	*Repetition 2*	*Repetition 3*	
Temperature	(°C)	29.30	29.29	29.31	29.30±0.01
pH	-	7.76	7.82	7.86	7.81±0.05
Turbidity	(NTU)	1.30	1.30	1.30	1.30±0.00
Dissolved oxygen	(mg L^{-1})	9.79	9.61	9.45	9.62±0.17
Total dissolved solids	(g L^{-1})	28.00	27.90	72.90	42.92±25.95
Salinity	ppt	27.69	27.68	27.70	27.69±0.01
Tool depth	m	2.50	2.45	2.45	2.47±0.03

Water quality parameters measured at the Binebas and Bowone sites generally remained within ranges suitable for marine organisms, including sea cucumbers (Tables 1–6).

Temperature conditions at both sites were consistent with values reported as optimal for the growth, metabolism, and survival of *Holothuria* species, particularly *Holothuria scabra* (James, 2004; Yu et al., 2018; Rodríguez-Forero et al., 2024). Temperature is an important environmental factor influencing physiological performance, metabolic efficiency, and thermal tolerance in sea cucumbers (Jobling, 1981; Cossins & Bowler, 1987; Kelsch & Neill, 1990; Haesemeyer, 2020). According to the Decree of the Indonesian State Minister of Environment No. 51 Year 2004, seawater temperature for marine biota should remain within natural conditions, and the measured values at both sites were still considered suitable for sea cucumber growth and survival.

The pH values recorded at both locations were also within the acceptable range for marine biota established by the Indonesian seawater quality standard (pH 7–8.5). Previous studies have shown that pH strongly influences sea cucumber growth and recruitment, with optimal conditions for *H. scabra* larvae occurring under slightly alkaline conditions (James, 2004; González-Durán et al., 2021). Similarly, turbidity values remained below the threshold of <5 NTU established by the Decree of the Indonesian State Minister of Environment No. 51 Year 2004, indicating suitable environmental conditions for marine organisms.

Dissolved oxygen concentrations at both sites were above the minimum level required for marine biota (>5 mg L^{-1}) according to Indonesian seawater quality standards. These values are also consistent with dissolved oxygen ranges reported as favourable for *Holothuria* culture and survival (James, 2004; Sithisak et al., 2013; Hartati et al., 2021). Adequate dissolved oxygen is particularly important for sea cucumbers because respiration occurs through respiratory trees, body surfaces, and tentacles (Zamani et al., 2018).

Salinity values at both sites were likewise within ranges considered suitable for sea cucumber habitats and aquaculture systems (Sithisak et al., 2013; Hartati et al., 2021), and remained within natural marine conditions as specified in the Indonesian seawater quality standards.

In contrast, total dissolved solids (TDS) showed relatively high values compared with those reported in previous studies (AbouElmaaty et al., 2023), although these concentrations are still generally consistent with normal tropical coastal seawater conditions. Overall, the measured physicochemical parameters indicate that the waters at both study sites remain generally suitable for sea cucumber growth and survival.

Heavy metal analysis showed that seawater at the study sites contained As (1.83–2.71 mg kg^{-1}), Cd (<0.01 mg kg^{-1}), Hg (0.06–0.08 mg kg^{-1}), and Pb (1.53–22.15 mg kg^{-1}) (Table 7).

Table 7
Heavy metal content in the water, substrate at Bowone and Binebas, each at 2 locations, and in sea cucumbers

	Result (mg kg^{-1})					
	Seawater				*Sediment*	*Sea cucumber*
Parameter	Bowone 1	Bowone 2	Binebas 1	Binebas 2		
Arsenic (As)	2.66	1.83	2.71	2.12	<0.04	<0.04
Cadmium (Cd)	<0.01	<0.01	<0.01	<0.01	0.01	0.003
Mercury (Hg)	0.06	0.06	0.08	0.07	0.03	0.04
Lead (Pb)	1.85	1.53	21.66	22.15	<0.005	0.01

Most of the obtained heavy metal concentrations exceeded the established seawater quality standards, particularly those for marine tourism and marine biota according to the Indonesian Government Regulation No. 22 of 2021 on the implementation of environmental protection and management. In contrast, Cd was detected only at relatively low concentrations. The distribution pattern of heavy metals indicated a greater accumulation in the water column, while Hg was also detected in sediment (0.03 mg kg^{-1}) and sea cucumber samples (0.04 mg kg^{-1}), suggesting the early stages of bioaccumulation processes (Table 8). The exceptionally high Pb concentrations recorded at the Binebas site suggest the presence of a localized pollution source, likely associated with nearby mining activities. Overall, the findings indicate substantial heavy metal contamination in the waters surrounding the Sangihe mining area, with concentrations exceeding environmental quality standards for most designated uses. These conditions highlight the need for stricter environmental management, continuous monitoring, and further studies assessing ecological and public health risks.

Table 8
Seawater quality standard according to Indonesian Government Regulation No. 22 Year 2021

Parameter	*Seawater quality standard*		
	Port	*Marine tourism*	*Marine organism*
Arsenic (As)	-	0.025	0.012
Cadmium (Cd)	0.01	0.002	0.001
Mercury (Hg)	0.003	0.002	0.001
Lead (Pb)	0.05	0.005	0.008

Comparison with quality standards. Arsenic (As) concentrations ranged from 1.83–2.71 mg kg^{-1}, greatly exceeding the seawater quality standards for marine tourism (0.025 mg kg^{-1}) and marine biota (0.012 mg kg^{-1}). The measured concentrations were more than 100 times higher than the established limits, indicating severe contamination and unsuitable conditions for marine tourism and aquatic life.

Cadmium (Cd) concentrations were detected at relatively low levels (<0.01 mg kg^{-1}). Compared with the quality standards for ports (0.01 mg kg^{-1}), marine tourism (0.002 mg kg^{-1}), and marine biota (0.001 mg kg^{-1}), Cd generally complied with port standards, but approached or exceeded the thresholds for marine organisms. Although present at low concentrations, Cd requires attention because of its chronic toxic effects and potential for bioaccumulation.

Mercury (Hg) concentrations ranged from 0.06–0.08 mg kg^{-1}, substantially exceeding the quality standards for ports (0.003 mg kg^{-1}), marine tourism (0.002 mg kg^{-1}), and marine biota (0.001 mg kg^{-1}). These values were approximately 20–80 times higher than the permitted limits, indicating serious contamination and a high potential risk to marine ecosystems, bioaccumulation processes, and human health.

Lead (Pb) concentrations ranged from 1.53–1.85 mg kg^{-1} at Bowone and 21.66–22.15 mg kg^{-1} at Binebas. These concentrations greatly exceeded the quality standards for ports (0.05 mg kg^{-1}), marine tourism (0.005 mg kg^{-1}), and marine biota (0.008 mg

kg^{-1}). In Binebas, Pb concentrations exceeded the marine tourism standard by more than 400 times, indicating extremely high and localized (hotspot) contamination.

Overall, the results indicate very high pollution levels for Pb and Hg, high contamination for As, and low to moderate contamination for Cd. Based on seawater quality standards, most sampling locations were unsuitable for marine tourism and posed significant risks to marine organisms, while several parameters also failed to comply with standards for port waters.

Ecologically, these contamination levels may contribute to ecosystem degradation, mortality, and reproductive disturbances in marine organisms. From a human health perspective, there is a potential risk of heavy metal exposure through the food chain, including the consumption of fish and sea cucumbers, particularly because Hg and Pb are highly neurotoxic. The exceptionally high Pb concentrations detected at Binebas further suggest the presence of a localized pollution source, possibly associated with mining activities.

Heavy metal concentration in seawater. The analysis showed that heavy metal concentrations in the waters of the study sites (Binebas and Bowone) varied among parameters (Table 1). Overall, the concentration pattern in seawater followed the order Pb > As > Hg > Cd. Arsenic (As) concentrations ranged from 1.83–2.71 mg kg^{-1}, with an average of approximately 2.33±0.40 mg kg^{-1}, indicating moderate spatial variation, with the highest concentration recorded at Binebas 1. Cadmium (Cd) was detected only at very low concentrations (<0.01 mg kg^{-1}). Mercury (Hg) concentrations ranged from 0.06–0.08 mg kg^{-1}, with an average of 0.067±0.01 mg kg^{-1}, suggesting a relatively homogeneous distribution among sampling sites. In contrast, lead (Pb) showed substantial spatial variation, ranging from 1.53–22.15 mg kg^{-1}, with an average concentration of 11.80±10.50 mg kg^{-1}. The exceptionally high Pb concentrations observed at the Binebas site indicate a strong spatial anomaly and suggest the presence of a localized contamination source.

Comparison with quality standards (exceedance ratio analysis). The results show arsenic (As) with an ER value of 150-225, mercury (Hg) with ER of 60-80, lead (Pb) with an ER of 190-2700, and cadmium (Cd) with ER less than 10. An ER value above 1 indicates that most parameters have exceeded the threshold, especially Pb, which shows a high level of pollution.

Distribution of heavy metals between compartments. The distribution of heavy metals shows a dominant pattern in the water column compared to sediments and organisms. Sediments show relatively low concentrations of heavy metals (e.g., Hg=0.03 mg kg^{-1}), while sea cucumbers show limited accumulation, except for Hg (0.04 mg kg^{-1}). This indicates that heavy metals are still in a dissolved or suspended phase, the deposition process into sediment is not yet optimal, and bioaccumulation is at an early stage. Nevertheless, the presence of Hg in all compartments indicates the existence of early trophic transfer.

Simple pollution index. The results show a very high CF for As (>100), a very high CF for Hg (>20), Pb: very high CF (>400), and Cd: medium CF. This confirms that the waters have experienced heavy to very heavy pollution.

Ecological implications and pollution sources. Significant spatial variation in Pb concentrations indicates the presence of localized pollution sources, likely associated with mining activities in the Binebas area. This pattern is consistent with previous studies identifying mining as a major source of heavy metal contamination in coastal waters (Tarras-Wahlberg et al., 2000). The detection of Hg in sediments and sea cucumber tissues suggests the occurrence of bioaccumulation and potential biomagnification processes, which may pose long-term risks to both ecosystems and human health. In addition, elevated heavy metal concentrations in the water column increase the likelihood of direct exposure to planktonic and nektonic organisms, potentially affecting community structure and ecosystem functioning.

Overall, the results indicate substantial heavy metal contamination in the study area, with Pb and Hg representing the most critical pollutants. The pronounced spatial variation further suggests the influence of localized contamination sources, while the presence of Hg in water, sediment, and biota indicates that environmental transfer and bioaccumulation processes have already begun. These findings support the concept that, during the early stages of contamination, heavy metals tend to remain predominantly in the water column before progressively accumulating in sediments and organisms.

The water quality assessment around the Sangihe mining area revealed elevated concentrations of arsenic (As), mercury (Hg), and lead (Pb), with variations among sampling locations (Bowone and Binebas). Most measured concentrations exceeded the seawater quality standards established for ports, marine tourism, and marine biota.

Arsenic concentrations ranged from 1.83–2.71 mg kg^{-1}, greatly exceeding the quality standards for marine tourism (0.025 mg kg^{-1}) and marine biota (0.012 mg kg^{-1}). These elevated concentrations indicate strong pollution pressure, likely associated with mining activities and the release of sulfide-bearing materials into the aquatic environment. Chronic arsenic exposure is known to have toxic effects on aquatic organisms.

Mercury concentrations ranged from 0.06–0.08 mg kg^{-1}, substantially exceeding the quality standards for all designated uses (0.001–0.003 mg kg^{-1}). Considering the strong bioaccumulative and biomagnifying properties of mercury, these concentrations indicate serious contamination and potential ecological and human health risks. The occurrence of Hg in seawater, sediments, and sea cucumbers confirms the transfer of contaminants among environmental compartments.

Lead concentrations were particularly high at the Binebas site (21.66–22.15 mg kg^{-1}), far exceeding the quality standards for ports (0.05 mg kg^{-1}), marine tourism (0.005 mg kg^{-1}), and marine biota (0.008 mg kg^{-1}). These results indicate intense local contamination, likely linked to mining activities. Elevated Pb concentrations may adversely affect marine organisms by disrupting physiological and neurological functions.

In contrast, cadmium (Cd) was detected at relatively low concentrations (<0.01 mg/kg), remaining below or close to the quality standard for port waters, although potentially approaching the threshold for marine organisms. Although Cd contamination was less severe compared to other metals, continued monitoring remains necessary because of its chronic toxicity and potential for accumulation.

The higher concentrations of heavy metals detected in the water column compared with sediments suggest that many contaminants are still present in dissolved or suspended forms, and that sediment deposition processes may still be ongoing. Nevertheless, the detection of Hg in sediments (0.03 mg kg^{-1}) and sea cucumbers (0.04 mg kg^{-1}) indicates the initiation of bioaccumulation processes. As benthic deposit feeders, sea cucumbers are widely recognized as sensitive bioindicators of sediment quality because they directly interact with and ingest sediment particles.

Overall, the findings demonstrate that waters surrounding the Sangihe mining area are under considerable heavy metal pollution pressure and fail to meet environmental quality standards for most designated uses, particularly marine tourism and marine biota protection. These conditions may contribute to ecosystem degradation, reduced habitat quality, and increased human health risks through seafood consumption. Consequently, stricter environmental management, continuous monitoring, and further studies on ecological and public health impacts are strongly recommended.

Heavy metals are high-density elements that can be toxic even at low concentrations. Major sources of heavy metals in aquatic environments include industrial activities, mining, agriculture, and domestic waste (Alloway, 2012). In marine ecosystems, heavy metals may occur in dissolved, suspended, or sediment-bound forms, with their distribution and bioavailability strongly influenced by physicochemical factors such as pH, salinity, temperature, and organic matter content (Förstner & Wittmann, 2012). Sediments serve as important indicators of long-term pollution because they can accumulate heavy metals over extended periods and may also act as secondary contamination sources under changing environmental conditions (Eggleton & Thomas, 2004).

Bioaccumulation occurs when organisms absorb contaminants from water or food sources, leading to increased concentrations within tissues over time. Metals such as Hg and Pb are particularly concerning because they can biomagnify through the food chain (Wang & Rainbow, 2008). Mercury, especially in the form of methylmercury, is highly neurotoxic and readily accumulates in aquatic organisms. Sea cucumbers (Holothuroidea), due to their deposit-feeding behaviour and close association with sediments, are widely used as bioindicators of marine pollution (Purcell et al., 2013). Mining activities can release heavy metals into aquatic systems through runoff and tailings disposal, potentially causing water quality degradation, habitat damage, physiological stress in marine organisms, and human health risks through seafood consumption (Islam & Tanaka, 2004).

Conclusions. Water quality parameters in the waters surrounding the Sangihe mining site, including temperature, pH, turbidity, dissolved oxygen, and salinity, were generally within ranges tolerable for marine organisms, including sea cucumbers. In contrast, heavy metal concentrations exceeded the established quality standards for most designated uses, indicating potential environmental and public health risks. Therefore, if mining activities could be a source of these contaminants, this relationship needs to be studied further in order to control mining waste with intensive monitoring of heavy metals in water, sediments, and biota, setting up restricted zones for community activities, assessing public health risks in coastal communities, and gradually carrying out environmental rehabilitation.

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Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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