JURNAL
KESEHATAN LINGKUNGAN
JURNAL DAN APLIKASI TEKNIK KESEHATAN LINGKUNGAN

ISSN 1829-9407 (Print)
ISSN 2581-0898 (Online)

Volume 23, No. 1, January 2026 ; Page: 75-86; *DOI: https://doi.org/10.31964/jkl.v23i1.1088*

Original Research

RISK ASSESSMENT OF HEAVY METAL EXPOSURE FROM SINANODONTA WOODIANA IN KRUENG MEUREUBO RIVER, WEST ACEH

Nanda Qoriansas[1,2], Ira Sahwadi[1,3], Riski Rahmayati[2], Rizki Andriani[2]
[1] Regional Health Laboratory (UPTD), West Aceh Regency, Aceh Province, Indonesia
[2] STIKes Medika Seramoe Barat, Meulaboh, West Aceh Regency, Aceh Province, Indonesia
[3] Nagan Raya District Health Office, Aceh Province, Indonesia
Industrial Road No. 12, Seunebok, Meulaboh, West Aceh Regency, Indonesia
Corresponden Author: Rizki Andriani
E-mail : rizkiandriani.qq@stikesmsb.ac.id

Article Info

Article history:

Received October 13, 2025
Revised January 19, 2026
Accepted January 26, 2026

Keywords:

EHRA
Chromium (Cr)
Lead (Pb)
Mercury (Hg)
Shellfish

ABSTRACT

Risk Assessment of Heavy Metal Exposure from Sinanodonta woodiana in Krueng Meureubo River, West Aceh. *The increasing intensity of industrial activities in the coastal area of West Aceh has the potential to contaminate aquatic environments with heavy metals such as chromium (Cr), lead (Pb), and mercury (Hg), which can accumulate in aquatic biota and pose health risks to humans. This study aimed to analyze the concentration of heavy metals in Sinanodonta woodiana, assess community exposure levels based on consumption patterns, and estimate non-carcinogenic health risks using the Environmental Health Risk Assessment (EHRA) approach. The study was conducted at four sampling sites along the Krueng Meureubo River and involved 141 respondents. Heavy metal concentrations were analyzed using Atomic Absorption Spectrophotometry, while health risks were assessed based on daily intake and Hazard Quotient (HQ) values. The results indicated that Pb (2.36–5.65 mg/kg) and Hg (1.10–53.27 mg/kg) concentrations in mussel tissue exceeded national food safety limits, whereas Cr concentrations (<0.0001 mg/kg) remained within acceptable levels. Risk characterization showed that 71.7% of respondents had HQ values greater than 1 for Pb and Hg, indicating potential non-carcinogenic health risks associated with regular mussel consumption. In contrast, Cr exposure did not present a significant health risk. These findings highlight that the consumption of freshwater mussels from the Krueng Meureubo River may pose health risks to coastal communities, underscoring the need for continuous monitoring of water quality and aquatic food safety to prevent long-term adverse health effects.*

INTRODUCTION

The coastal area of West Aceh is a densely populated region that has experienced a rapid increase in human activities, particularly industrial operations. Several high-intensity industrial activities, including coal processing, gold mining, and steam power plants, are located in this region and exert considerable pressure on aquatic environments[(1)]. Uncontrolled discharges of organic, inorganic, and suspended wastes into water bodies have the potential to degrade water quality and contribute to environmental pollution[(2–3)]. Among these pollutants, heavy metals are of major concern due to their persistence, bioaccumulative properties, and potential to cause adverse health effects when entering the human body through the food chain.

Chromium (Cr), lead (Pb), and mercury (Hg) are among the most hazardous heavy metals commonly associated with industrial and anthropogenic activities and are widely recognized for their toxicological impacts[4]. Chromium may originate from natural geological processes such as groundwater interactions, erosion, and rock–water contact[5–6]; however, industrial activities and mining operations can significantly increase its concentration in aquatic environments. Chromium is non-biodegradable and capable of accumulating in biological tissues, posing risks to aquatic organisms and humans[7]. Its toxicity is associated with its ability to penetrate cell membranes and induce DNA damage through oxidative stress mechanisms[8].

Lead (Pb) is a non-essential metal that accumulates in body tissues, particularly in bones, kidneys, and the nervous system, and is well known for its high toxicity[9]. Mercury (Hg), especially in its methylated form, is considered one of the most toxic heavy metals in aquatic ecosystems due to its ability to cross the blood–brain barrier and the placenta, potentially causing neurological damage and developmental disorders in fetuses[10].

Freshwater mussels such as *Sinanodonta woodiana* are commonly found in the Krueng Meureubo River in West Aceh and serve as an important source of animal protein for local communities. This species is widely consumed due to its relatively large meat size and ease of collection. In addition to its nutritional value, including protein and other bioactive compounds[11–12], *S. woodiana* is a filter-feeding organism capable of processing large volumes of water to obtain nutrients. This feeding behavior also facilitates the accumulation of heavy metals and other pollutants in its tissues, often at concentrations exceeding those in the surrounding environment[13–14]. Consumption of shellfish contaminated with heavy metals can have serious impacts on human health, including kidney dysfunction, liver damage, and carcinogenic effects[15–16]. Lead is particularly concerning due to its neurotoxic effects, which are associated with DNA damage and oxidative stress[17], while mercury, especially methylmercury, has been linked to disorders of the nervous system and renal function[4]. Chronic exposure to Cr, Pb, and Hg through the regular consumption of contaminated shellfish may therefore increase long-term health risks in exposed populations.

Several studies conducted in West Aceh have reported heavy metal contamination in aquatic environments exceeding established quality standards. Previous investigations by Munandar and Alamsyah (2016)[18], Edwarsyah and Iqbal (2017)[19], Warni et al. (2017)[20], and Ukhty et al. (2020)[21] documented elevated concentrations of Hg, Cd, and Pb in water bodies in this region. More recent research by Qoriansas et al. (2024)[22] confirmed Cr^{6+} contamination in the Krueng Meureubo River at concentrations of 0.10 mg/L and 0.08 mg/L, exceeding the safety limits specified in the Ministry of Health Regulation No. 492 of 2010. These findings indicate a serious environmental and public health concern for communities that rely on river water and aquatic organisms as food sources.

Studies from other regions in Indonesia further support these concerns. Nurhayati et al. (2019)[23] reported bioaccumulation of Pb and Hg in green mussels from the coastal waters of Java, while Andriani et al. (2022)[24] documented similar findings in mussels collected from the Makassar fish auction. Mursidi (2015)[25] reported a cancer risk of 1.5 per 10,000 population due to Cr^{6+} exposure in East Java, and Fatmayani et al. (2022)[26] identified renal function disorders among communities consuming contaminated mussels in Makassar. However, most existing studies have focused primarily on environmental contamination levels or isolated toxic effects, while comprehensive assessments of non-carcinogenic health risks resulting from combined exposure to Cr^{6+}, Pb, and Hg through freshwater mussel consumption remain limited, particularly in West Aceh.

Considering the high frequency of mussel consumption among the local population, reaching 3–5 servings per week[1], a comprehensive health risk assessment is urgently required.

Therefore, this study aims to quantify the concentrations of Cr^{6+}, Pb, and Hg in *Sinanodonta woodiana* consumed by communities along the Krueng Meureubo River, West Aceh, and to characterize non-carcinogenic health risks using an Environmental Health Risk Assessment (EHRA) approach. The findings of this study are expected to provide a scientific basis for risk mitigation strategies and to support environmental quality management policies aimed at protecting public health in the coastal areas of West Aceh.

MATERIALS AND RESEARCH METHODS

Study Design and Location

This study employed a quantitative approach to determine heavy metal concentrations in freshwater clams, assess community consumption patterns, and estimate non-carcinogenic health risks using the Environmental Health Risk Analysis (EHRA) approach. The research was conducted at four sampling points along the Krueng Meureubo River, West Aceh, representing upstream to downstream river conditions and illustrating the spatial distribution of heavy metal contamination.

Mesjid Tuha Waters (Point 1) are located in the upstream section of the Krueng Meureubo River and are predominantly influenced by residential settlements and agricultural land use. Marek Waters (Point 2) are situated in the middle section of the river and receive inputs from several tributaries as well as agricultural activities along the riverbanks. Rundeng Waters (Point 3) are located in the mid-lower section of the river and are characterized by relatively calm water flow, making this area a potential site for sediment deposition and accumulation of heavy metals transported from upstream. Pasi Mesjid Waters (Point 4) are located in the downstream area near the estuary and coastal zone, where community fishing activities and tidal influences are prominent.

Sample Collection and Respondents

Biological samples consisted of *Sinanodonta woodiana* clams, with one kilogram collected from each sampling point. Human subjects included 141 members of coastal communities, evenly distributed across the four study locations. The number of respondents was determined using the Kadam and Bhalerao formula(27). Inclusion criteria were: age between 18 and 65 years, shellfish consumption of at least three times per week, and residence within a 1 km radius of the river.

Heavy Metal Analysis and Health Risk Assessment

The concentrations of Pb, Hg, and Cr in clam samples were analyzed using Atomic Absorption Spectrophotometry (AAS) at the Laboratory of the Standardization and Industrial Service Center, Banda Aceh. Data on intake rate, exposure frequency, exposure duration, and other risk-related variables were collected using a structured questionnaire developed based on the WHO Human Health Risk Assessment Toolkit(28). The questionnaire was validated by two environmental toxicology experts prior to field implementation. Respondents' body weight was measured directly using a digital scale and incorporated into the calculation of Pb, Hg, and Cr intake.

A systematic evaluation of health risks associated with the consumption of shellfish contaminated with Cr, Pb, and Hg was conducted using the Environmental Health Risk Analysis (EHRA) framework, which consists of four stages: hazard identification, exposure assessment, dose–response analysis, and risk characterization.

Hazard Identification

Hazard identification was conducted to determine specific risk agents that may cause adverse health effects upon exposure. Measured concentrations of Pb and Hg were compared with the limits established in the Indonesian Food and Drug Authority (BPOM RI) Regulation No. 9 of 2022(29), which sets maximum permissible levels of <1.0 mg/kg for Pb and <0.5 mg/kg for Hg in processed foods. Chromium concentrations were evaluated using international reference standards from the Centre for Food Safety (CFS), Food and Environmental Hygiene Department, Hong Kong SAR[30–31], which specify a limit of 1.0 mg/kg for Cr in certain categories of seafood, such as oysters and crustaceans. This reference was applied due to the absence of an established Cr limit in processed foods under current BPOM RI regulations[29].

Exposure Assessment

Exposure assessment estimated the amount of heavy metals entering the human body through shellfish consumption. Calculations were based on questionnaire data and included parameters such as intake rate, exposure frequency, exposure duration, and body weight, which was measured directly using a digital scale. The exposure intake value was calculated using the following equation:

$$I = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where:
I = intake value or Estimated Daily Intake (EDI) (mg/kg/day)
C = concentration of heavy metals in clams (mg/kg)
IR = clam consumption rate per day (kg/day)
EF = exposure frequency per year (days/year)
ED = exposure duration or consumption period (years)
BW = respondent's body weight (kg)
AT = average exposure time for non-carcinogenic effects (days)

Dose–Response Analysis and Risk Characterization

Dose–response analysis was conducted to evaluate the relationship between the exposure dose of heavy metals (Cr, Pb, and Hg) and potential non-carcinogenic health effects. The reference value used was the Reference Dose (RfD), representing the safe threshold for non-carcinogenic exposure. In the absence of nationally established RfD values, reference values were obtained from the Integrated Risk Information System (IRIS) of the United States Environmental Protection Agency (US EPA)[10]. This approach is consistent with the 2012 Environmental Health Risk Analysis Guidelines, which permit the use of international toxicity benchmarks when national data are unavailable.

The RfD values applied in this study were 0.0035 mg/kg/day for Pb, 0.0003 mg/kg/day for Hg, and 0.003 mg/kg/day for Cr. Non-carcinogenic risk was assessed by comparing the estimated daily intake (I) with the corresponding RfD value using the Hazard Quotient (HQ), calculated as follows:

$$HQ = \frac{I}{RfD}$$

where:
HQ = Hazard Quotient, the ratio between the actual dose and the reference doseI
I = Intake (mg/kg/day)
RfD =Reference Dose (mg/kg/day)

An HQ value <1 indicates that exposure is within acceptable limits, whereas an HQ ≥1 suggests a potential non-carcinogenic health risk requiring further attention[32–33].

Ethical Considerations

This study received ethical approval from the Health Research Ethics Committee of Poltekkes Kemenkes Aceh (Approval No. DP.04.03/12.7/132/2025). All research procedures were conducted in accordance with ethical principles for human research. Informed consent was obtained from all participants prior to data collection. Participant safety and comfort were prioritized, potential risks were minimized, and data confidentiality was strictly maintained in compliance with applicable ethical standards.

RESEARCH RESULTS AND DISCUSSION

Hazard Identification

Hazard identification is the initial stage in Environmental Health Risk Analysis (EHRA), aimed at recognizing potential hazards that may arise from exposure to heavy metals on human health. In this study, the identified sources of hazard come from the heavy metals Pb, Hg, and Cr, which accumulate in the tissues of the clam Sinanodonta woodiana consumed by the local community around the Krueng Meurebo River, West Aceh.

Profile of the Mussel Sinanodonta woodiana in the Meureubo River

The Meureubo River is a major river in West Aceh Regency and serves as an important habitat for freshwater organisms, including the mussel *Sinanodonta woodiana*, which is commonly found in calm, muddy river sections and functions as a bioindicator of water quality. *S. woodiana* is a freshwater bivalve from the family Unionidae that is widely distributed in tropical and subtropical regions, including Indonesia, and has adapted well to riverine environments in West Aceh [34]. Morphologically, this clam has a dark brown to black shell with a smooth and glossy surface (Figure 1). The shell is elongated and ovoid, measuring 8–15 cm in length, and the inner side of the shell (nacre) is silvery white. The dorsal part of the shell tends to be thick and strong, serving to protect the internal organs from fluctuating aquatic environmental conditions.

Figure 1. Sinanodonta woodiana clams from the Krueng Meureubo River, West Aceh.

As a filter-feeding organism, S. woodiana has the ability to accumulate heavy metals dissolved in the water column or associated with suspended particles, particularly within its soft tissues. Its high bioaccumulation capacity, coupled with tolerance to environmental fluctuations, makes this species a suitable bioindicator for assessing heavy metal contamination in freshwater ecosystems[35].

Heavy Metal Concentrations in Sinanodonta woodiana from the Meureubo River

Table 1 presents the concentrations of Pb, Hg, and Cr in Sinanodonta woodiana clams collected from four sampling points along the Meureubo River: Point 1 (upstream), Point 2 (midstream), Point 3 (mid–downstream), and Point 4 (downstream).

Table 1. Concentration of Heavy Metals Pb, Hg, and Cr in Sinanodonta woodiana Clams in the Meureubo River Estuary

Concentration of Heavy Metals	Point 1	Point 2	Point 3	Point 4
Pb (mg/kg)	3,91	5,65	2,36	5,34
Hg (mg/kg)	53,27	3,71	1,10	13,29
Cr (mg/kg)	< 0,0001	< 0,0001	< 0,0001	< 0,0001

Table 1 shows that Pb concentrations in *Sinanodonta woodiana* ranged from 2.36 to 5.65 mg/kg. The highest concentration was observed at Point 2 (5.65 mg/kg), while the lowest was recorded at Point 3 (2.36 mg/kg). All measured Pb concentrations exceeded the maximum permissible limit for heavy metal contamination in processed fishery products established by BPOM RI Regulation No. 9 of 2022, which is 1.0 mg/kg. The elevated Pb concentration at Point 2 (Marek Waters) may be attributed to agricultural activities along the riverbanks and tributary inputs transporting pesticide residues, phosphate fertilizers, and metal-laden sediments from the surrounding watershed in the midstream section of the river. Relatively high Pb concentrations were also detected at Point 1 (3.91 mg/kg) and Point 4 (5.34 mg/kg), indicating that Pb contamination is widespread from upstream to the estuarine area, likely due to domestic wastewater discharges and residues from community activities along the riverbanks. This finding is consistent with a study by Lahati et al. (2022), which reported that elevated Pb concentrations in clams are closely associated with human and agricultural activities surrounding aquatic environments[(36)].

As presented in Table 1, Hg concentrations ranged from 1.10 to 53.27 mg/kg, with the highest value detected at Point 1 (53.27 mg/kg), an upstream area dominated by residential settlements and agricultural land use. This concentration far exceeded the safety limit stipulated by BPOM RI Regulation No. 9 of 2022, which is 0.5 mg/kg. The extremely high Hg levels in the upstream section suggest potential inputs from domestic wastewater, the application of heavy metal–based pesticides, or effluents from household and agricultural activities. Given the volatile nature of mercury and its propensity for bioaccumulation through the food chain, *S. woodiana* clams at this location are at a particularly high risk of mercury accumulation. Although the Hg concentration at Point 3 (1.10 mg/kg) was relatively lower than at other sampling points, it still exceeded the regulatory threshold, indicating persistent Hg contamination along the river continuum to Point 4 (13.29 mg/kg), which is located near the estuary and influenced by fishing activities and tidal dynamics. Similar findings were reported by Nur et al. (2023), who demonstrated that elevated Hg levels in shellfish are associated with the accumulation of domestic waste and other anthropogenic inputs[(37)].

In contrast, Cr concentrations at all sampling points were below the instrument detection limit (<0.0001 mg/kg), as shown in Table 1. These values are substantially lower than the international safety threshold of 1.0 mg/kg established by the Centre for Food Safety (CFS), Hong Kong (2025). This result indicates that anthropogenic activities along the Meureubo River have not led to significant Cr contamination in the aquatic environment. Chromium in this system is likely present predominantly in its trivalent form (Cr^{3+}), which is relatively stable and less soluble than other heavy metal species. These findings are in agreement with the study by Rudiyanti et al. (2023), which also reported low Cr concentrations (<0.3 mg/kg) in clams from Semarang waters, suggesting that Cr is generally not a dominant bioaccumulative metal in Indonesian aquatic ecosystems[(38)].

Characteristics of Subject/Respondent Samples

Table 2. Demographic Characteristics of Respondents (n=141)

Characteristic	Mean ± SD	Min–Max	n	(%)
Age (years)	44.78 ± 15.57	17–80	–	–
Sex				
Male	–	–	48	34.0
Female	–	–	93	66.0
Educational Level				
Primary	–	–	44	31.2
Secondary	–	–	83	58.9
Higher	–	–	14	9.9
Occupation				
Employed	–	–	65	46.1
Unemployed	–	–	76	53.9
Health Check-Up When Ill				
Yes	–	–	69	48.9

Characteristic	Mean ± SD	Min–Max	n	(%)
No	–	–	72	51.1
Symptoms Experienced While Consuming Shellfish				
Abdominal pain	–	–	12	8.5
Nausea and vomiting	–	–	12	8.5
Diarrhea	–	–	7	5.0
Loss of appetite	–	–	3	2.1
Weakness and fatigue	–	–	13	9.2
Headache	–	–	31	22.0
Skin rash and itching	–	–	47	33.3
Weight loss	–	–	8	5.7
Mild fever	–	–	4	2.8

Based on Table 2, the mean age of the respondents was 44.78 ± 15.57 years, with an age range of 17–80 years. This distribution indicates that the respondents represent adult to elderly age groups, which are generally active in economic and social activities within coastal communities. Female respondents constituted the majority of the study population (66%). This predominance may be attributed to the greater involvement of women in household activities, which increased their availability during the data collection process.

Regarding educational attainment, most respondents had completed secondary education (58.9%), while more than half were unemployed (53.9%). These characteristics suggest that the community in the study area predominantly has a low-to-middle educational background. Such conditions may influence the level of awareness and knowledge regarding potential health risks associated with the consumption of shellfish contaminated with heavy metals[(23)]. Only 48.9% of respondents reported seeking health check-ups when experiencing illness, whereas 51.1% had never undergone a medical examination, indicating limited health-seeking behavior at formal healthcare facilities. Health complaints reported during shellfish consumption varied among respondents. The most frequently reported symptoms were skin rashes and itching (33.3%), followed by headaches (22.0%), as well as abdominal pain and nausea or vomiting, each reported by 8.5% of respondents. These symptoms may be indicative of exposure to heavy metals such as mercury and lead, which are known to accumulate in shellfish[(23–24,39)]. Although the reported symptoms were generally mild to moderate, these findings highlight a potential health risk associated with the long-term and repeated consumption of shellfish in the study area.

Exposure Analysis

Exposure analysis is conducted to calculate the amount of heavy metal intake entering the human body through the consumption of shellfish. The exposure pathway used in this study is oral ingestion, as shellfish are directly consumed by the local community as a source of animal protein.

Table 3. Analysis of Heavy Metal Exposure of Pb, Hg, and Cr in Communities Consuming Sinanodonta woodiana Clams in the Krueng Meureubo River

Location	Concentration	N	Intake (mg/kg/day)			
			Min	Max	Mean	Std.Deviasi
Point 1-4	Cr	141	0.00000	0.00023	0.00006	0.00004
	Pb		0.00000	9.80816	2.67452	2.01455
	Hg		0.00000	94.00588	10.19342	16.57924

Table 3 presents the results of heavy metal exposure to Cr, Pb, and Hg among communities consuming Sinanodonta woodiana clams from four sampling points in the Krueng Meureubo River. The calculations indicate that the highest average intake value is found for Hg at 10.19342 mg/kg/day, with a range of 0.00000–94.00588 mg/kg/day, followed by Pb at 2.67452 mg/kg/day, and Cr at 0.00006 mg/kg/day. The highest standard deviation was also observed in Hg (16.57924 mg/kg/day), indicating substantial variation in exposure among respondents, presumably due to differences in consumption locations and the frequency of clam intake.

In general, the findings indicate that mercury (Hg) exhibits the highest exposure levels compared to other heavy metals. This aligns with the characteristic of Hg, which easily accumulates in the tissues of aquatic organisms through the food chain and is subject to biomagnification. Meanwhile, chromium (Cr) exposure shows the lowest value (<0.00023 mg/kg/day) due to Cr levels at all sampling points being below the laboratory detection limit. Lead (Pb) intake values still demonstrate considerable variation among respondents, reflecting potential differences in exposure at each river site. When compared to the Reference Dose (RfD) recommended by the US EPA (0.0030 mg/kg/day for Cr, 0.0035 mg/kg/day for Pb, and 0.0003 mg/kg/day for Hg), the average intake value for Hg exceeds the safe limit. This indicates a potential non-carcinogenic risk to the community from consuming shellfish from the Krueng Meureubo River, whereas Cr and Pb levels remain below the safe threshold.

Risk Characterization

The risk characterization or Hazard Quotient (HQ) is the final stage in the EHRA process, conducted to determine the extent of potential health risks arising from heavy metal exposure through the consumption of Sinanodonta woodiana clams by communities around the Krueng Meureubo River. The risk characterization calculation process is carried out by comparing the daily intake of heavy metals (obtained from the exposure analysis stage) with the Reference Dose (RfD), which is the threshold dose considered safe for humans for non-carcinogenic effects. The risk is deemed acceptable if HQ ≤ 1, whereas HQ > 1 indicates a potential non-carcinogenic health risk to individuals or populations exposed.

Table 4. Distribution of Heavy Metal Risk Values of Pb, Hg, and Cr in Communities Consuming Sinanodonta woodiana Clams in the Krueng Meureubo River

Heavy Metals	HQ ≤ 1	HQ> 1	Total
	n (%)	n (%)	n (%)
Cr	141 (100 %)	0 (0 %)	141 (100 %)
Pb	40 (28.3 %)	101 (71.7 %)	141 (100 %)
Hg	16 (11.3 %)	125 (88.7 %)	141 (100 %)

Table 4 presents the distribution of non-carcinogenic risk values, expressed as Hazard Quotients (HQ), for Cr, Pb, and Hg among individuals consuming Sinanodonta woodiana clams. The analysis showed that all respondents (100%) had HQ values ≤1 for Cr, indicating that chromium exposure through clam consumption remains below the reference dose and does not pose a non-carcinogenic health risk.

In contrast, Pb exposure exhibited substantially higher risk levels. A total of 71.7% of respondents (n = 101) had HQ values >1, suggesting that the majority of individuals consuming clams from the Krueng Meureubo River are potentially at risk of non-carcinogenic health effects due to lead exposure exceeding the established reference dose (RfD = 0.0035 mg/kg/day).

The highest non-carcinogenic risk was observed for mercury (Hg), with 88.7% of respondents (n = 125) exhibiting HQ values >1. This finding indicates that mercury represents the most dominant health risk among the three heavy metals evaluated in this study. Overall, these results demonstrate that exposure to Hg and Pb may pose significant non-carcinogenic health risks to local communities, particularly among individuals who routinely consume shellfish from the Krueng Meureubo River. This elevated risk is likely attributable to the strong bioaccumulation and biomagnification potential of these metals within aquatic organisms, which subsequently enter the human food chain[(4)].

CONCLUSIONS AND RECOMMENDATIONS

The findings of this study demonstrate that freshwater clams (Sinanodonta woodiana) collected from the Krueng Meureubo River are contaminated with heavy metals at varying concentrations. Risk characterization revealed that exposure to mercury (Hg) and lead (Pb) through clam consumption exceeds the acceptable non-carcinogenic threshold (HQ > 1), indicating potential health risks for communities that regularly consume these clams. In contrast, chromium (Cr) exposure remained within safe limits (HQ ≤ 1) and did not pose a significant non-carcinogenic health risk.

Based on these results, continuous monitoring of water quality and aquatic food safety in the Krueng Meureubo River is strongly recommended. Risk mitigation measures, including increased public awareness regarding safe shellfish consumption and stricter regulation and control of potential pollution sources, are essential to reduce long-term health risks associated with heavy metal exposure among coastal communities.

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