

Lead contamination in coastal sediments, Buyat Bay: Spatial assessment in North Sulawesi, Indonesia

Glorya Rondonuwu^{*1}, Sri Seprianto Maddusa², Jootje Umboh³

^{1, 2, 3} Faculty of Public Health, Sam Ratulangi University, Manado, Indonesia

ABSTRACT

Heavy metal contamination remains a persistent environmental and public health concern in coastal ecosystems, yet recent information on lead (Pb) accumulation in Buyat Bay sediments is limited; this study provides an updated site-specific assessment of Pb distribution and sediment-quality status. This study aimed to analyze Pb concentrations in sediments of Buyat Bay, North Sulawesi, Indonesia, and compare the measured values with the National Oceanic and Atmospheric Administration (NOAA) Sediment Quality Guidelines. A descriptive survey design was applied through field sampling and laboratory analysis. Sediment samples were collected from 16 purposively selected sampling points in November 2025 and analyzed at the Center for Health Laboratory of Makassar using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS). Pb was detected in all sediment samples, with concentrations ranging from 2.6145 to 30.2823 µg/g and an average concentration of 6.7405 µg/g. The highest concentration was recorded at Point 9, indicating spatial variation in Pb accumulation across the bay. All concentrations were below the NOAA Effects Range Low value of 46.7 µg/g, suggesting a relatively low probability of adverse biological effects. Nevertheless, the widespread detection of Pb supports continued environmental surveillance, integrated monitoring of sediments and marine biota, and preventive coastal management to minimize future ecological and public health risks.

ABSTRAK

Kontaminasi logam berat masih menjadi masalah lingkungan dan kesehatan masyarakat yang persisten di ekosistem pesisir. Namun, informasi terkini mengenai akumulasi timbal (Pb) pada sedimen di Teluk Buyat masih terbatas. Penelitian ini memberikan penilaian terbaru yang spesifik lokasi mengenai distribusi Pb dan status kualitas sedimen. Penelitian ini bertujuan untuk menganalisis konsentrasi Pb pada sedimen di Teluk Buyat, Sulawesi Utara, Indonesia, serta membandingkan nilai yang diperoleh dengan *Sediment Quality Guidelines* dari National Oceanic and Atmospheric Administration (NOAA). Penelitian menggunakan desain survei deskriptif melalui pengambilan sampel lapangan dan analisis laboratorium. Sampel sedimen dikumpulkan dari 16 titik sampling yang dipilih secara purposif pada November 2025 dan dianalisis di Balai Besar Laboratorium Kesehatan Makassar menggunakan metode *Inductively Coupled Plasma–Mass Spectrometry* (ICP-MS). Pb terdeteksi pada seluruh sampel sedimen dengan konsentrasi berkisar antara 2,6145 hingga 30,2823 µg/g dan rata-rata sebesar 6,7405 µg/g. Konsentrasi tertinggi ditemukan pada Titik 9, yang menunjukkan adanya variasi spasial akumulasi Pb di kawasan teluk. Seluruh konsentrasi Pb berada di bawah nilai *Effects Range Low* (ERL) NOAA sebesar 46,7 µg/g, yang menunjukkan bahwa kemungkinan terjadinya efek biologis merugikan relatif rendah. Meskipun demikian, terdeteksinya Pb pada seluruh titik sampling menunjukkan perlunya pengawasan lingkungan secara berkelanjutan, pemantauan terpadu terhadap sedimen dan biota laut, serta pengelolaan pesisir secara preventif untuk meminimalkan risiko ekologis dan kesehatan masyarakat di masa mendatang.

ARTICLE INFO

Keywords

coastal pollution; environmental monitoring; heavy metals; lead contamination; marine sediment

Article History

Submit : 26 April 2026
In Review : 12 May 2026
Accepted : 12 August 2026

AUTHOR(S) INFO

Correspondence Email

gloriarondonuwu121@student.unsrat.ac.id

Address

Jalan Kampus Unsrat, Kelurahan Kleak, Kecamatan Malalayang, Manado, Sulawesi Utara 95115, Indonesia



INTRODUCTION

Heavy metal pollution remains a major environmental and public health concern worldwide, particularly in coastal and marine ecosystems where contaminants from terrestrial and maritime activities converge. Mining, industrial operations, transportation, urban runoff, domestic waste disposal, and other anthropogenic activities can introduce persistent metals into aquatic environments, where they may remain for prolonged periods and accumulate in sediments and organisms (UNEP, 2025). Coastal sediments are especially important because they function both as repositories and potential secondary sources of contaminants when changes in hydrodynamic or physicochemical conditions remobilize deposited metals. Recent evidence indicates that continuing urbanization and industrial development have intensified heavy metal pressures in coastal environments, creating ecological risks and potential human exposure through water, fisheries, and other ecosystem services (El-Sharkawy et al., 2025).

Among toxic metals, lead (Pb) is of particular public health importance because exposure can affect multiple organ systems and no level of exposure is considered completely free of adverse effects. Pb can accumulate in the body and has been associated with neurological impairment, anemia, renal dysfunction, cardiovascular effects, and reproductive and developmental disorders (WHO, 2024; Simatupang et al., 2024). Children and pregnant women are particularly vulnerable because Pb can impair neurological development and may be mobilized from maternal bone during pregnancy, thereby exposing the developing fetus. Chronic environmental exposure is therefore relevant even when contamination does not produce immediate clinical symptoms, because repeated exposure through contaminated water, food, soil, or other environmental media may contribute to cumulative health risks (Handayani et al., 2025).

In Indonesia, heavy metal contamination of coastal ecosystems is increasingly important because coastal communities commonly depend on marine resources for food, livelihoods, and daily activities. Once introduced into aquatic environments, metals may associate with suspended particles and subsequently settle in bottom sediments. They may also enter aquatic organisms and be transferred through trophic interactions, creating pathways for bioaccumulation and, depending on the metal and ecological conditions, increasing exposure at higher trophic levels (United States Environmental Protection Agency, 2020; Oros, 2025). Pb contamination is particularly relevant to food safety because accumulation in edible marine organisms may create a potential exposure pathway for populations consuming seafood from contaminated areas (Widiyanto et al., 2024). Consequently, effective prevention requires an integrated approach combining source control, periodic environmental surveillance, sediment and biota monitoring, seafood-safety assessment, and risk communication to communities potentially exposed to contaminated coastal resources.

Scientific literature increasingly recognizes sediment monitoring as an essential component of coastal pollution assessment. In contrast to water samples, which may represent relatively short-term environmental conditions, sediments can retain particle-associated metals and provide evidence of contaminant accumulation over longer periods. Sediment measurements can therefore be compared with sediment quality guidelines to identify concentrations at which adverse biological effects may become more likely. Indonesian investigations have demonstrated spatial variation in Pb concentrations in coastal sediments and emphasize the importance of location-specific surveillance because contamination patterns are influenced by sources, sediment characteristics, currents, and depositional processes (Sastra et al., 2023; Al Fauzan et al., 2024; Siregar et al., 2025). Sediment quality guidelines, including effect-based benchmarks, consequently provide a useful screening framework for interpreting ecological significance (NOAA, 2022).

Environmental monitoring can also function as an upstream public health intervention when it is linked to exposure prevention. Integrated assessment of sediment, water, and aquatic organisms can help identify contaminant pathways before substantial human exposure occurs and can guide targeted measures such as pollution-source reduction, safer mining practices, fisheries monitoring, and community risk communication. This approach is particularly important in mining-affected coastal areas, where historical contamination may coexist with continuing inputs from watersheds. Studies in

North Sulawesi have demonstrated that mining-associated trace metals can occur in edible marine organisms, while recent assessment of the Buyat River has identified environmental pressures associated with artisanal gold-mining activities (Tamburini et al., 2022; Lagoari et al., 2025). Such evidence supports sustained environmental surveillance as part of preventive health protection for coastal populations.

Buyat Bay is located on the southern coast of the Minahasa Peninsula in North Sulawesi and has a distinctive history of mining-related environmental concern. Large-scale gold mining by PT Newmont Minahasa Raya began in the 1990s, with submarine tailings disposal occurring during mine operations until production ceased in 2004; post-mining environmental monitoring subsequently continued (Rayhan & Pramesty, 2023). The environmental characteristics of the bay are additionally influenced by local geology. Volcanic and sedimentary formations, weathering, erosion, and terrestrial runoff may naturally transport mineral particles and trace elements toward the coastal environment (Mokoagow et al., 2023). More recently, artisanal and small-scale gold-mining activities within the Buyat watershed have remained a potential source of environmental pressure, with evidence of water-quality impacts in the Buyat River, which drains toward the bay (Lagoari et al., 2025).

Despite the historical attention given to mining-related pollution in Buyat Bay, recent information specifically characterizing Pb accumulation in its sediments remains limited compared with earlier concern regarding mercury and arsenic. This gap is important because sediment contamination may persist after major pollution sources have ceased and may provide an early indication of continuing or renewed environmental exposure. Updated Pb measurements can therefore support evidence-based environmental health interventions, including routine surveillance, contaminant-source management, ecological risk screening, and protection of coastal communities that depend on local marine resources. The novelty of this study lies in providing an updated, site-specific assessment of Pb concentrations in Buyat Bay sediments and interpreting the measurements against applicable sediment quality guideline values. Accordingly, this study aimed to analyze lead (Pb) concentrations in sediments of Buyat Bay, North Sulawesi, Indonesia, using a descriptive survey involving field sampling and laboratory analysis, and to compare the measured concentrations with established sediment quality guidelines.

METHODS

Study Design and Location

This study employed a descriptive survey design using field sampling and laboratory analysis to determine lead (Pb) concentrations in coastal sediments. The research was conducted in the coastal waters of Buyat Bay, North Sulawesi, Indonesia. Sediment sampling was carried out in November 2025, while laboratory analysis was subsequently performed at the Center for Health Laboratory of Makassar.

Study Population and Sample

The study population consisted of bottom sediments within the coastal waters of Buyat Bay. The study sample comprised sediment collected from 16 sampling points distributed across the study area. Sampling points were selected using a purposive sampling technique based on scientific and environmental considerations, including proximity to potential pollution sources, surrounding coastal human activities, accessibility, and characteristics of the sampling locations. This approach was intended to provide spatial representation of Pb concentrations across different parts of the bay.

The inclusion criteria were surface sediments collected from predetermined sampling points within Buyat Bay, sediments that could be obtained from the upper seabed layer at an approximate depth of 10–15 cm, and samples that were collected, labeled, stored, and transported in accordance with laboratory sample-handling requirements. Samples that were insufficient in quantity, visibly contaminated during handling, improperly labeled, or otherwise unsuitable for laboratory analysis were excluded.

Sediment Sampling and Sample Handling

Sediment samples were collected from the surface layer of the seabed at an approximate depth of 10–15 cm. Each sample was transferred into a clean container to minimize external contamination. Containers were labeled with the sampling-point code and relevant sampling information immediately after collection. The sediment samples were subsequently stored and transported to the laboratory using appropriate sample-handling procedures to maintain sample integrity prior to analysis.

The geographical distribution of the 16 sediment collection points is presented in [Figure 1](#). The sampling locations were designed to capture possible spatial differences in Pb accumulation associated with local coastal characteristics and potential contaminant inputs.

Figure 1

Sampling locations of sediment collection points in Buyat Bay

Laboratory Analysis

Prior to instrumental analysis, sediment samples were prepared according to the standard laboratory protocol applied by the Center for Health Laboratory of Makassar. Lead concentrations were determined using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS). ICP-MS was selected because of its high sensitivity and capacity to quantify trace concentrations of metals in environmental samples. The analytical results were expressed as micrograms of Pb per gram of sediment ($\mu\text{g/g}$).

Laboratory procedures, including sample preparation, instrumental measurement, and reporting of analytical results, were conducted according to the laboratory's established quality-control procedures. The Pb concentration obtained for each sampling point was subsequently entered into the study dataset for descriptive and comparative analysis.

Data Analysis and Presentation

Laboratory results were analyzed descriptively to characterize the distribution of Pb concentrations in Buyat Bay sediments. Descriptive statistics included the minimum concentration, maximum concentration, and arithmetic mean across all sampling points. Individual concentrations were also compared between sampling points to identify spatial variation and locations with relatively higher Pb accumulation.

To evaluate sediment contamination status, Pb concentrations were compared with the National Oceanic and Atmospheric Administration (NOAA) Sediment Quality Guidelines, particularly the Effects Range Low (ERL) benchmark of $46.7 \mu\text{g/g}$. Concentrations below the ERL were interpreted as having a relatively low probability of adverse biological effects associated with Pb exposure in sediment-dwelling organisms. The findings were presented in tables and narrative form to facilitate comparison among sampling points and interpretation against the sediment-quality benchmark.

Research Procedure

The research procedure consisted of determining sampling locations, collecting sediment samples from the 16 predetermined points, labeling and preserving samples, transporting samples to the laboratory, preparing samples according to laboratory protocols, analyzing Pb concentrations using ICP-MS, compiling laboratory results, calculating descriptive statistics, and comparing Pb concentrations with the NOAA ERL guideline. This sequence was applied consistently to all sediment samples to support comparability of the analytical results.

Ethical Considerations and Informed Consent

This study involved only environmental sediment samples and did not involve human participants, identifiable personal information, human biological specimens, or experimental animals.

Therefore, individual informed consent was not applicable. Field and laboratory activities were conducted in accordance with applicable environmental sampling procedures, laboratory safety requirements, and institutional regulations relevant to the collection and analysis of environmental samples.

RESULTS AND DISCUSSION

Lead Concentrations and Spatial Distribution in Buyat Bay Sediments

The findings demonstrate that Pb was present throughout the sediment of Buyat Bay, although its distribution was spatially heterogeneous and all measured concentrations remained below the selected sediment-quality guideline. Pb was detected at all 16 sampling points, indicating that the metal is distributed across the study area rather than restricted to a single location. Concentrations ranged from 2.61 to 30.28 µg/g, with an average of 6.74 µg/g. The lowest concentration was recorded at Point 6 (2.61 µg/g), whereas the highest concentration occurred at Point 9 (30.28 µg/g). Most sampling points showed relatively similar concentrations between approximately 2.61 and 7.41 µg/g, while Point 9 was markedly higher, at approximately 4.5 times the overall mean (see Table 2). This pattern suggests localized Pb enrichment rather than uniformly elevated contamination throughout the bay.

Table 1
Lead (Pb) Concentrations in Sediment Samples from Buyat Bay

Sampling point	Pb concentration (µg/g)	NOAA ERL (µg/g)	Category
Point 1	3.3515	46.7	Below ERL
Point 2	4.8172	46.7	Below ERL
Point 3	5.9467	46.7	Below ERL
Point 4	4.1129	46.7	Below ERL
Point 5	6.0217	46.7	Below ERL
Point 6	2.6145	46.7	Below ERL
Point 7	4.3637	46.7	Below ERL
Point 8	2.8219	46.7	Below ERL
Point 9	30.2823	46.7	Below ERL
Point 10	5.4064	46.7	Below ERL
Point 11	7.4052	46.7	Below ERL
Point 12	4.7037	46.7	Below ERL
Point 13	4.3122	46.7	Below ERL
Point 14	5.0966	46.7	Below ERL
Point 15	3.1763	46.7	Below ERL
Point 16	3.4156	46.7	Below ERL
Average	6.7405	46.7	Below ERL

Sediments are effective repositories for heavy metals because particulate-bound contaminants can settle, adsorb onto mineral surfaces, and remain within depositional environments for extended periods. Consequently, sediment measurements can reflect longer-term contaminant inputs more effectively than a single water-column measurement. The pronounced concentration at Point 9 may be related to local differences in sediment texture, organic matter, hydrodynamics, depositional conditions, or proximity to contaminant inputs. However, because these environmental variables were not simultaneously quantified, attribution of the elevated concentration to a particular source cannot be established from the present data alone. Studies from Panjang Island similarly show that sediment grain size strongly influences Pb accumulation, with finer sediments generally providing greater adsorption capacity (Al Fauzan et al., 2024).

The spatial variability observed in Buyat Bay is consistent with previous studies of Indonesian coastal environments. Afu and Luturmas (2022) detected Pb in sediments from Tanjung Tiram, South Konawe, and reported differences among sampling stations associated with coastal activities, including vessel traffic and other anthropogenic pressures. Their findings support the role of coastal sediment as an accumulation medium for metals entering aquatic environments. Similarly, Sastra et al. (2023) identified Pb in surface sediments at Sampur Beach, Bangka, although contamination was classified as relatively low, illustrating that detectable Pb may occur even where guideline-based ecological concern remains limited.

The results also correspond with Fathona et al. (2025), who reported substantially higher sediment Pb concentrations in the northern waters of Belitung Regency, ranging from approximately 10.08–50.08 mg/kg during the easterly season and 10.96–60.72 mg/kg during the westerly season. Their study demonstrated that Pb distribution was affected by seasonal flow, geographical position, sediment grain size, erosion, and terrestrial runoff. Likewise, Tamba et al. (2025) reported spatial differences in Pb concentrations among seawater, sediments, and green mussels along the northern coast of Semarang, further supporting the influence of localized environmental conditions and anthropogenic activities on coastal Pb distribution.

Compared with these studies, the principal advantage of the present investigation is the relatively dense spatial coverage of 16 sediment sampling points within Buyat Bay. This distribution allows localized enrichment, particularly at Point 9, to be distinguished from the generally lower concentrations observed throughout most of the bay.

The spatial pattern is scientifically important because reliance solely on an average concentration could obscure localized areas of elevated contamination. Although the mean Pb concentration was only 6.74 µg/g, Point 9 reached 30.28 µg/g. Therefore, environmental interpretation should consider individual sampling locations in addition to summary statistics. The finding provides a basis for future source-tracing studies focusing on locations with comparatively high Pb accumulation.

From a practical perspective, Point 9 should be prioritized in subsequent monitoring. Additional measurements of sediment grain size, total organic carbon, pH, redox conditions, water Pb concentrations, current patterns, and proximity to river or human-activity inputs would help determine whether this elevation reflects natural geochemical variability, historical deposition, or continuing anthropogenic input. Repeated sampling across dry and rainy seasons would also clarify whether the observed pattern is persistent or seasonally dependent.

Interpretation Based on NOAA Sediment Quality Guidelines

Comparison with the NOAA Sediment Quality Guidelines showed that all 16 Pb concentrations were below the Effects Range-Low (ERL) value of 46.7 µg/g. Even the highest concentration at Point 9 represented approximately 64.8% of the ERL, while the mean concentration represented approximately 14.4%. The study objective of determining Pb concentrations and evaluating them against a sediment-quality benchmark was therefore achieved.

The ERL represents a concentration below which adverse biological effects are expected to occur relatively infrequently; it should not be interpreted as an absolute boundary between safe and toxic sediment. For Pb, the NOAA framework specifies an ERL of 46.7 mg/kg dry weight and an Effects Range-Median (ERM) of 218 mg/kg. The original guideline database showed a substantially lower frequency of biological effects below the ERL than at concentrations between the ERL and ERM or above the ERM (NOAA, 2022). Therefore, the Buyat Bay results indicate a relatively low probability of Pb-related adverse sediment effects based on this screening approach, but they do not demonstrate the complete absence of ecological risk.

The importance of maintaining this distinction is demonstrated by studies examining Pb simultaneously in sediment and marine organisms. Ekamaida et al. (2025) detected Pb in sediments, water, and oysters (*Saccostrea cucullata*) from the Cunda Strait, Lhokseumawe. Their analysis showed a positive pattern between Pb concentrations in oysters and environmental media, indicating that sediment and water can contribute to Pb exposure in aquatic organisms. The study also identified sediment fraction and organic matter as factors associated with metal distribution.

Similarly, Triyanto et al. (2024) investigated Pb in water, sediment, and the seagrass *Thalassia hemprichii* at Kelapa Dua Island. Sediment concentrations ranged from approximately 0.006 to 0.41 ppm, whereas Pb concentrations were substantially higher in seagrass roots and leaves, with leaves reaching 14.5–28 ppm. This finding demonstrates that comparatively low concentrations in sediment do not necessarily exclude accumulation in biological tissues. Accordingly, the below-ERL status of Buyat Bay sediments should not be interpreted as direct evidence that seafood or other marine organisms are free from Pb contamination.

The detection of Pb at every sampling point indicates that Pb inputs have occurred across Buyat Bay. Sediments can serve as both sinks and potential secondary sources of contaminants. Disturbance caused by waves, currents, storms, dredging, benthic activity, or other resuspension processes may alter metal mobility and increase opportunities for interaction with aquatic organisms. Consequently, present concentrations may represent stored contamination even when Pb concentrations in overlying water are temporarily low.

The findings therefore support continued ecological surveillance rather than the conclusion that monitoring is no longer necessary. Sediment-quality guidelines are most appropriately used as screening tools, and stronger ecological assessment would integrate sediment chemistry with measurements of water, benthic organisms, fish or shellfish, and, where feasible, toxicity or bioavailability indicators. Such an integrated approach would provide a more complete assessment of the ecological significance of Pb in Buyat Bay.

Public Health Relevance of the Findings

From a public health perspective, the principal finding is that current Pb concentrations in Buyat Bay sediments are below the selected ecological screening benchmark, but environmental Pb remains detectable throughout the bay. Sediment concentration alone cannot quantify human health risk because this study did not measure Pb in drinking water, seafood, or human biological samples. Therefore, no direct conclusion regarding human Pb exposure or health effects should be drawn from the sediment data.

Nevertheless, sediment surveillance has preventive value because it can identify environmental contamination before substantial exposure becomes evident in human populations. For coastal communities that depend on marine resources, monitoring sediments together with edible fish, mollusks, or other locally consumed organisms would provide stronger evidence regarding potential exposure pathways.

The Buyat Bay findings extend previous Indonesian evidence showing that Pb contamination is strongly location-dependent. Concentrations were lower than the upper levels reported by Fathona et al. (2025) in northern Belitung, while the occurrence of spatial variation resembles patterns reported by Afu and Luturmas (2022), Sastra et al. (2023), Al Fauzan et al. (2024), and Tamba et al. (2025). Evidence from Ekamaida et al. (2025) and Triyanto et al. (2024) further demonstrates why environmental assessment should extend beyond sediment concentrations to biological accumulation.

The contribution of the present study is particularly relevant to Buyat Bay because it provides an updated, site-specific dataset from an area with a history of mining-related environmental concern. The findings establish a contemporary baseline against which future changes can be evaluated and identify Point 9 as a location deserving greater investigative attention.

The results support a preventive environmental-health intervention centered on periodic, integrated monitoring rather than remediation based solely on the present Pb concentrations. Priority measures should include repeated sediment sampling at the same points, intensified surveillance around Point 9, seasonal assessment, characterization of sediment properties, examination of riverine and land-based contaminant inputs, and measurement of Pb in water and representative marine organisms consumed by local communities.

These interventions would allow early identification of increasing contamination and provide evidence for source control before ecological or human exposure becomes substantial. Community risk communication should also emphasize that concentrations below an ecological guideline do not

indicate the complete absence of Pb, while avoiding unsupported conclusions about health risk. Overall, the study indicates that Pb contamination in Buyat Bay sediments is currently below the NOAA ERL across all sampled locations, yet its universal detection and marked spatial heterogeneity justify continued environmental surveillance as an upstream public health protection strategy.

CONCLUSION

Lead (Pb) was detected in all sediment samples collected from Buyat Bay, with concentrations ranging from 2.6145 to 30.2823 µg/g and an average concentration of 6.7405 µg/g. All measured concentrations were below the NOAA Effects Range Low (ERL) guideline value of 46.7 µg/g, indicating a relatively low probability of adverse biological effects based on the selected sediment-quality benchmark. Nevertheless, the detection of Pb at all sampling points confirms the presence of persistent heavy metal inputs within the bay and highlights spatial variation in contaminant accumulation. These findings provide updated baseline information on Pb contamination in Buyat Bay and support the importance of environmental surveillance as a preventive public health intervention. Continuous monitoring of sediments, water, and marine biota, particularly edible species, is recommended to identify changes in contamination and potential exposure pathways. Future studies should incorporate seasonal sampling, sediment characteristics, contaminant-source identification, and ecological or human health risk assessment to provide a more comprehensive evaluation of long-term Pb exposure and to strengthen evidence-based coastal management strategies.

ACKNOWLEDGMENT

The authors would like to express sincere gratitude to the Faculty of Public Health, Sam Ratulangi University, for academic support throughout this study. Appreciation is also extended to the supervisors for their guidance and valuable suggestions during the research process. The authors also thank the Center for Health Laboratory of Makassar for laboratory analysis assistance, as well as all parties who contributed to the completion of this study

FUNDING

The author(s) reported there is no funding associated with the work featured in this article

AUTHORS' INFORMATION

Glorya Rondonuwu is a Researcher affiliated with the Faculty of Public Health, Sam Ratulangi University, Manado, Indonesia. Sri Seprianto Maddusa, SKM., M.Kes is a Lecturer and Researcher at the Faculty of Public Health, Sam Ratulangi University, Manado, Indonesia. Prof. dr. Jootje M. L. Umboh, MS is a Full Professor at the Faculty of Public Health, Sam Ratulangi University, Manado, Indonesia.

AUTHORS' CONTRIBUTION

Glorya Rondonuwu conceptualized the study, participated in data collection and analysis, and prepared the original manuscript. Sri Seprianto Maddusa contributed to the research methodology, interpretation of the findings, and manuscript revision. Jootje M. L. Umboh provided academic supervision and critically reviewed the manuscript for important intellectual content. All authors read and approved the final version of the manuscript.

COMPETING INTEREST

The author(s) declare no potential conflict of interest with respect to the research, authorship, or publication

REFERENCES

- Afu, L.O.A. and Luturmas, A. (2022) 'Content of heavy metals lead (Pb) and cadmium (Cd) in sediments in Tanjung Oyster Waters, South Konawe', *Journal of Fish Health*, 2(1), pp. 8–13.
- Ekamaida, E., Kusmana, C. et al. (2025) 'Cadmium (Cd) and lead (Pb) levels in oysters, water, and sediment in the Cunda Strait, Lhokseumawe City', *Indonesian Journal of Marine Sciences*, 30(2).
- El-Sharkawy, M., Alotaibi, M.O., Li, J., Du, D. and Mahmoud, E. (2025) 'Heavy metal pollution in coastal environments: Ecological implications and management strategies: A review', *Sustainability*, 17(2), p. 701.
- Fathona, S., Rachmayani, R., Nurhidayati, A.U. and Utami, D.A. (2025) 'Study of heavy metal lead (Pb) in the northern waters of Belitung Regency', *Bulletin of the Marine Geology*, 40(1), pp. 28–43.
- Fauzan, A.A., Utami, D.A., Rachmayani, R. and Nurhidayati, A.U. (2024) 'Study of heavy metal lead (Pb) content in the coral reef

- environment of Panjang Island, Banten', *Bulletin of the Marine Geology*, 39(1), pp. 42–58.
- Fendjalanga, S.N.M., Krisyeb, Y. and Abubakar, A. (2023) 'Konsentrasi logam berat timbal (Pb) pada sedimen di perairan Pantai Kupa-Kupa Kabupaten Halmahera Utara', *Journal of Coastal and Deep Sea*, 1(1), pp. 13–21.
- Handayani, C.O., Zu'amah, H. and Sukarjo, S. (2025) 'Human health risk assessment of heavy metals in the Serayu River water, Central Java-Indonesia', *Journal of Environmental Health*, 17(2).
- Lagoari, M.C., Riogilang, H. and Hendratta, L.A. (2025) 'Analisis kualitas air Sungai Buyat sebagai dampak kegiatan pertambangan emas rakyat', *TEKNO*, 23(91).
- Mokoagow, D., Kasim, M., Hutagalung, R. and Akasea, N. (2023) 'Geologi daerah Buyat dan sekitarnya, Kecamatan Kotabunan, Kabupaten Bolaang Mongondow Timur, Provinsi Sulawesi Utara', *Journal of Applied Geoscience and Engineering*, 2(2), pp. 94–107.
- NOAA (2022) *Sediment Quality Guidelines*. National Oceanic and Atmospheric Administration.
- Oros, A. (2025) 'Bioaccumulation and trophic transfer of heavy metals in marine fish: Ecological and ecosystem-level impacts', *Journal of Xenobiotics*, 15(2), p. 59.
- Rayhan, A. and Pramesty, W.A. (2023) 'Implementasi Minamata Convention on Mercury terhadap kasus pencemaran merkuri dan arsen di Teluk Buyat Indonesia', *Tirtayasa Journal of International Law*, 2(1).
- Sastra, K., Nugraha, M.A. and Pamungkas, A. (2023) 'Status kontaminasi logam berat timbal (Pb) dan tembaga (Cu) pada sedimen permukaan Pantai Sampur, Kabupaten Bangka Tengah', *Journal of Tropical Marine Science*, 6(2), pp. 137–146.
- Simatupang, M.M., Veronika, E., Irfandi, A. and Azteria, V. (2024) 'Potential impacts of lead on health: a review of environmental exposure, population at risk, and toxic effects', *Journal of Environmental Health*, 16(3), pp. 277–288.
- Siregar, R.S., Putra, D.P.E. and Nugraha, A. (2025) 'Distribution and accumulation of lead (Pb) in coastal sediments of Belitung waters', *Bulletin of Marine Geology*, 40(1), pp. 15–27.
- Tamba, S.N., Yulianto, B. and Widowati, I. (2025) 'Kandungan timbal (Pb) pada air laut, sedimen, dan kerang hijau (*Perna viridis* Linnaeus, 1758) di Pantai Utara, Semarang', *Journal of Marine Research*, 14(4), pp. 759–772.
- Tamburini, M., Badocco, D., Ercadi, R., Turicchia, E., Zampa, G., Gasparini, F. et al. (2022) 'Bioaccumulation of mercury and other trace elements in the edible Holothurian *Holothuria atra* in relation to gold mining activities in North Sulawesi, Indonesia', *Frontiers in Marine Science*, 9, p. 863629.
- Triyanto, H.C., Nuraini, R.A.T. and Haryanti, D. (2024) 'Akumulasi logam berat timbal (Pb) pada air, sedimen, dan lamun (*Thalassia hemprichii*) di Pulau Kelapa Dua, Kepulauan Seribu', *Journal of Marine Research*, 13(1), pp. 37–44.
- UNEP (2025) *Heavy metals*. United Nations Environment Programme. Available at: <https://www.unep.org/cep/heavy-metals> (Accessed: 19 November 2025).
- United States Environmental Protection Agency (2020) *Technical fact sheet: Bioaccumulation and biomagnification*. Available at: <https://www.epa.gov> (Accessed: 8 December 2025).
- Widiyanto, T., Pratiwi, N.T.M. and Setyobudiandi, I. (2024) 'Bioaccumulation of lead (Pb) in edible marine fish and its potential health risk in Indonesian coastal waters', *Journal of Environmental Health*, 16(4), pp. 301–312.
- World Health Organization (2024) *Lead poisoning and health*. Geneva: World Health Organization. Available at: <https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health> (Accessed: 20 November 2025).