BIODIVERSITAS
Volume 27, Number 4, April 2026
Pages: 15

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270428

Assessment of heavy metals in sediments and edible shellfish from Youtefa Bay, Papua, Indonesia

ROSYE HEFMI RECHNELTY TANJUNG[1,♥], ERVINA INDRAYANI[2], LALU PANJI IMAM AGAMAWAN[2], BAIGO HAMUNA[2]

[1]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Cenderawasih. Jl. Kamp Wolker, Jayapura 99351, Papua, Indonesia. Tel./fax.: +62-813-4488-2854, ♥email: hefmitanjung@yahoo.co.id

[2]Department of Marine Science and Fisheries, Faculty of Mathematics and Natural Sciences, Universitas Cenderawasih. Jl. Kamp Wolker, Jayapura 99351, Papua, Indonesia

Manuscript received: 13 November 2025. Revision accepted: 18 April 2026.

Abstract. *Tanjung RHR, Indrayani E, Agamawan LPI, Hamuna B. 2026. Assessment of heavy metals in sediments and edible shellfish from Youtefa Bay, Papua, Indonesia. Biodiversitas 27 (4): d270428. https://doi.org/10.13057/biodiv/d270428.* The main gaps in the environmental quality research on Youtefa Bay are the lack of comprehensive information on heavy metal contamination in sediments and consumable biota, and the absence of a temporal evaluation linking changes in metal content to potential ecological and public health risks. This study aims to assess eight heavy metals simultaneously (Hg, Pb, As, Cr, Cd, Ni, Zn, and Cu) in sediments and edible shellfish from Youtefa Bay, Indonesia, and evaluate ecological and food safety risks through contamination factor (CF), ecological risk index (E_i, E_{RI}), biota-sediment accumulation factor (BSAF), and multivariate analyses. Analysis of metal content in sediments and shellfish was performed using Atomic Absorption Spectrometry instruments with QA/QC procedures and reported based on dry-weight. Sediment results revealed elevated Ni content, reaching up to 401 mg/kg at St.3, exceeding threshold effect levels (TEL), while Cd showed the highest ecological risk contribution, with E_i values up to 126 at St.3, indicating moderate ecological risk. In sediments, the order of heavy metal content is Ni > Cr > Zn > Cu > Pb > Cd > As > Hg. BSAF analysis indicated species-specific accumulation patterns, with higher bioaccumulation potential for Cd and Cu in certain taxa. Principal component analysis (PCA) explained 81.3% of total variance, separating Ni-dominated sediment signals from Cd-associated ecological risk patterns. Although spatial variability was evident, overall findings indicate localized metal enrichment and potential health concerns, particularly for Cd. The accumulation of Cd, Ni, and Zn in all three shellfish species exceeded international safe consumption limits (FAO and WHO), indicating a potentially serious health risk to the surrounding community. Overall, the results of this study highlight potential ecological and food security concerns and emphasize the need for continued monitoring and improved pollution management in Youtefa Bay.

Keywords: Coastal sediments, ecological risk, heavy metals, shellfish bioaccumulation, Youtefa Bay

INTRODUCTION

Contamination due to heavy metals has emerged as a serious problem and a focal point of scientific investigation worldwide because they can accumulate in water bodies (Fan et al. 2020; Hamuna and Tanjung 2021; Tanjung et al. 2022, 2024; Rozirwan et al. 2024; Ristea et al. 2025), sediments (Tanjung et al. 2019; Fan et al. 2020; Harmesa and Cordova 2021; El Boudammoussi et al. 2024), and aquatic biota (Alam et al. 2023; Emon et al. 2023). In aquatic ecosystems, sediments act as the ultimate sink for metals through flocculation and adsorption processes (Peng et al. 2018). Accumulated metals can harm benthic organisms (Salam et al. 2019; Lee et al. 2022; El Boudammoussi et al. 2024), enter the food chain (Chen et al. 2016; Le et al. 2025), and pose long-term ecological and human health risks when concentrations exceed safe thresholds (Chai et al. 2017; El Boudammoussi et al. 2024; Chang et al. 2025).

Youtefa Bay is a semi-enclosed bay with various potential and natural resources of high economic value (Wijayanti et al. 2013; Tebaiy et al. 2014; Rumahorbo et al. 2019, 2020; Hamuna et al. 2020; Sari et al. 2022). Currently, water quality in Youtefa Bay is concerning and has deteriorated due to the rapid increase in human activities in recent years, both around the bay and along the rivers flowing into it. Various studies have shown pollution in Youtefa Bay (Manalu et al. 2011; Sari et al. 2020). Specifically, studies concerning heavy metals, both those accumulated in sediments and marine biota in Youtefa Bay, are minimal. On the other hand, it is imperative to measure and evaluate the extent of contamination by heavy metals. Information related to several metals accumulated in Youtefa Bay sediments was previously reported by Hamuna and Wanimbo (2021), where the content of several heavy metals exceeded recommended quality standards and has the potential to have negative ecological impacts. Temporal study is particularly important in semi-enclosed systems such as Youtefa Bay, where hydrodynamic confinement may enhance pollutant retention. However, temporal comparisons should be interpreted with caution because differences in sampling designs among studies may produce concentration variations attributable to methodological discrepancies rather than actual environmental changes. Nevertheless, temporal comparisons are still necessary to assess trends indicating whether heavy metal levels in Youtefa Bay are rising or falling. Regarding heavy metal accumulation in aquatic biota in Youtefa Bay, Hasmi and Mallongi (2016) and Hasmi (2024) previously reported heavy metal content in fish (Family Mugilidae) and shellfish, respectively. However, both studies only examined Pb metal. Many metals are hazardous when present at very high levels in marine biota and can pose health risks if consumed. Therefore, a similar, but more comprehensive, study with a larger number of heavy metals examined is necessary.

This study aimed to assess and evaluate the content of specific heavy metals that may accumulate in sediments and shellfish collected from Youtefa Bay, including Hg, Pb, As, Cr, Cd, Ni, Zn, and Cu. These eight heavy metals have high toxicity to marine biota and humans. It is crucial to evaluate multiple metal contents to identify potential synergistic risks that a single pollutant focus would miss. Specifically, this study aims to: (i) evaluate the current contamination status and ecological risk of eight heavy metals in sediments from Youtefa Bay; (ii) assess the accumulation of eight heavy metals in selected multi-species edible shellfish from the Tobati mangrove zone; and (iii) conduct an indicative comparison with previously published sediment data to explore possible temporal changes. The novelty of this study lies in its multi-metal, multi-matrix, and multi-species approach. These findings are highly relevant to ecosystem and public health and provide a strong basis for formulating effective regulations and policies to control heavy metal pollution in Youtefa Bay.

Based on the increasing anthropogenic pressures in Youtefa Bay, this study hypothesizes that heavy metal concentrations in sediments and edible shellfish exhibit spatial variability and that metals with higher sediment contamination factors, particularly Cd and Ni, contribute disproportionately to ecological risk and bioaccumulation patterns. Specifically, we examine whether sediment metal enrichment is reflected in shellfish tissue concentrations and whether ecological risk indices identify Cd as a dominant contributor to overall site-level risk.

MATERIALS AND METHODS

Study area

Sediment and shellfish samples were collected from Youtefa Bay, Jayapura City, Papua, Indonesia (Figure 1). Sediment samples were collected from 21 to 22 June 2025 at four sites representing different environmental settings within the bay, including mangrove ecosystems, coastal waters, and a river estuary (Table 1). Shellfish samples were collected only from the mangrove ecosystem in Tobati Village (red polygon in Figure 1) on 23 to 25 June 2025, and the results are interpreted as representative of this zone rather than the entire bay.

Table 1. Sediment sampling sites and environmental characteristics in Youtefa Bay, Jayapura City, Papua, Indonesia

Sites	Location	Coordinates	Ecosystem type	General description
St.1	Tobati	140°42'16.69"E; 2°34'56.98"S	Mangrove	Mangrove ecosystem adjacent to traditional coastal settlements and small-scale fisheries; influenced by Hanyaan River discharge from densely populated areas
St.2	Enggros	140°42'26.86"E; 2°35'54.27"S	Coastal waters	Coastal waters bordered by traditional villages; characterized by small-scale fishing activities
St.3	Acai River estuary	140°41'11.91"E; 2°36'48.34"S	Estuary	Main fluvial input to Youtefa Bay; receives runoff from urbanized and densely populated catchments
St.4	Nafri	140°43'16.32"E; 2°37'45.99"S	Mangrove	Mangrove ecosystem influenced by coastal settlements and adjacent open coastal waters

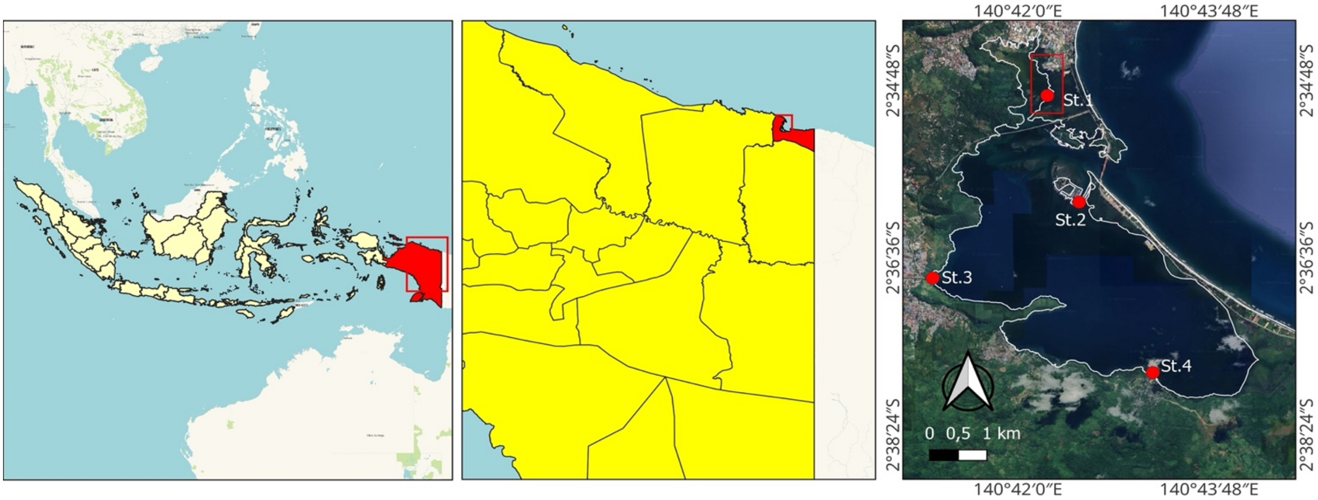

Figure 1. Map of Youtefa Bay, Jayapura City, Papua, Indonesia, showing four sediment sampling sites (St.1 to St.4) and the shellfish samples collection area (red polygon)

Figure 2. Three species of shellfish were sampled in this study. A. *Geloina expansa*, B. *Vasticardium elongatum*, and C. *Anadara antiquata*. Scale bar: 5 cm

Sampling techniques and heavy metal detection

Samples of sediment have been obtained using PVC pipes (8 cm diameter) and a grab sampler (20 × 20 cm). At each study site, sediment sampling was conducted at three points spaced approximately 25 m apart, with one sample collected from each point, resulting in three independent samples per site (n = 3) to represent within-site spatial variability. A 250 g sediment sample was taken at each point, stored in polyethylene plastic, and labeled for analysis in the laboratory. Sample preparation represents the foundational phase in the detection of heavy metals. 100 gr of sediment samples undergo a cleaning process with distilled water and are then dried in an oven at a temperature between 103-105°C for a period of 6 hours. Once it was verified that the samples were sufficiently dry, they were carefully ground into a fine powder using a pestle and mortar, and then sieved through a 100-mesh sieve to ensure uniform and homogeneous granules. Subsequently, the sediment samples are digested, with a dry weight of 0.5 g for each sample. The samples are placed in beakers, followed by the addition of concentrated HNO_3 (5 mL). The samples undergo heating using an electric heater set to 150°C until a volume of 1 mL is achieved, followed by a cooling phase. 100 mL of distilled water was incorporated. The water was subsequently filtered using Whatman filter paper (0.45 μm) and put into a 25 mL volumetric flask. Distilled water is added to produce a final sample ready for measurement. The digestion procedure was conducted following the acid digestion protocol for sediments as outlined by the United States Environmental Protection Agency (USEPA 1996). Finally, the detection and measurement of metal content of Hg, Pb, As, Cd, Cr, Ni, Zn, and Cu in each sample using an Atomic Absorption Spectrometry (AAS) instrument at wavelengths of 253.65, 283.31, 193.7, 228.8, 357.9, 232, 213.86, and 324.75 nm, respectively.

Shellfish samples were collected using a free-collection technique. During the study, three shellfish species were obtained: *Geloina expansa* (Mousson, 1849) (formerly known as *Polymesoda erosa*), *Vasticardium elongatum* (Bruguière, 1789), and *Anadara antiquata* (Linnaeus, 1758) (Figure 2). For each species, 3-4 individuals were composited into a single sample to reduce individual variability, and three composite samples (n = 3) were analyzed as biological replicates. The shell length ranged from 7.5-8.9 cm for *G. expansa*, 6.3-8.4 cm for *V. elongatum*, and 5.8-7.2 cm for *A. antiquata*. A total of three samples from each shellfish species were analyzed in the laboratory to detect their heavy metal content. In brief, the stages of metal detection in shellfish samples are the same as heavy metal detection in sediment samples, which include sample preparation, sample drying, grinding and sieving, sample digestion, sample filtration, and detection of heavy metal content using an AAS instrument at a specific wavelength. The difference is in the sample drying time, where shellfish samples are dried using a heating oven for a longer time (± 24 hours) because they contain more water.

Quality assurance and quality control

Throughout the analytical process, procedures for quality assurance and quality control were implemented to guarantee the reliability of the data. Calibration curves for all analyzed metals were established using multi-point external standards that encompassed the pertinent concentration ranges for environmental samples, with linear regression producing correlation coefficients (r^2) exceeding 0.995. The detection limits (DL, mg/kg) for each metal were as follows: Hg 0.004, Pb 0.02, As 0.003, Cr 0.09, Cd 0.04, Ni 0.5, Zn 0.67, and Cu 1.2. Procedural blanks were included in each analytical batch to check for contamination and consistently showed concentrations below the DLs. Analytical precision was evaluated through the analysis of duplicate samples conducted every 25 samples, ensuring that relative standard deviations remained below 10%. Periodic recalibration and recovery checks using standard solutions were conducted to monitor instrument performance and analytical accuracy, ensuring that recoveries remained within acceptable analytical ranges.

Data analysis

Evaluation of heavy metal content

The mean content of each metal in the sediment at each study site was evaluated using the threshold effect level (TEL) established by the Canadian Environmental Quality Guidelines for Hg, Pb, As, Cr, Cd, Zn, and Cu (CCME 2001) and the National Oceanic and Atmospheric Administration (NOAA) for Ni metal (Buchman 2008). The combined use of these sources is justified because not all metals are covered uniformly by a single guideline framework. Meanwhile, the mean content of each heavy metal in shellfish meat was evaluated and compared with the standards set by the Food and Drug Monitoring Agency of the Republic of Indonesia (BPOM 2009), the joint FAO/WHO (FAO/WHO 2011), the Food and Agriculture Organization (FAO 1983), and the World Health Organization (WHO 1989). Food safety comparisons for shellfish are presented as screening-level evaluations, recognizing that most international standards are defined on a wet-weight basis.

Degree of contamination and ecological risk

The contamination factor (CF) serves as a tool for assessing the degree of contamination related to each toxic substance (including heavy metals) that accumulates in sediments in aquatic environments. The CF value is calculated using the equation (Turekian and Wedepohl 1961):

$$\mathrm{CF} = \frac{\mathrm{CM_{sediment}}}{\mathrm{CM_{background}}}$$

Where: $\mathrm{CM_{sediment}}$ is the mean content of a particular metal in the sediment. $\mathrm{CM_{background}}$ is reference metal values that use the average metal values in shale (Hg = 0.4, Pb = 20, As = 13, Cr = 90, Cd = 0.3, Ni = 68, Zn = 95, and Cu = 45) (Turekian and Wedepohl 1961). The global shale background values are applied because there are no background shale values for tropical coastal systems (including Indonesia), and this is recognized as a source of uncertainty that may influence the assessment of contamination levels and risk categorization. CF values are divided into four categories, namely $\mathrm{CF} \geq 6$ (very high), $3 \geq \mathrm{CF} < 6$ (significant), $1 \geq \mathrm{CF} < 3$ (moderate), and $\mathrm{CF} < 1$ (low).

The ecological risk factor monomial (Ei) and ecological risk index (ERI) serve as instruments for assessing and evaluating the potential ecological risks associated with heavy metals, whether singly or in multiple combinations at a particular site (Yi et al. 2016). The $\mathrm{E_i}$ and $\mathrm{E_{RI}}$ values are computed according to the following equations (Hakanson 1980):

$$\mathrm{E_i} = \mathrm{Tr_i} \times \mathrm{CF_i}$$

$$\mathrm{E_{RI}} = \sum \mathrm{E_i}$$

Where: $\mathrm{Tr_i}$ indicates the toxic response factor of each heavy metal (Hg = 40, As = 10, Cr = 2, Pb/Cu = 5, Cd = 30, Ni = 6, and Zn = 1). $\mathrm{E_i}$ values are divided into five categories, namely $\mathrm{E_i} \geq 320$ (severe risk), $160 \geq \mathrm{E_i} < 320$ (heavy risk), $80 \geq \mathrm{E_i} < 160$ (considerable risk), $40 \geq \mathrm{E_i} < 80$ (moderate risk), and $\mathrm{E_i} < 40$ (low risk). Meanwhile, there are four categories for the $\mathrm{E_{RI}}$ values, namely $\mathrm{E_{RI}} \geq 600$ (severe risk), $300 < \mathrm{E_{RI}} < 600$ (considerable risk), $150 < \mathrm{E_{RI}} < 300$ (moderate risk), and $\mathrm{E_{RI}} < 150$ (low risk).

Biota-sediment accumulation factor

The BSAF serves to assess the abilities of biota to gather metals from their surrounding environment (Djikanović et al. 2018; Melake et al. 2023). The BSAF indicates the proportion of a specific contaminant, including metals, found in biotic organisms compared to their amount in sediment, as described by the equation (Djikanović et al. 2018):

$$\mathrm{BSAF} = \frac{\mathrm{CM_{biota}}}{\mathrm{CM_{sediment}}}$$

Where: $\mathrm{CM_{biota}}$ represents the mean concentration of each metal measured in shellfish tissue. For the calculation of the Biota-Sediment Accumulation Factor (BSAF), $\mathrm{CM_{sediment}}$ refers exclusively to the metal content measured at site St.1 (Tobati mangrove), which was selected as the reference site due to its direct spatial correspondence with the shellfish collection area and the availability of paired sediment-biota samples, thereby ensuring consistency in exposure conditions; however, this approach may limit the representativeness of spatial variability across the study area. A BSAF value <1 indicates insignificant accumulation. Conversely, a BSAF value greater than 1 indicates significant accumulation (Hao et al. 2019). It should be noted that the digestion procedure reflects the total metal concentration and not the bioavailable fraction, which may influence the interpretation of BSAF values in terms of ecological absorption processes.

Statistical analysis

In this study, all statistical tests were performed using Minitab v19 software. Heavy metal content is presented as mean ± standard deviation, based on three replicates for each metal at each sediment station and for each shellfish species ($n = 3$ for each metal at each sediment site and shellfish species). Prior to further statistical analysis, data normality was assessed using the Ryan-Joiner test, which is implemented as the standard normality test in Minitab and is considered a reliable alternative to the Shapiro-Wilk test, particularly for small sample sizes. Spearman correlation analysis was employed to examine the relationships among metals. The variations in heavy metal content across different study sites and shellfish species were analyzed through one-way ANOVA, subsequently applying Tukey's post hoc test ($n = 3$ for each metal at each sediment site and shellfish species). Following Mohajane and Manjoro (2022), principal component analysis (PCA) with Varimax rotation and correlation analysis were utilized to determine if the eight metals under examination stemmed from shared pollution sources, using pooled sediment data across sites ($n = 12$ for each metal). Temporal differences in sediment metal content between 2021 (Hamuna and Wanimbo 2021) and 2025 (this study) were assessed using the Mann-Whitney U test, a non-parametric method suitable for datasets that deviate from normality (Afzal et al. 2024). This temporal comparison was treated as an indicative inter-study analysis due to differences in sampling design and spatial coverage between the datasets (2025: $n = 12$, surface sediments; 2021: $n = 14$, surface sediments and up to 1 m depth). In this study, the Mann-Whitney test was used to determine temporal differences in median values from all combined data for the content of each heavy metal in the sediments in Youtefa Bay. All statistical tests applied a significance level (α) of 0.05.

RESULTS AND DISCUSSION

Heavy metal contamination status in sediment

Heavy metals content in sediment

The contents of Hg, Pb, As, Cr, Cd, Ni, Zn, and Cu detected in sediment samples at four study sites in Youtefa Bay are detailed in Table 2. The dominant metal content was higher at site St.3 (Acai River estuary), except for As. The mean metal content decreased in the following order: Ni > Cr > Zn > Cu > Pb > Cd > As > Hg. The ANOVA results indicated that there were significant differences in the mean content of Hg (F-value 13.35; p-value 0.002), Pb (F-value 40.21; p-value 0.000), As (F-value 84.63; p-value 0.000), Cr (F-value 1596.26; p-value 0.000), Ni (F-value 839.79; p-value 0.000), Zn (F-value 386.28; p-value 0.000), and Cu (F-value 508.97; p-value 0.000) between the four study sites. The exception was the comparison of mean Cd content (F-value 0.87; p-value 0.497). In detail, the results of Tukey's post hoc test revealed that the mean Hg content at site St.3 was significantly different from the other three sites (vs. St.1, p-value 0.005; vs. St.2, p-value 0.002; vs. St.4, p-value 0.009). Furthermore, the mean As content at site St.1 significantly differed from the other three sites (p-value 0.000). Similarly, there was a significant difference in the mean content of Cr, Ni, and Cu metal at site St.3 compared with the other three sites (p-value 0.000). The mean content of Pb and Zn metal at site St.3 was also significantly different from St.1 (p-value 0.000), St.2 (p-value 0.000), and St.4 (p-value 0.001 for Pb; p-value 0.000 for Zn). Likewise, between St.2 and St.4, there were significant differences in the mean content of Pb (p-value 0.023) and Zn (p-value 0.015). Significant differences were also found in the mean content of Cr and Ni between St.1 and St.2 (p-value 0.002 for Cr; p-value 0.006 for Ni), Cr and Cu between St.1 and St.4 (p-value 0.020 for Cr; p-value 0.014 for Cu), and the mean content of Cu between St.2 and St.4 (p-value 0.005). However, the observed spatial differences also show varying degrees of within-site variability, as indicated by the SD values. For several metals with significant ANOVA and Tukey results (e.g., Pb, Zn, Cu, and Hg), the mean ± SD ranges partially overlap among some stations, whereas Cr and Ni display more consistent separation, particularly at St.3. This indicates that spatial differences in metal content in sediments are not uniform across all metals and site pairs. Thus, the observed differences are interpreted as relative enrichment patterns among study sites.

The mean content of Hg, As, and Pb in sediments at all study sites has not exceeded the TEL set by the CCME (2001); thus, they do not represent a significant threat to aquatic life. Conversely, the mean Ni content at all study sites significantly exceeded the TEL set by the NOAA (Buchman 2008). This indicates that the spatial accumulation of Ni in sediments in Youtefa Bay is very high. This corresponds to an enrichment factor (EF-TEL) range of approximately 1.9-25.2, further confirming moderate to very high enrichment levels and suggesting both anthropogenic and geogenic contributions to Ni contamination in the study area, consistent with established interpretations of enrichment factor and sediment quality guideline exceedance (Sutherland 2000; Loska et al. 2004). Similarly, the mean content of Cd (except at site St.2) has exceeded the TEL, but not significantly. The mean content of Cu was found to exceed the TEL at two study sites, including St.3 and St.4. Meanwhile, Zn was found to exceed the TEL at site St.3.

A comparison of the average heavy metal content in the sediments of Youtefa Bay with various other coastal areas in Indonesia reveals a complex accumulation pattern (Table 3). Although the content of Hg and Pb are at relatively low levels compared to the regional averages presented, Youtefa Bay shows very high levels of Cd, Cr, and Ni pollution. The Cd and Ni content recorded in Youtefa Bay is among the highest compared to all the presented data, far exceeding the figures reported in industrial areas such as Jakarta Bay (Kusuma et al. 2015; Cordova et al. 2016; Budiyanto and Lestari 2017; Zuraida et al. 2018) or the Mahakam Delta (Effendi et al. 2016).

Table 2. Maximum, minimum, and mean (± standard deviation) content of some heavy metals detected in sediment samples from Youtefa Bay (mg/kg dry-weight)

Sites		Hg	Pb	As	Cr	Cd	Ni	Zn	Cu
St.1	Maximum	0.075	7.91	1.152	51.72	1.08	76.68	40.56	16.12
	Minimum	0.025	6.49	0.851	37.91	0.63	68.42	30.41	12.53
	Mean±SD	0.051±0.03	7.14±0.72	0.97±0.16	43.84±7.11	0.87±0.23	71.80±4.33	36.08±5.18	13.88±1.96
St.2	Maximum	0.051	7.01	0.106	11.03	0.74	32.59	33.27	13.02
	Minimum	0.021	3.67	0.091	8.62	0.32	28.64	27.84	11.66
	Mean±SD	0.037±0.02	5.23±1.68	0.10±0.01	9.65±1.24	0.52±0.21	30.31±2.04	31.27±2.99	12.15±0.76
St.3	Maximum	0.148	20.04	0.008	363.23	2.52	422.53	166.03	85.54
	Minimum	0.103	16.52	0.005	339.17	0.43	382.22	150.76	77.26
	Mean±SD	0.129±0.02	18.29±1.76	0.01±0.00	352.17±12.15	1.26±1.11	401.4±20.23	157.51±7.79	81.11±4.17
St.4	Maximum	0.066	12.03	0.207	23.22	1.37	44.92	52.84	24.41
	Minimum	0.045	8.32	0.184	19.73	0.83	36.12	45.13	20.7
	Mean±SD	0.058±0.01	10.08±1.86	0.18±0.03	21.33±1.76	1.09±0.27	39.97±4.50	48.87±3.86	22.35±1.89
TEL:									
CCME (2001)		0.13	30.20	7.24	52.30	0.70	-	124.00	18.70
Buchman (2008)		-	-	-	-	-	15.90	-	-

Table 3. Comparison of mean heavy metal content (mg/kg) in sediments from Youtefa Bay with other studies in Indonesia

References	Location	Hg	Pb	As	Cr	Cd	Ni	Zn	Cu
This study	Youtefa Bay, Jayapura	0.07	10.19	0.31	106.75	0.94	135.87	68.43	32.37
Hamuna and Wanimbo (2021)	Youtefa Bay, Jayapura	0.08	19.80	0.15	12.10	2.99	17.67	106.08	28.55
Shintianata et al. (2024)	Ujung Kulon, Banten	NR	NR	NR	7.56	NR	NR	18.95	11.01
Krisbiantoro et al. (2023)	Rupat Strait, Dumai	NR	12.83	NR	NR	0.81	NR	34.86	4.77
Juniardi et al. (2022)	Banten Bay	NR	9.63	NR	NR	0.95	NR	NR	NR
Sembel et al. (2022)	Doreri Bay, Manokwari	NR	50.56	NR	NR	NR	NR	NR	NR
Sitorus et al. (2020)	Balikpapan Bay	NR	2.63	0.39	NR	2.53	NR	NR	1.39
Harmesa et al. (2020)	Cimanuk estuary, West Java	NR	12.24	NR	NR	0.17	31.17	74.32	28.75
Zuraida et al. (2018)	Jakarta Bay	NR	23.00	NR	100.74	0.06	NR	122.80	17.66
Budiyanto and Lestari (2017)	Jakarta Bay	NR	31.40	NR	NR	0.70	29.40	408.00	49.80
Cordova et al. (2016)	Jakarta Bay (estuary)	0.47	28.80	NR	NR	0.28	19.78	441.91	55.36
Cordova et al. (2016)	Jakarta Bay (20 km from coastal)	0.28	14.87	NR	NR	0.22	18.06	82.05	14.79
Effendi et al. (2016)	Mahakam Delta, East Kalimantan	NR	27.59	2.00	47.31	1.07	57.24	186.61	27.66
Kusuma et al. (2015)	Jakarta Bay	NR	38.53	NR	NR	1.37	26.72	109.01	33.13
Budiyanto and Lestari (2015)	Lampung Bay	NR	24.75	NR	NR	0.08	NR	118.48	22.99
Armid et al. (2014)	Kendari Bay	NR	9.74	NR	24.03	0.07	NR	NR	NR

Note: NR indicates data not reported

Furthermore, the Cd content in Youtefa Bay is also among the highest, only surpassed by findings in Balikpapan Bay (Sitorus et al. 2020). However, these inter-regional differences should be interpreted cautiously, as methodological variations (e.g., differences in sediment grain size fraction, digestion methods, analytical techniques, and reporting basis) may introduce uncertainties that can influence reported concentrations. Therefore, the observed differences may not fully represent true variations in contamination intensity but rather indicate relative enrichment patterns under differing methodological frameworks. The relatively high content of Cd, Cr, and Ni in Youtefa Bay indicates a greater level of metal enrichment compared to various other coastal environments, highlighting the necessity for localized evaluations and standardized analytical methods in future regional comparisons.

Temporal comparison of heavy metals in sediments

Figure 3 presents a temporal comparison of heavy metal content in sediments in Youtefa Bay. There were fluctuations in the mean content of the eight metals studied in Youtefa Bay compared to those previously reported by Hamuna and Wanimbo (2021). A significant rise was noted in the mean content of Cr (p-value: 0.009) and Ni (p-value: 0.000). The mean content of As and Cu in sediments was also found to have increased, but not significantly. At the same time, the mean content of the other four metals (Hg, Pb, Cd, and Zn) decreased compared to that reported by Hamuna and Wanimbo (2021). A significant decrease occurred for the mean content of Pb (p-value: 0.007) and Cd (p-value: 0.000).

This study also presents important information regarding the trend of heavy metal content in the sediments of Youtefa Bay. Temporally, the Ni metal content showed a very significant increase, especially at the mouth of the Acai River (site St.3). The increase in Ni metal content in the sediment can be attributed to the complex interaction between geogenic and anthropogenic sources, particularly in areas without nickel mining activity (Kusumaningsih et al. 2024; Ikhsani et al. 2025). This condition aligns with the environmental characteristics of Jayapura City. The geological composition of the Jayapura City area is characterized by ultramafic rocks and lateritic soils, which are naturally rich in Ni metal (Haryati et al. 2021). Consequently, weathering and erosion serve as the main processes for the mobilization of Ni metal from the parent material into the river system (Tamehe et al. 2024). This phenomenon is evident in areas like Nafri, Abepura District (the coastal area of Youtefa Bay), which shows strong indications of geogenic contribution to heavy metal loads in sedimentary rocks and laterites, including Ni metal (Datu et al. 2024; Msiren et al. 2024). Nonetheless, human activities also play a role in the buildup of Ni in Youtefa Bay.

The Acai River, along with various other rivers traversing densely populated regions and small-scale industries, is subjected to inputs from domestic waste, urban activities, and garbage disposal. This situation may lead to an increase in the heavy metal load downstream into Youtefa Bay (Tonapa et al. 2023; Bungasalu et al. 2025). The study conducted by Bungasalu et al. (2025) reveals that the Ni metal concentration in sediments along the Acai River is notably elevated, with values ranging from 19.02 to 57.06 mg/kg, which is strongly believed to originate from household chemical inputs and waste from food processing factories using metal equipment. Additionally, Youtefa Bay serves as a deposition zone with calm water conditions, allowing metal-rich suspended sediments to accumulate. The accumulation process can increase significantly during the rainy season, when sediment transport increases as a result of increased river flow, lifting particulate material from upstream areas and carrying it to the river mouth, causing a surge in total Ni over time (Couceiro et al. 2009). This aligns with the condition of the Acai River, where water flow increases during the rainy season, carrying a large amount of anthropogenic materials and waste into Youtefa Bay. Thus, the high Ni content in sediments in Youtefa Bay today is likely the result of a combination of natural geological supply, the influence of human activities along the river and coast, and hydrological dynamics that promote heavy metal deposition.

Contamination factor and ecological risks

Table 4 presents the examination of heavy metal contamination in sediments at four sites in Youtefa Bay. CF values indicate contamination from several of the studied heavy metals. At all study sites, CF values for Hg, As, and Pb were below one. Referring to the CF value criteria, the contamination levels of Hg, Pb, and As indicate low contamination. Similarly, the heavy metals Cr, Zn, and Cu showed low contamination at the three study sites, except at site St.3 (significant for Cr and moderate for Zn and Cu). Based on the CF value, Ni metal contamination was categorized as low at sites St.2 and St.4. However, it was classified as significant contamination at the other two study sites, namely, St. 1 and St. 3. Contamination with the Cd metal was classified as moderate risk at St.1 and St.2 sites, whereas it was classified as significant at St.3 and St.4 sites. Overall, the contamination levels of Ni and Cd at the four sites were relatively high.

The results of the E_i analysis produced the following sequence: Cd > Ni > Hg > Cu > Pb > Cr > Zn > As. The E_i values for Hg, Pb, As, Cr, Ni, Zn, and Cu consistently fall within the low-risk category across all sites. This indicates that the current presence of these metals in the sediments does not pose an anticipated ecological risk, even though certain sites showed comparatively high accumulation levels. In contrast to the possible ecological risks associated with the accumulation of Cd metal, which is predominantly categorized as considerable, the exception is site St.2 (moderate risk). Furthermore, the E_{RI} analysis indicates that the potential ecological risk at sites St.1, St.2, and St.4 falls into the low-risk category. Meanwhile, the E_{RI} value at site St.3 (the Acai River estuary) falls into the moderate risk category.

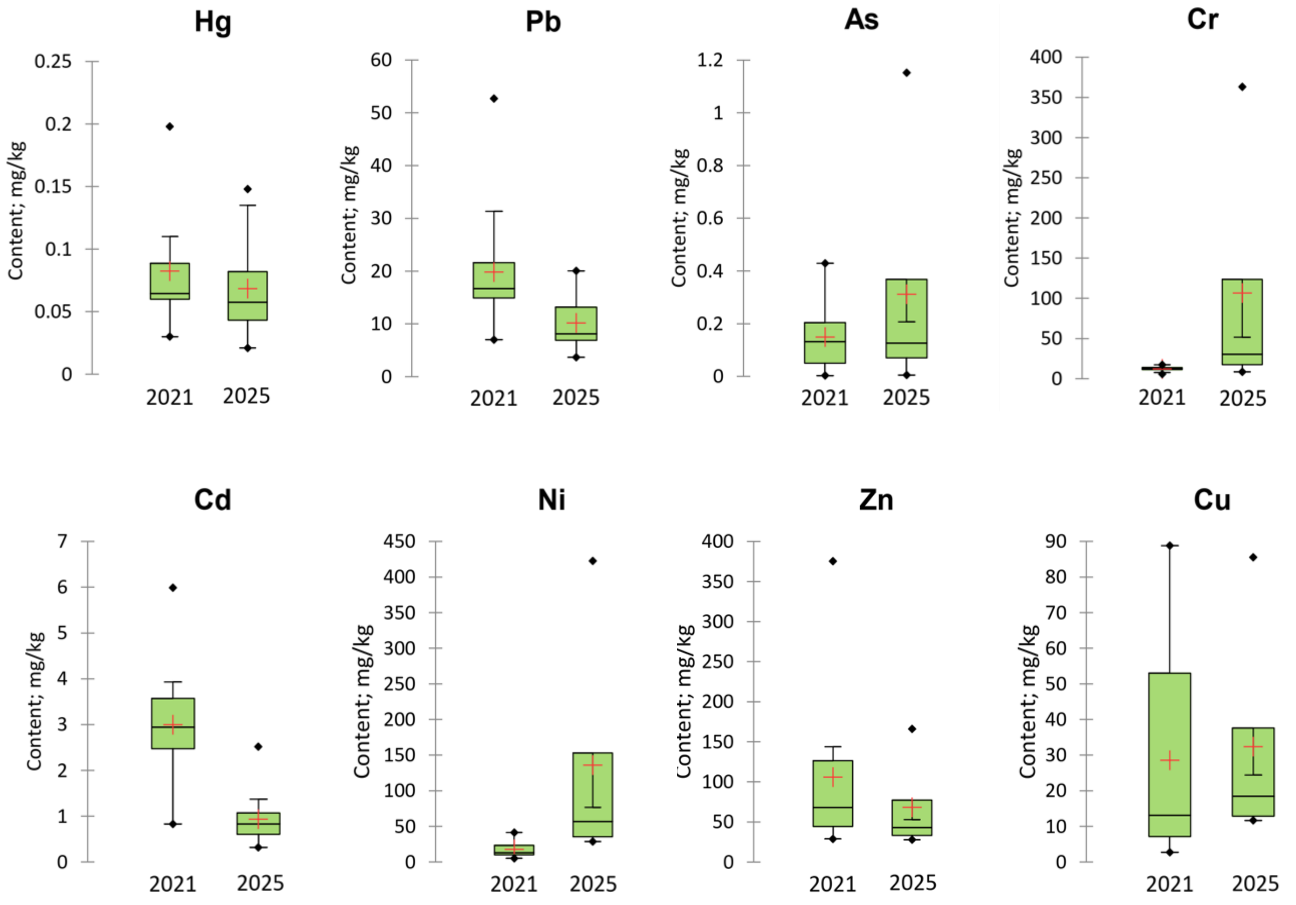

Figure 3. Comparison of heavy metal content in sediments in Youtefa Bay between 2021 (Hamuna and Wanimbo 2021) and 2025 (this study)

Table 4. CF, E_i, and E_{RI} values of heavy metals in sediments from Youtefa Bay

Sites	Indices	Hg	Pb	As	Cr	Cd	Ni	Zn	Cu
St.1	CF	0.13	0.36	0.07	0.49	2.90	1.06	0.38	0.31
	E_i	5.10	1.79	0.74	0.97	87.00	6.34	0.38	1.54
	E_{RI}					103.86			
St.2	CF	0.09	0.26	0.01	0.12	1.73	0.45	0.33	0.27
	E_i	3.70	1.31	0.07	0.21	52.00	2.67	0.33	1.35
	E_{RI}					61.65			
St.3	CF	0.32	0.92	0.00	3.91	4.20	5.90	1.66	1.80
	E_i	12.90	4.57	0.00	7.83	126.00	35.42	1.66	9.01
	E_{RI}					197.39			
St.4	CF	0.15	0.50	0.01	0.24	3.63	0.59	0.51	0.50
	E_i	5.80	2.52	0.14	0.47	109.00	3.53	0.51	2.48
	E_{RI}					124.46			

Heavy metal contamination in sediments poses an ecological risk, particularly due to Cd metal. The threat is evident from the E_i value of Cd, which falls into the moderate to considerable risk category, significantly higher than other heavy metals. Cd is a metal with a high toxic response factor (Hakanson 1980). Consequently, even though it is detected at low levels in sediments, the high toxic response factor significantly impacts the estimation of higher E_i values. This effect also impacts the high contribution of Cd to the E_{RI} index, namely 63.83-87.58% (Figure 4). This finding is similar to many prior investigations regarding the proportion of each heavy metal in estimating ecological risks (Farsani et al. 2019; Karthikeyan et al. 2020; Liu et al. 2022; Nastuti et al. 2024; Pinkey et al. 2024; Tanjung et al. 2025), including a previous study in Youtefa Bay (Hamuna and Wanimbo 2021). However, it should be noted that the toxic response factor applied in this study follows the standard values proposed by Hakanson (1980) and was not subjected to sensitivity analysis, which may influence the magnitude of E_i and E_{RI} estimates. In addition, the use of a global shale baseline as a reference may introduce uncertainty, as it may not fully represent local geochemical background conditions. Ecologically, the impact of Cd metal on aquatic biota is very significant (Ray and Vashishth 2024). Cd metal tends to accumulate in detoxification and storage organs, particularly the liver and kidneys of fish, which can lead to impaired function of these two vital organs (Prabowo et al. 2016; Taslima et al. 2022), as well as causing morphological and histological changes in the fish liver (Agbugui and Abe 2022). Additionally, aquatic biota (especially fish) will experience difficulty reproducing due to abnormal oocyte shape, unfilled follicles, loss of follicular lining, retraction and condensation of cytoplasm, and decreased sperm motility and viability (Baatrup 1991; Taslima et al. 2022).

Heavy metal contamination status in shellfish

Heavy metals content in shellfish

The metal content detected in samples of three shellfish species from Youtefa Bay is given in Table 5. Hg and Cr were not detected in any shellfish samples, as their concentrations were below the instrumental detection limits (DL: 0.004 mg/kg for Hg and 0.09 mg/kg for Cr). It is important to note that all concentrations are expressed on a dry-weight basis; therefore, direct comparison with regulatory thresholds reported in wet-weight units may introduce bias unless appropriate conversion factors are applied, representing an important interpretive limitation of this study. The mean content of heavy metals in each shellfish species decreased in the following order: Zn > Ni > Cu > As > Cd > Pb > Cr/Hg (*G. expansa* and *V. elongatum*) and Zn > Cu > Ni > Cd > As > Pb > Cr/Hg (*A. antiquata*).

The ANOVA results indicated that there were significant differences in the content of several metals between shellfish species, namely As (F-value 19.28; p-value 0.002), Cd (F-value 91.81; p-value 0.000), Ni (F-value 30.38; p-value 0.001), Zn (F-value 18.86; p-value 0.003), and Cu (F-value 23.68; p-value 0.001). The exception was the comparison of mean Pb content (F-value 0.10; p-value 0.910) between the three shellfish species. Furthermore, Tukey's post hoc test revealed significant differences in the mean As content between *G. expansa* and *V. elongatum* (p-value 0.012) and also between *G. expansa* and *A. antiquata* (p-value 0.002). Significant differences in the mean content of Cd and Ni occurred between *A. antiquata* and *G. expansa* (p-value 0.000 for Cd; p-value 0.002 for Ni) and between *A. antiquata* and *V. elongatum* (p-value 0.000 for Cd; p-value 0.001 for Ni). For the mean content of Zn and Cu, significant differences occurred between *V. elongatum* and *G. expansa* (p-value 0.015 for Zn; p-value 0.006 for Cu) and between *V. elongatum* and *A. antiquata* (p-value 0.002 for Zn; p-value 0.001 for Cu). The relatively large standard deviation observed for As in *V. elongatum* (SD = 0.43) compared to its mean likely reflects high intra-sample variability or the presence of outlier values, which may be associated with heterogeneous exposure conditions or differential bioaccumulation capacity among individual organisms.

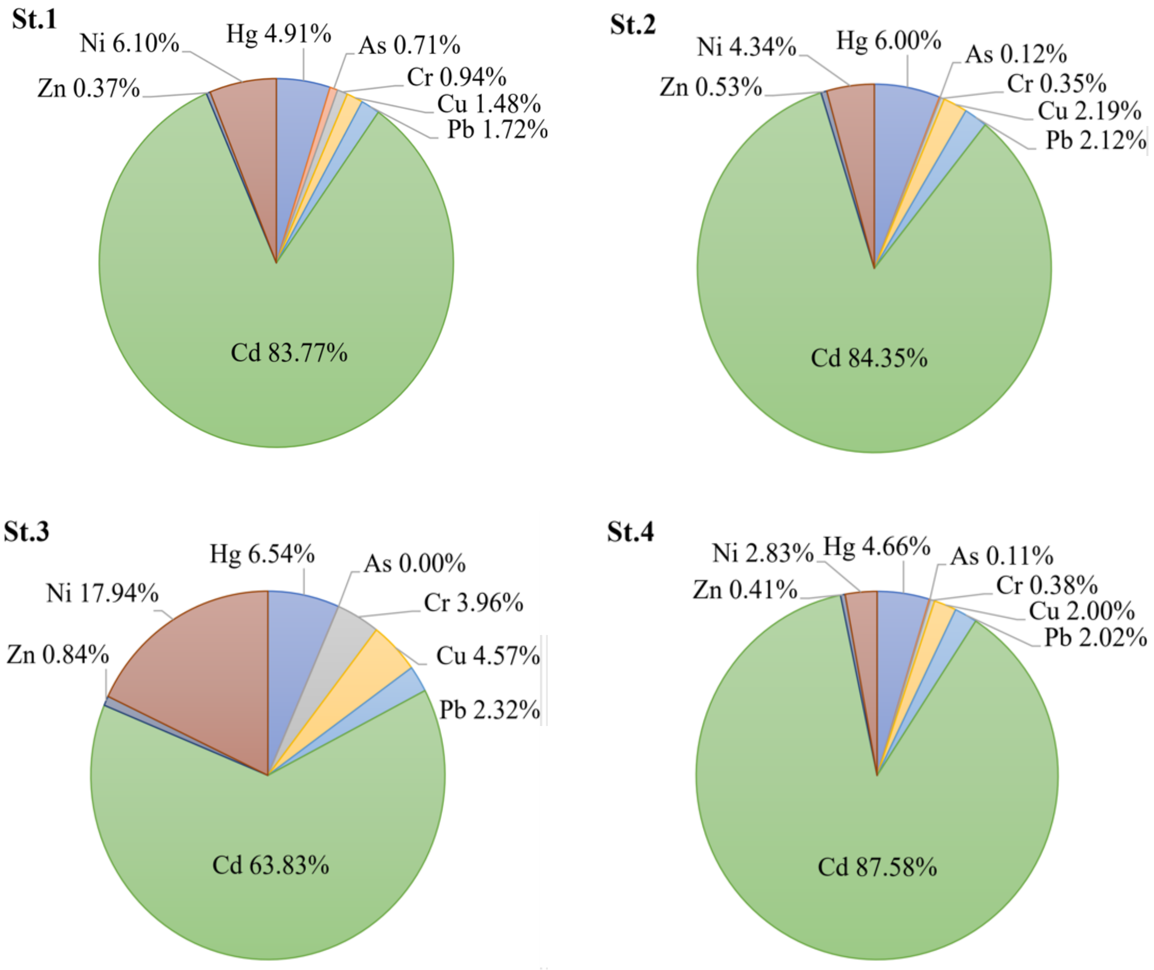

Figure 4. Contribution of the E_i value of each heavy metal to the E_{RI} value at each study site

Table 5. Maximum, minimum, and mean (± standard deviation) content of some heavy metals detected in samples of three shellfish species from Youtefa Bay (mg/kg dry-weight)

Species		**Hg**	**Pb**	**As**	**Cr**	**Cd**	**Ni**	**Zn**	**Cu**
G. expansa	Maximum	ND	0.14	0.98	ND	0.26	26.02	82.91	9.57
	Minimum	ND	0.09	0.64	ND	0.17	18.92	73.21	5.93
	Mean±SD	ND	0.12±0.03	0.83±0.17	ND	0.21±0.04	21.81±3.55	77.65±4.85	7.75±0.91
V. elongatum	Maximum	ND	0.14	0.50	ND	0.21	27.84	65.87	16.55
	Minimum	ND	0.09	0.36	ND	0.09	19.26	54.32	12.12
	Mean±SD	ND	0.11±0.02	0.41±0.43	ND	0.14±0.05	23.57±3.50	60.66±4.78	14.46±1.82
A. antiquata	Maximum	ND	0.19	0.33	ND	1.24	5.19	90.05	5.85
	Minimum	ND	0.08	0.19	ND	0.95	3.98	81.52	5.09
	Mean±SD	ND	0.13±0.05	0.27±0.06	ND	1.09±0.12	4.56±0.49	85.47±3.51	5.38±0.34
Maximum threshold:									
BPOM (2009)		1.00	1.50	1.00	-	1.00	-	-	20.00
FAO (1983)		0.50	0.50	1.00	-	0.05	1.00	30.00	30.00
WHO (1989)		-	2.00	-	-	1.00	1.00	100.00	30.00
FAO/WHO (2011)		0.50	1.50	-	0.10	1.00	-	120.00	30.00

Note: ND indicates heavy metals not detected

The content of Pb, As, and Cu found in three shellfish species is still compliant with the thresholds established by BPOM (2009), FAO (1983), WHO (1989), and FAO/WHO (2011). However, the As metal content detected in the *G. expansa* is quite high and has approached the threshold permitted by BPOM (2009) and FAO (1983). Likewise, the maximum value of the Cu content detected in the *V. elongatum* has approached the threshold set by BPOM

(2009). Meanwhile, Cd, Ni, and Zn detected in the shellfish samples have exceeded the permitted threshold. The Cd content in *G. expansa* and *V. elongatum* has surpassed the threshold allowed by FAO (1983). Meanwhile, in *A. antiquata*, it has exceeded the thresholds permitted by BPOM (2009), FAO (1983), WHO (1989), and FAO/WHO (2011). The Zn content only exceeded the threshold set by FAO (1983). However, it has approached the threshold set by WHO (1989), especially that detected in *A. antiquata*. The Ni content detected in the three shellfish species is very high and exceeds the threshold set by the FAO (1983) and WHO (1989). These interpretations should be considered cautiously due to the dry-weight versus wet-weight discrepancy, which may lead to apparent overestimation when directly compared to food safety standards typically expressed in wet-weight units.

The findings of this study regarding the simultaneous content of eight heavy metals (Hg, Pb, As, Cr, Cd, Ni, Zn, and Cu) in three edible shellfish species (*G. expansa*, *V. elongatum*, and *A. antiquata*) represent a significant novelty for understanding the heavy metal contamination status in Youtefa Bay. Each shellfish species has a unique ability to accumulate different heavy metals. Previous studies conducted by Hasmi (2024) only focused on one priority metal (lead) in five other shellfish species (*Bathyarca petunculoidus*, *Anadara granosa*, *Anadara ovalis*, *Barbatia obliquata*, and *Strombus canarium*) in Youtefa Bay. The results were not significantly different from the Pb content found in the three shellfish species in this study. However, this comprehensive multi-metal study gives a more accurate and complete picture of the total toxicity burden that these filter-feeding organisms have to deal with. Multi-metal studies on shellfish species are crucial for accurate contamination assessment (Yulianto et al. 2019; Shue et al. 2014; Lee et al. 2022; Kim et al. 2025). Additionally, understanding the total pollution load in aquatic ecosystems is crucial, as it can reveal different accumulations of each metal (Fan et al. 2020; Lee et al. 2022; Putri and Angraini 2022; Yu et al. 2022). Furthermore, the comparison of inter-metal content reveals a unique pattern: the essential metal Zn accumulates higher within the shells, but this finding is accompanied by unexpectedly high accumulation of two non-essential metals (Ni and Cd), exceeding the permissible limits for consumption. In the context of risk assessment, it is important to distinguish between essential metals (e.g., Zn and Cu), which are required for biological functions but may become toxic at high concentrations, and non-essential metals (e.g., Ni and Cd), which have no known biological role and are generally toxic even at low concentrations. This could indicate that during multi-metal exposure, synergistic, antagonistic, or additive interaction effects can occur between different metals (Duan et al. 2025).

The relatively high accumulation of Cd, Ni, and Zn in several shellfish samples, including concentrations exceeding recommended threshold values, indicates potential health implications associated with shellfish consumption by local communities. However, the health implications discussed in this study are presented as preliminary screening-level concerns rather than the results of a comprehensive quantitative risk assessment. Cd is a non-essential metal recognized for its carcinogenic properties at elevated concentrations, posing a risk of long-term adverse effects on human health (Ahmed et al. 2015; Lee et al. 2022; Kotacho et al. 2024; Ray and Vashishth 2024). Cd poisoning varies depending on the route of exposure (Charkiewicz et al. 2023), with the most frequently documented effects being harm to the respiratory and renal systems (Agbugui and Abe 2022). Continuous accumulation of Cd may result in damage to kidney tubules, which is marked by kidney dysfunction, proteinuria, and heightened excretion of calcium and phosphorus in urine (Nordberg and Nordberg 2022; Charkiewicz et al. 2023). Cd metal can also cause neurological disorders, leading to weakness and total damage to bones (Rahimzadeh et al. 2017; Charkiewicz et al. 2023). On the other hand, recorded Ni accumulation has the potential to disrupt the functioning of vital organs, including the heart, lungs, liver, kidneys, brain, and spinal cord, and could lead to DNA damage (Genchi et al. 2020; Dudek-Adamska et al. 2021; Agbugui and Abe 2022). At extreme levels, Ni toxicity has been documented to induce contact dermatitis (Agbugui and Abe 2022) and may interfere with reproductive and developmental functions (Damayanty et al. 2023). Meanwhile, the metal Zn is classified as an essential and non-carcinogenic metal, with relatively low toxicity compared to Cd or Ni. However, at high levels, Zn can still cause gastrointestinal symptoms such as nausea, vomiting, and diarrhea (Jaishankar et al. 2014), and can also disrupt muscle coordination (Al-Taee et al. 2020).

The simultaneous occurrence of Cd, Ni, and Zn at relatively elevated levels in shellfish from Youtefa Bay suggests a potential health concern, especially for sensitive groups like children and pregnant women, if consumption occurs over extended periods. These findings highlight the need for continued monitoring and more detailed, quantitative health risk assessments, as well as the application of precautionary measures, including dietary diversification and the limitation of consumption of specific shellfish species, until comprehensive risk evaluations become available.

Table 6. BSAF mean value (± standard deviation) in three shellfish species

Species	Hg	Pb	As	Cr	Cd	Ni	Zn	Cu
G. expansa	ND	0.02±0.00	0.86±0.18	ND	0.24±0.05	0.30±0.05	2.15±0.14	0.56±0.13
V. elongatum	ND	0.02±0.00	0.44±0.07	ND	0.16±0.07	0.33±0.06	1.68±0.16	1.04±0.16
A. antiquata	ND	0.02±0.01	0.27±0.07	ND	1.25±0.17	0.06±0.01	2.37±0.12	0.39±0.03

Note: ND indicates heavy metals not detected

Biota-sediment accumulation factor

Table 6 presents the BSAF values for three shellfish species in Youtefa Bay, calculated using sediment data from St.1, which was selected due to the availability of paired sediment-biota samples and consistent analytical measurements; therefore, the results primarily reflect local conditions at this site and may not fully represent spatial variability across the bay. The study findings show that the BSAF value of Zn is dominantly higher compared to other metals. The order of BSAF values in shellfish is as follows: Zn > As > Cu > Ni > Cd > Pb > Hg/Cr in *G. expansa*; Zn > Cu > As > Ni > Cd > Pb > Hg/Cr in *V. elongatum*; and Zn > Cd > Cu > As > Ni > Pb > Hg/Cr in *A. antiquata*. It should be noted that non-detected (ND) values (e.g., Hg and Cr) were excluded from BSAF ratio calculations to avoid numerical bias, and thus comparisons were limited to detected content only. Variations in BSAF sequences between species reflect differences in biological characteristics and specific responses of organisms to metal exposure in sediments. The ANOVA results indicated that there were significant differences in the BSAF value of As metal (F-value 19.28; p-value 0.002), Cd (F-value 91.81; p-value 0.000), Ni (F-value 30.38; p-value 0.001), Zn (F-value 18.85; p-value 0.003), and Cu (F-value 23.68; p-value 0.001) between the three shellfish species. The exception is the comparison of BSAF values of Pb metal (F-value 0.10; p-value 0.910). In detail, the results of Tukey's post hoc test revealed that the BSAF of As metal in *G. expansa* was significantly different from *V. elongatum* (p-value 0.012) and *A. antiquata* (p-value 0.002). Furthermore, the BSAF of Cd metal in *A. antiquata* was significantly different from the other two species (p-value 0.000). Likewise, the BSAF of Ni metal in *A. antiquata* was significantly different from *G. expansa* (p-value 0.002) and *V. elongatum* (p-value 0.001). Significant differences were also found in the BSAF of Cu and Zn metals in the *V. elongatum,* which were significantly different from *G. expansa* (p-value 0.006 for Cu; p-value 0.002 for Zn) and *A. antiquata* (p-value 0.015 for Cu; p-value 0.002 for Zn).

The predominantly high BSAF values for Zn indicate that Zn is more readily taken up and stored by shellfish tissues than other metals under similar environmental conditions. This is consistent with findings from studies in other coastal systems, where Zn often exhibits high BSAF values due to its essential nature and is readily absorbed by benthic organisms, particularly bivalves, which are active filter feeders (Melake et al. 2023; Zhang et al. 2023). Conversely, non-essential metals often exhibit low BSAF values because organisms tend to inhibit the accumulation of toxic metals as a form of detoxification mechanism (Melake et al. 2023).

Multivariate relationships among heavy metals based on Spearman correlation and PCA

The Spearman correlation analysis indicated robust and significant positive correlations ($p<0.05$) among six metals: Hg, Pb, Cr, Ni, Zn, and Cu. In contrast, As and Cd did not exhibit significant correlations with this group of metals (Table 7). Prior to principal component analysis (PCA), data suitability was confirmed by a Kaiser-Meyer-Olkin (KMO) value of 0.746 and a highly significant Bartlett's test of sphericity ($\chi^2 = 137.01$; df = 28; $p<0.001$), indicating that the dataset was appropriate for multivariate analysis. PCA utilizing Varimax rotation revealed two components that collectively accounted for 81.3% of the total variance. The first component represented 66.6% of the variance and was distinguished by high loadings of Hg, Pb, Cr, Ni, Zn, and Cu (Table 8; Figure 5), indicating coherent distribution patterns and similar geochemical behavior among these metals. Using a loading threshold of |0.70| (Hair et al. 2010), all six metals show strong contributions to Factor 1, confirming the robustness of this grouping. The second component explained 14.7% of the variance, with Cd exhibiting an extremely strong negative loading (-0.975), far exceeding the significance threshold and clearly dominating Factor 2. This indicates that a distinct controlling process governs Cd and is statistically separated from the main metal assemblage. Meanwhile, as shown, there was weak loading and it did not meet the threshold criterion, suggesting a limited contribution to both factors.

Table 7. Spearman correlation coefficient between heavy metals

	Hg	Pb	As	Cr	Cd	Ni	Zn
Pb	**0.860**						
As	-0.378	-0.427					
Cr	**0.727**	**0.727**	-0.189				
Cd	0.266	0.382	0.179	0.245			
Ni	**0.811**	**0.706**	-0.168	**0.909**	0.315		
Zn	**0.832**	**0.895**	-0.462	**0.685**	0.441	**0.692**	
Cu	**0.846**	**0.937**	-0.448	**0.713**	0.389	**0.664**	**0.965**

Note: bold indicates significant correlation at the 0.05 level

Table 8. Rotated factor loadings of PCA

Variables	Factor 1	Factor 2
Hg	0.864	-0.286
Pb	0.883	-0.179
As	-0.232	0.033
Cr	0.983	-0.107
Cd	0.217	-0.975
Ni	0.973	-0.169
Zn	0.944	-0.216
Cu	0.948	-0.164
Variance	5.3289	1.1788
% Variance	0.666	0.147

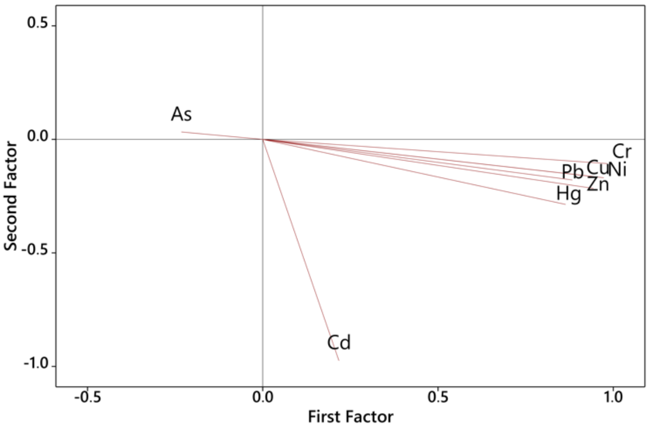

Figure 5. PCA (with Varimax rotation) plot of eight heavy metals

The clustering of Hg, Pb, Cr, Ni, Zn, and Cu in the first principal component reflects similarity in spatial distribution and geochemical behavior rather than definitive source identity. Similar metal groupings (Cr-Cu-Ni-Pb-Zn) have been extensively documented in sediment studies utilizing multivariate statistics and are typically understood as reflecting common controlling processes or input pathways rather than verified sources (Facchinelli et al. 2001; Chen et al. 2016). Accordingly, the association between increased levels of these metals at St.3 and human activities within the Acai River catchment, such as settlements, commercial activities, and transportation, is presented as a likely explanation rather than a conclusive attribution, aligning with findings from similar coastal environments (Alloway 2013; Armid et al. 2014).

The separation of As and Cd into different principal components suggests that different controlling processes or pathways may influence these metals. The dominance of Cd in Factor 2, combined with its weak correlations with other metals (Table 6), further supports its independent geochemical behavior. Previous studies have reported that Cd often behaves independently of other heavy metals and may reflect more specific inputs or biogeochemical controls, while As, natural geochemical processes can influence distribution; however, confirmation of such mechanisms requires dedicated source-tracing data (Alloway 2013; Saha et al. 2021). Therefore, interpretations regarding the behavior and potential origin of As and Cd in this study are presented cautiously and remain tentative, based solely on statistical patterns observed in the dataset.

Study limitations

This study is constrained by limitations associated with the spatial coverage, analytical approach, and temporal comparability of the dataset. Sampling was focused on sediments and shellfish without accompanying source-tracing analyses, so the observed patterns of heavy metal accumulation cannot be definitively attributed to anthropogenic inputs or natural processes such as river runoff and erosion. In addition, shellfish sampling was restricted to mangrove ecosystems, which limits the representativeness of bioaccumulation results with respect to the range of environmental conditions and metal availability across all ecological zones of Youtefa Bay. From an analytical perspective, uncertainty may also be influenced by biological factors of the organisms (age, size, physiological condition, and season) as well as potential technical bias related to sample preparation and instrument sensitivity. Furthermore, this study did not include measurements of water quality parameters (e.g., pH, salinity, and dissolved oxygen), which are important in controlling metal mobility, speciation, and bioavailability in aquatic systems. The absence of these parameters limits a more comprehensive interpretation of metal behavior and environmental dynamics. Moreover, this study did not include metal speciation analysis (e.g., differentiation between inorganic and organic forms of As metal), which represents an important limitation because their chemical forms strongly control metal toxicity, mobility, and bioavailability. As a result, the measured total metal concentrations may not fully reflect the biologically available or toxic fractions. Furthermore, temporal comparisons with previously published data were conducted as indicative inter-study comparisons due to differences in sampling design and data coverage, which adds additional uncertainty to the interpretation. Overall, the accumulation of these limitations necessitates caution in interpreting the results and in formulating management recommendations based on the findings of this study.

In conclusion, this study indicates that heavy metal concentrations in Youtefa Bay exhibit spatial and temporal variability. Sediment analysis showed elevated Ni content, reaching up to 401 mg/kg at St.3, exceeding threshold effect levels (TEL), while Cd exhibited the highest ecological risk contribution, with individual ecological risk (E_i) values up to 126 at St.3, indicating moderate ecological risk. Overall ecological risk index (E_{RI}) values ranged from low to moderate across sampling sites. In shellfish, Cd and As content in certain species exceeded recommended food safety limits on a dry-weight basis, indicating potential human health concerns. Biota-sediment accumulation factor (BSAF) results revealed species-specific accumulation patterns, with relatively higher bioaccumulation potential for Cd and Cu. Multivariate analysis (PCA) explained 81.3% of total variance and distinguished Ni-dominated sediment influence from Cd-associated ecological risk patterns. Based on these findings, management efforts should be approached cautiously and include sustained environmental monitoring, strengthened control of land-based and riverine pollutant inputs, and improved public awareness regarding shellfish consumption, alongside further studies incorporating source-tracing approaches, metal bioavailability, and quantitative human health risk assessments (e.g., Estimated Daily Intake and Target Hazard Quotient) to support more effective management of Youtefa Bay. In addition, further studies incorporating water quality parameters are recommended to improve interpretation of metal dynamics in Youtefa Bay.

ACKNOWLEDGEMENTS

The authors are very grateful to the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, for funding this study through *Penelitian Fundamental Reguler* Grants in 2025 (Grant number: 065/C3/DT.05.00/PL/2025; sub-number: 270/UN20.2.1/PG/2025).

REFERENCES

Afzal I, Begum S, Iram S, Shabbir R, Shahat AA, Javed T. 2024. Comparative analysis of heavy metals toxicity in drinking water of selected industrial zones in Gujranwala, Pakistan. Sci Rep 14: 30639. https://doi.org/10.1038/s41598-024-82138-8.

Agbugui MO, Abe GO. 2022. Heavy metals in fish: Bioaccumulation and health. Brit J Earth Sci Res 10 (1): 47-66. https://doi.org/10.37745/bjesr.2013.

Ahmed MK, Baki MA, Islam MS, Kundu GK, Habibullah-AlMamun M, Sarkar SK, Hossain MM. 2015. Human health risk assessment of heavy metals in tropical fish and shellfish collected from the river Buriganga, Bangladesh. Environ Sci Pollut Res 22 (20): 15880-15890. https://doi.org/10.1007/s11356-015-4813-z.

Alam M, Rohani MdF, Hossain MdS. 2023. Heavy metals accumulation in some important fish species cultured in commercial fish farm of Natore, Bangladesh and possible health risk evaluation. Emerg Contam 9: 100254. https://doi.org/10.1016/j.emcon.2023.100254.

Alloway BJ. 2013. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability (3rd ed.). Springer.

Al-Taee SK, Karam H, Ismail HKh. 2020. Review on some heavy metal toxicity on freshwater fishes. J Appl Vet Sci 5 (3): 78-86. https://doi.org/10.21608/JAVS.2020.100157.

Armid A, Shinjo R, Zaeni A, Sani A, Ruslan R. 2014. The distribution of heavy metals including Pb, Cd and Cr in Kendari Bay surficial sediments. Mar Pollut Bull 84 (1-2): 373-378. https://doi.org/10.1016/j.marpolbul.2014.05.021.

Baatrup E. 1991. Structural and functional effects of heavy metals on the nervous system, including sense organs, of fish. Comp Biochem Physiol C: Comp Pharmacol 100: 253-257. https://doi.org/10.1016/0742-8413(91) 90163-N.

BPOM. 2009. Peraturan Kepala Badan Pengawas Obat dan Makanan Republik Indonesia Nomor HK.00.06.1.52.4011 tentang Penetapan Batas Maksimum Cemaran Mikroba dan Kimia dalam Makanan. Badan Pengawas Obat dan Makanan Republik Indonesia, Jakarta. [Indonesian]

Buchman MF. 2008. NOAA Screening Quick Reference Tables: NOAA OR&R Report 08-1. National Oceanic and Atmospheric Administration, Seattle, WA.

Budiyanto F, Lestari L. 2015. The assessment of sediment contamination level in the Lampung Bay, Indonesia: Heavy metal perspective. J Segara 11 (1): 71-78. https://doi.org/10.15578/segara.v11i1.9085.

Budiyanto F, Lestari L. 2017. Temporal and spatial distribution of heavy metal in sediment of urban coastal waters: A case study in Jakarta Bay, Indonesia. Bull Mar Geol 32 (1): 1-10. https://doi.org/10.32693/bomg.32.1.2017.364.

Bungasalu BA, Anou KN, Sinaga ES, Ngaderman H, Bunga M, Molama M. 2025. Spatial distribution and source identification of heavy metal pollution in urban river sediments: A case study from the Acai River, Jayapura, Papua. BIOLINK: Jurnal Biologi Lingkungan Industri Kesehatan 12 (1): 130-135. https://doi.org/10.31289/biolink.v12i1.15640.

CCME. 2001. Canadian Sediment Quality Guidelines for the Protection of Aquatic Life: Summary Tables. Canadian Council of Ministers of the Environment, Winnipeg.

Chai L, Li H, Yang Z, Min X, Liao Q, Liu Y, Men S, Yan Y, Xu J. 2017. Heavy metals and metalloids in the surface sediments of the Xiangjiang River, Hunan, China: Distribution, contamination, and ecological risk assessment. Environ Sci Pollut Res 24: 874-885. https://doi.org/10.1007/s11356-016-7872-x.

Chang F, Zhou M, Leng Y, Zou X, Dai Y, Ke C, Xiong W, Li Z. 2025. Heavy metal contamination in surface sediments of Wanfeng Lake, Southwest China: Spatial distribution patterns and ecological risk assessment. Earth 6: 51. https://doi.org/10.3390/earth6020051.

Charkiewicz AE, Omeljaniuk WJ, Nowak K, Garley M, Nikliński J. 2023. Cadmium toxicity and health effects: A brief summary. Molecules 28 (18): 6620. https://doi.org/10.3390/molecules28186620.

Chen H, Chen R, Teng Y, Wu J. 2016. Contamination characteristics, ecological risk and source identification of trace metals in sediments of the Lean River (China). Ecotoxicol Environ Saf 125: 85-92. https://doi.org/10.1016/j.ecoenv.2015.11.042.

Cordova MR, Purbonegoro T, Puspitasari R, Hindarti D. 2016. Assessing contamination level of Jakarta Bay nearshore sediments using green mussel (*Perna viridis*) larvae. Mar Res Indonesia 41 (2): 67-76. https://doi.org/10.14203/mri.v41i2.130.

Couceiro F, Rauen W, Millward GE, Lin B, Turner A, Falconer R. 2009. Transport and reactivity of nickel in estuarine sediments: Results from a high capacity flume. Mar Chem 117: 71-76. https://doi.org/10.1016/j.marchem.2009.06.005.

Damayanty S, Misdayanti M, Ainurafiq A. 2023. Literatur review: Risiko kesehatan melalui konsumsi ikan yang mengandung logam berat nikel (Ni). Jambura J Health Sci Res 5 (4): 134-142. https://doi.org/10.37311/jjhsr.v5i4.20940. [Indonesian]

Datu AT, Hartiningsih E, Indrajati R. 2024. Studi mineralogi pada batuan sedimen dan laterit di daerah Abepantai Kampung Nafri Distrik Abepura, Kota Jayapura, Papua. Manufaktur: Publikasi Sub Rumpun Ilmu Keteknikan Industri 2 (4): 22-28. https://doi.org/10.61132/manufaktur.v2i4.755. [Indonesian]

Djikanović V, Skorić S, Spasić S, Naunovic Z, Lenhardt M. 2018. Ecological risk assessment for different macrophytes and fish species in reservoirs using biota-sediment accumulation factors as a useful tool. Environ Pollut 241: 1167-1174. https://doi.org/10.1016/j.envpol.2018.06.054.

Duan Y, Zhu S, Song Y, Zhu D, Zhong M, Chen L, Luo X. 2025. Application of traditional and reverse labeling approaches to assess dietary bioavailability of metals in biofilms. Environ Intl 202: 109648. https://doi.org/10.1016/j.envint.2025.109648.

Dudek-Adamska D, Lech T, Konopka T, Kościelniak P. 2021. Nickel content in human internal organs. Biol Trace Elem Res 199: 2138-2144. https://doi.org/10.1007/s12011-020-02347-w.

Effendi H, Kawaroe M, Mursalin M, Lestari DF. 2016. Ecological risk assessment of heavy metal pollution in surface sediment of Mahakam Delta, East Kalimantan. Procedia Environ Sci 33: 574-582. https://doi.org/10.1016/j.proenv.2016.03.110.

El Boudammoussi M, El Hammoudani Y, Reklaoui K, Dimane F, Haboubi K. 2024. Trace element correlations in mussels and sediments on the Moroccan Mediterranean coast. Ecol Eng Environ Technol 25 (7): 106-117. https://doi.org/10.12912/27197050/188025.

Emon FJ, Rohani MF, Sumaiya N, Jannat MFT, Akter Y, Shahjahan M, Abdul Kari Z, Tahiluddin AB, Goh KW. 2023. Bioaccumulation and bioremediation of heavy metals in fishes: A review. Toxics 11 (6): 510. https://doi.org/10.3390/toxics11060510.

Facchinelli A, Sacchi E, Mallen L. 2001. Multivariate statistical and GIS-based approach to identify heavy metal sources in soils. Environ Pollut 114: 313-324. https://doi.org/10.1016/S0269-7491(00)00243-8.

Fan H, Chen S, Li Z, Liu P, Xu C, Yang X. 2020. Assessment of heavy metals in water, sediment, and shellfish organisms in typical areas of the Yangtze River Estuary, China. Mar Pollut Bull 151: 110864. https://doi.org/10.1016/j.marpolbul.2019.110864.

FAO [Food and Agriculture Organization]. 1983. Compilation of Legal Limits for Hazardous Substances in Fish and Fishery Products. FAO Fishery Circular No. 464, Food and Agriculture Organization.

FAO/WHO. 2011. Evaluation of Certain Food Additives and the Contaminants Mercury, Lead, and Cadmium. International Programme on Chemical Safety Seventy-third Report of the Joint FAO/WHO Expert Committee on Food Additives WHO Technical Report Series No. 960.

Farsani MN, Haghparast RJ, Naserabad SS, Moghadas F, Bagheri T, Gerami MH. 2019. Seasonal heavy metal monitoring of water, sediment, and common carp (*Cyprinus carpio*) in Aras Dam Lake of Iran. Intl J Aquat Biol 7 (3): 123-131. https://doi.org/10.22034/ijab.v7i3.597.

Genchi G, Carocci A, Lauria G, Sinicropi MS, Catalano A. 2020. Nickel: Human health and environmental toxicology. Intl J Environ Res Public Health 17 (3): 679. https://doi.org/10.3390/ijerph17030679.

Hair JF, Black WC, Babin BJ, Anderson RE. 2010. Multivariate Data Analysis (7th ed.). Pearson, New York.

Hakanson L. 1980. An ecological risk index for aquatic pollution control: A sedimentological approach. Water Res 14 (8): 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8.

Hamuna B, Pujiyati S, Dimana L, Natih INMN, Alianto A. 2020. Distribution and density of demersal fishes in Youtefa Bay, Papua, Indonesia: A study using hydroacoustic technology. Indian J Fish 67 (1): 30-35. https://doi.org/10.21077/ijf.2019.67.1.88578-05.

Hamuna B, Tanjung RHR. 2021. Heavy metal content and spatial distribution to determine the water pollution index in Depapre waters, Papua, Indonesia. Curr Appl Sci Technol 21 (1): 1-11. https://doi.org/10.14456/cast.2021.4.

Hamuna B, Wanimbo E. 2021. Heavy metal contamination in sediments and its potential ecological risks in Youtefa Bay, Papua Province, Indonesia. J Ecol Eng 22 (8): 209-222. https://doi.org/10.12911/22998993/139116.

Hao Z, Chen L, Wang C, Zou X, Zheng F, Feng W, Zhang D, Peng L. 2019. Heavy metal distribution and bioaccumulation ability in marine organisms from coastal regions of Hainan and Zhoushan, China. Chemosphere 226: 340-350. https://doi.org/10.1016/j.chemosphere.2019.03.132.

Harmesa H, Cordova MR. 2021. A preliminary study on heavy metal pollutants chrome (Cr), cadmium (Cd), and lead (Pb) in sediments and beach morning glory vegetation (*Ipomoea pes-caprae*) from Dasun Estuary, Rembang, Indonesia. Mar Pollut Bull 162: 111819. https://doi.org/10.1016/j.marpolbul.2020.111819.

Harmesa H, Lestari L, Budiyanto F. 2020. Distribution of heavy metals in seawater and sediments in Cimanuk estuary, West Java, Indonesia. Oseanologi dan Limnologi Indonesia 5 (1): 19-32. https://doi.org/10.14203/oldi.2020.v5i1.310. [Indonesian]

Haryati E, Dahlan K, Mantiri SYY, Singir B. 2021. Profil dan karakteristik mineral nikel laterit di daerah Angkasapura, Kota Jayapura, Papua, Indonesia. Jurnal Fisika 11 (2): 95-104. https://doi.org/10.15294/jf.v11i2.33067. [Indonesian]

Hasmi H, Mallongi A. 2016. Health risk analysis of lead exposure from fish consumption among communities along Youtefa Gulf, Jayapura. Pakistan J Nutr 15 (10): 929-935. https://doi.org/10.3923/pjn.2016.929.935.

Hasmi H. 2024. Shells that have been polluted by lead around Youtefa Bay in Jayapura City have potential risk of non-carcinogenic. UNEJ e-Proceeding.

Ikhsani IY, Harmesa H, Budiyanto F, Thoha H, Fitriya N, Kaisupy MT, Wibowo SPA, Lestari L. 2025. Heavy metals contamination in Jakarta Bay sediment: Geoaccumulation assessment and implication for environmental health. Mar Pollut Bull 216: 117983. https://doi.org/10.1016/j.marpolbul.2025.117983.

Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. 2014. Toxicity, mechanism, and health effects of some heavy metals. Interdiscip Toxicol 7 (2): 60-72. https://doi.org/10.2478/intox-2014-0009.

Juniardi E, Sulistiono S, Hariyadi S. 2022. Heavy metals (Pb and Cd) contents in the seawater and sediment in Panjang and Pamujaan Besar Islands, Banten Bay, Indonesia. IOP Conf Ser: Earth Environ Sci 950: 012052. https://doi.org/10.1088/1755-1315/950/1/012052.

Karthikeyan P, Marigoudar SR, Mohan D, Nagarjuna A, Sharma KV. 2020. Ecological risk from heavy metals in Ennore estuary, South East coast of India. Environ Chem Ecotoxicol 2: 182-193. https://doi.org/10.1016/j.enceco.2020.09.004.

Kim HNT, Duong V-H, Chu T-T, Pham-Thi T-X, Nguyen X-Q, Vu SV, Van TP, Ta D-T, Duong D-T, Tursunov O, Priyadharshini M, Musthafa MS, Hegedűs M, Shahrokhi A, Kovács T. 2025. Mussels as bioindicators for the rapid detection of heavy metal fluctuations in marine coastal waters: A case study of seasonal bioaccumulation monitoring and assessment of *Perna viridis* from the Gulf of Tonkin Coastline, Hai Phong, Vietnam. Water 17: 2552. https://doi.org/10.3390/w17172552.

Kotacho AA, Yimer GT, Sota SS, Berego YS. 2024. Heavy metal levels and human health risk implications associated with fish consumption from the lower Omo River (Lotic) and Omo delta Lake (Lentic), Ethiopia. PeerJ 12: e17216. https://doi.org/10.7717/peerj.17216.

Krisbiantoro A, Retnawaty SF, Fitri Y, Utami K. 2025. Analisis konsentrasi logam berat pada sedimen dan air laut di perairan Selat Rupat. Life Sci 14 (2): 156-164. https://doi.org/10.15294/unnesjlifesci.v14.i2.23772. [Indonesian]

Kusuma AH, Prartono T, Atmadipoera AS, Arifin T. 2015. Sebaran logam berat terlarut dan terendapkan di perairan Teluk Jakarta. Jurnal Teknologi Perikanan dan Kelautan 6 (1): 41-49. https://doi.org/10.24319/jtpk.6.41-49. [Indonesian]

Kusumaningsih ARP, Prartono T, Koropitan AF, Khotib M, Hartanto MT, Natih NMN. 2024. Potential sources and contamination levels of Pb and Ni in surface sediment of Lampung Bay, Indonesia. Environ Res Eng Manag 80 (4): 118-126. https://doi.org/10.5755/j01.erem.80.4.34563.

Le SX, Nguyen BV, Bui HTM, Le NV, Dinh HV, Le KD, Cao ST, Nguyen K. 2025. Bioaccumulation of selected heavy metals in bivalve molluscs from Northeastern Vietnam: Implications for safe seafood utilization. Res Ecol 7 (3): 115-134. https://doi.org/10.30564/re.v7i3.9805.

Lee KJ, Kang EH, Yoon M, Jo MR, Yu HS, Son KT. 2022. Concentration of heavy metals in shellfishes and health risk assessment from Korean coastal areas. Fish Aquat Sci 25 (12): 626-636. https://doi.org/10.47853/FAS.2022.e57.

Liu X, Dadzie AA, Yuan L, Xing S, Zhou X, Xiao S. 2022. Analysis and potential ecological risk assessment of heavy metals in surface sediments of the freshwater ecosystem in Zhenjiang City, China. SN Appl Sci 4: 258. https://doi.org/10.1007/s42452-022-05127-4.

Loska K, Wiechuła D, Korus I. 2004. Metal contamination of farming soils affected by industry. Environ Intl 30 (2): 159-165. https://doi.org/10.1016/S0160-4120(03)00157-0.

Manalu J, Nurjaya IW, Surjono HS, Kholil K. 2011. Analisis tingkat pencemaran air dengan metode indeks pencemaran di Teluk Youtefa, Jayapura, Provinsi Papua. Berita Biologi 10 (6): 749-761. https://doi.org/10.14203/beritabiologi.v10i6.1942. [Indonesian]

Melake BA, Endalew SM, Alamirew TS, Temesegen LM. 2023. Bioaccumulation and biota-sediment accumulation factor of metals and metalloids in edible fish: A systematic review in Ethiopian surface waters. Environ Health Insights 17: 11786302231159349. https://doi.org/10.1177/1178630223115934.

Mohajane C, Manjoro M. 2022. Sediment-associated heavy metal contamination and potential ecological risk along an urban river in South Africa. Heliyon 8: e12499. https://doi.org/10.1016/j.heliyon.2022.e12499.

Msiren MFI, Hartiningsih E, Meak KKW. 2024. Studi keterdapatan unsur logam di daerah Kampung Nafri, Distrik Abepura, Kota Jayapura, Papua. Manufaktur: Publikasi Sub Rumpun Ilmu Keteknikan Industri 2 (4): 29-39. https://doi.org/10.61132/manufaktur.v2i4.756. [Indonesian]

Nastuti R, Soeprobowati TR, Sudarno S. 2024. Contaminant and assessment of heavy metals in Maninjau Lake, West Sumatera, Indonesia. Revista De Gestão Social E Ambiental 18 (4): e07061. https://doi.org/10.24857/rgsa.v18n4-193.

Nordberg M, Nordberg GF. 2022. Metallothionein and cadmium toxicology—historical review and commentary. Biomolecules 12 (3): 360. https://doi.org/10.3390/biom12030360.

Peng W, Li X, Xiao S, Fan W. 2018. Review of remediation technologies for sediments contaminated by heavy metals. J Soils Sediments 18 (4): 1701-1719. https://doi.org/10.1007/s11368-018-1921-7.

Pinkey PD, Nesha M, Bhattacharjee S, Chowdhury MGZ, Fardous Z, Bari L, Koley NJ. 2024. Toxicity risks associated with heavy metals to fish species in the Transboundary River-Linked Ramsar Conservation Site of Tanguar Haor, Bangladesh. Ecotoxicol Environ Saf 269: 115736. https://doi.org/10.1016/j.ecoenv.2023.115736.

Prabowo R, Purwanto P, Sunoko HR. 2016. Akumulasi Cadmium (Cd) pada ikan wader merah (*Puntius bramoides* C.V.) di Sungai Kaligarang. Indones J Math Nat Sci 39 (1): 1-10. https://doi.org/10.15294/ijmns.v39i1.7693. [Indonesian]

Putri WAE, Anggraini N. 2022. Akumulasi logam berat (Cu dan Pb) pada kerang darah *Anadara granosa* yang berasal dari perairan muara Sungai Musi. Jurnal Penelitian Sains 24 (1): 24-28. https://doi.org/10.56064/jps.v24i1.678. [Indonesian]

Rahimzadeh MR, Rahimzadeh MR, Kazemi S, Moghadamnia A. 2017. Cadmium toxicity and treatment: an update. Caspian J Intl Med 8 (3): 135-145. https://doi.org/10.22088/cjim.8.3.135.

Ray S, Vashishth R. 2024. From water to plate: Reviewing the bioaccumulation of heavy metals in fish and unraveling human health risks in the food chain. Emerg Contam 10: 100358. https://doi.org/10.1016/j.emcon.2024.100358.

Ristea E, Pârvulescu OC, Lavric V, Oros A. 2025. Assessment of heavy metal contamination of seawater and sediments along the Romanian Black Sea coast: Spatial distribution and environmental implications. Sustainability 17 (6): 2586. https://doi.org/10.3390/su17062586.

Rozirwan R, Az-Zahrah SAF, Khotimah NN, Nugroho RY, Putri WAE, Fauziyah F, Melki M, Agustriani F, Siregar YI. 2024. Ecological risk assessment of heavy metal contamination in water, sediment, and polychaeta (*Neoleanira tetragona*) from coastal areas affected by aquaculture, urban rivers, and ports in South Sumatra. J Ecol Eng 25 (1): 303-319. https://doi.org/10.12911/22998993/175365.

Rumahorbo BT, Hamuna B, Keiluhu HJ. 2020. An assessment of the coastal ecosystem services of Jayapura City, Papua Province, Indonesia. Environ Socio-econom Stud 8 (2): 45-53. https://doi.org/10.2478/environ-2020-0011.

Rumahorbo BT, Keiluhu HJ, Hamuna B. 2019. The economic valuation of mangrove ecosystem in Youtefa Bay, Jayapura, Indonesia. Ecol Quest 30 (1): 47-54. https://doi.org/10.12775/EQ.2019.003.

Saha S, Reza AHMS, Roy MK. 2021. Arsenic geochemistry of the sediments of the shallow aquifer and its correlation with the groundwater, Rangpur, Bangladesh. Appl Water Sci 11: 166. https://doi.org/10.1007/s13201-021-01495-1.

Salam MA, Paul SC, Noor SNBM, Siddiqua SA, Aka TD, Wahab R, Aweng ER. 2019. Contamination profile of heavy metals in marine fish and shellfish. Glob J Environ Sci Manag 5 (2): 225-236. https://doi.org/10.22034/gjesm.2019.02.08.

Sari A, Tuwo A, Rani C, Saru A. 2020. Water quality study and pollution index based on Physicochemical parameters in the Youtefa Bay tourism area, Jayapura. IOP Conf Ser: Earth Environ Sci 564: 012030. https://doi.org/10.1088/1755-1315/564/1/012030.

Sari A, Tuwo A, Saru A, Rani C. 2022. Diversity of fauna species in the mangrove ecosystem of Youtefa Bay Tourism Park, Papua, Indonesia. Biodiversitas 23 (9): 4490-4500. https://doi.org/10.13057/biodiv/d230915.

Sembel L, Setijawati D, Yona D, Risjani Y. 2022. Spatio-temporal of heavy metal Pb (Lead) in seawater, sediment, and different organs of *Cymodocea rotundata* in Doreri Gulf, Manokwari, West Papua, Indonesia. Biodiversitas 23 (5): 2482-2492. https://doi.org/10.13057/biodiv/d230528.

Shintianata D, Lubis AA, Sugiharto U, Andini FP, Meiliastri SS, Elias MdS. 2024. Tracing heavy metal dynamics in mangrove sediments: A study from Ujung Kulon National Park. Ilmu Kelautan: Indones J Mar Sci 2 (4): 519-529. https://doi.org/10.14710/ik.ijms.29.4.519-529.

Shue M-F, Chen W-D, Su C-C, Lu M-C. 2014. Heavy metals in bivalve mollusks collected from Da-Peng Bay Lagoon in South-Southwestern Taiwan. J Toxicol Environ Health - A: Curr Issues 77 (4): 214-222. https://doi.org/10.1080/15287394.2013.861377.

Sitorus S, Ilang Y, Nugroho RA. 2020. Analisis kadar logam Pb, Cd, Cu, As pada air, sedimen dan bivalvia di pesisir Teluk Balikpapan. Dinamika Lingkungan Indonesia 7 (2): 89-94. https://doi.org/10.31258/dli.7.2p89-94. [Indonesian]

Sutherland R. 2000. Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. Environ Geol 39: 611-627. https://doi.org/10.1007/s002540050473.

Tamehe LS, Zhao Y, Xu W, Gao J. 2024. Ni(Co) laterite deposits of Southeast Asia: A review and perspective. Minerals 14: 134. https://doi.org/10.3390/ min14020134.

Tanjung RHR, Hamuna B, Yonas MN. 2019. Assessing heavy metal contamination in marine sediments around the coastal waters of Mimika Regency, Indonesia. J Ecol Eng 20 (11): 35-42. https://doi.org/10.12911/22998993/113411.

Tanjung RHR, Indrayani E, Agamawan LPI, Hamuna B. 2024. Water quality assessment to determine the trophic state and suitability of Lake Sentani (Indonesia) for various utilisation purposes. Water Cycle 5: 99-108. https://doi.org/10.1016/j.watcyc.2024.02.006.

Tanjung RHR, Indrayani E, Agamawan LPI, Hamuna B. 2025. Ecological and human health risks assessment related to heavy metals in surface sediments and some fish species in Lake Sentani, Indonesia. Case Stud Chem Environ Eng 11: 101148. https://doi.org/10.1016/j.cscee.2025.101148.

Tanjung RHR, Yonas MN, Suwito S, Maury HK, Sarungu Y, Hamuna B. 2022. Analysis of surface water quality of four rivers in Jayapura Regency, Indonesia: CCME-WQI approach. J Ecol Eng 23 (1): 73-82. https://doi.org/10.12911/22998993/143998.

Taslima K, Al-Emran M, Rahman MS, Hasan J, Ferdous Z, Rohani MdF, Shahjahan Md. 2022. Impacts of heavy metals on early development, growth, and reproduction of fish: A review. Toxicol Rep 9: 858-868. https://doi.org/10.1016/ j.toxrep.2022.04.013.

Tebaiy S, Yulianda F, Fahrudin A, Muchsin I. 2014. Fish community structure at the seagrass beds habitat in Youtefa Bay, Jayapura, Papua. Jurnal Iktiologi Indonesia 14 (1): 49-65. https://doi.org/10.32491/jii.v14i1.95. [Indonesian]

Tonapa VG, Manalu J, Siallagan J, Walukouw AF, Warpur M. 2023. Analisis status mutu air pada sungai-sungai yang bermuara ke Teluk Youtefa. Portal Sipil 12 (2): 54-60. https://doi.org/10.58839/jps.v12i2.1298. [Indonesian]

Turekian KK, Wedepohl KH. 1961. Distribution of the elements in some major units of the Earth's crust. Geol Soc Am Bull 72: 175-192. https://doi.org/10.1130/0016-7606(1961)72[175:DOTEIS]2.0.CO;2.

USEPA. 1996. Method 3050B: Acid Digestion of Sediments, Sludges, and Soils. Revision 2. United States Environmental Protection Agency, Washington, DC. https://doi.org/10.1520/D3974-09.

WHO. 1989. Heavy Metals-Environmental Aspects: Environment Health Criteria No. 85. World Health Organization, Geneva.

Wijayanti T, Surbakti SB, Renyaan SJ. 2013. Studi ekologi moluska bernilai ekonomi pada hutan mangrove di Teluk Youtefa Kota Jayapura. Jurnal Biologi Papua 5 (2): 60-67. https://doi.org/10.31957/jbp.525. [Indonesian]

Yi Y-J, Sun J, Tang C-H, Zhang S-H. 2016. Ecological risk assessment of heavy metals in sediment in the upper reach of the Yangtze River. Environ Sci Pollut Res 23 (11): 11002-11013. https://doi.org/10.1007/s11356-016-6296-y.

Yu X, Sun L, Zhu X, Bian G, Zhou W, Cao Q, Hong M. 2022. Distribution characteristics and risk assessment of heavy metals in seawater, sediment, and shellfish in the inner and outer Daya Bay, Guangdong. Front Mar Sci 9: 1064287. https://doi.org/10.3389/fmars.2022.1064287.

Yulianto B, Oetari PS, Februhardi S, Putranto TWC, Soegianto A. 2019. Heavy metals (Cd, Pb, Cu, Zn) concentrations in edible bivalves harvested from the Northern Coast of Central Java, Indonesia. IOP Conf Ser: Earth Environ Sci 259: 012005. https://doi.org/10.1088/1755-1315/259/1/012005.

Zhang S, Fu K, Gao S, Liang B, Lu J, Fu G. 2023. Bioaccumulation of heavy metals in the water, sediment, and organisms from the sea ranching areas of Haizhou Bay in China. Water 15 (12): 2218. https://doi.org/10.3390/w15122218.

Zuraida R, Rahardiawan R, Permanawati Y, Adhirana I, Ibrahim A, Nurdin N, Permana H. 2018. Late Holocene heavy metals record of Jakarta Bay sediments. Bull Mar Geol 33 (2): 127-138. https://doi.org/10.32693/bomg.33.2.2018.569.