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Assessment of Heavy Metal Contaminations in Coastal Sediments due to Nickel Mining Activities in Morowali Regency, Central Sulawesi, Indonesia

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Abstract

This work was conducted to determine the heavy metal concentrations in sediments; assess the level of contamination using a contamination index and identify potential sources of heavy metal contamination using multivariate analysis. This work employed contamination indices to evaluate sediment pollution levels. Heavy metal concentrations were analyzed statistically by determining the minimum, maximum, mean, and Standard Deviation (SD) values. According to the contamination factor (Cf), Cd showed very high contamination levels, whereas Sn, Ni, and Pb showed moderate contamination. Hg, As, Cr, and Cu were classified as having low contamination levels. The degree of contamination (Cdeg) ranged from low to high across the sampled sites, reflecting varied levels of pollution severity. Multivariate statistical analyses, including Principal Component Analysis (PCA), Pearson correlation matrix, and Cluster Analysis (CA), were used to identify the potential sources of heavy metal contamination; Cu, Sn, Ni, Hg, and Cr are attributed to natural geological processes, whereas Pb, Cd, and As are linked to anthropogenic activities, likely originating from the nickel mining industry. In conclusion, this work underscores the complex environmental impact of nickel mining in Morowali, highlighting the need for stringent environmental management practices to mitigate further degradation and safeguard coastal ecosystems in Central Sulawesi.

1. Introduction

Heavy metal contamination is a significant global environmental and public health challenge [1]. Human endeavors such as mining, farming, and manufacturing can be released them into the environment [2, 3]. Heavy metals move into the soil, sediment, and water through natural or anthropogenic sources such as agriculture, mining, industrial plants, sewage, and vehicles [4]. Natural sources include heavy metals transported through river systems, rock weathering, deep-sea hydrothermal activity, dust particles carried by wind, and sediment flows. The rate of heavy metal pollution in ecosystems has increased in tandem with industrial expansion. In aquatic environments, heavy metals can kill organisms and have catastrophic effects on their health [5]. Concern over dangerously high amounts of harmful metals in aquatic biota is growing [6]. Risks associated with heavy metal contamination include crop growth restriction, decreased agricultural output, and the most importantly the introduction of hazardous metals into the food chain. Heavy metal pollution is a major environmental concern because of its toxicity in the food chain, heavy metal pollution has grown to be a major environmental concern [5]. Human health is greatly impacted by

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heavy metal contamination because metals such as lead, cadmium, mercury, and arsenic build up in the body through exposure to food and the environment [7].

Heavy metals that are initially required for different metabolic processes become poisons for aquatic species when the amount of heavy metals in the water increase [8]. In addition to their toxicity, heavy metals accumulate in sediments and biota as a result of marine life's bioconcentration, bioaccumulation, and biomagnification [9]. Animals that absorb heavy metals are typically no longer expelled from their systems. As a result, these metals tend to accumulate in the body [10, 11]. Thus, these metals persist throughout the food chain. This is due to the fact that predators at one trophic level consume their contaminated prey from lower trophic levels [12]. Therefore, harmful metals, easily accumulate in the multi-cellular marine macroalgae, when introduced into aquatic environments, where seaweeds are cultivated or found natively. As a result, metals accumulate in the food chain, beginning with absorption at the primary producer level, and ultimately making their way to the consumer, where they are absorbed by the body.

Heavy metals such as lead (Pb), nickel (Ni), chromium (Cr), copper (Cu), mercury (Hg), cadmium (Cd), arsenic (As), tin (Sn), and zinc (Zn) enter water and settle in the sediment [8]. Sediments are part of an aquatic ecosystem that provide spawning, foraging, habitat, and breeding grounds for various marine organisms. Contamination with heavy metals and other pollutants can reduce the abundance of key organisms in the ecology, trade, and recreation of sediments. Heavy metals quickly accumulate in the environment, have substantial bioavailability, and do not decompose rapidly. Once introduced into the environment, they readily enter the marine biota and human food chain [13].

In biological systems, heavy metals are linked to oxidative stress, in which Reactive Oxygen Species (ROS) production overwhelms the body's antioxidant defences [14, 15]. Cell damage results from disequilibrium, which compromises important macromolecules such as proteins, DNA, and lipids [16]. Among the heavy metals known to induce oxidative stress are arsenic (As), cobalt (Cd), lead (Pb), and mercury (Hg). They essentially deprive normal cellular homeostasis by targeting, inhibiting, or reducing the activity of antioxidant enzymes such as Glutathione Peroxidase (GPx), Catalase (CAT), and SuperOxide Dismutase (SOD) [17]. This exacerbates the oxidative damage and causes apoptosis. In aquatic animals, prolonged exposure to the metals can result in several diseases such as immune system damage, metabolic abnormalities, reproductive issues, and elevated mortality rates [18]. Exposure to arsenic has been reported to induce changes in hematological parameters and irregularity in enzyme activity in fishes, thus causing physiological disturbances and oxidative stress [15]. In addition to improving hematological and biochemical parameters, sodium selenite has also shown protective antioxidant properties against heavy metal toxicities like Cd^{2+} and Cr^{3+} in rainbow trout (O. mykiss) [16]. Fish exposed to Pb^{2+} and Cu^{2+} were found to suffer serious oxidative stress due to evidence of such changes in antioxidant enzyme activity and blood biochemistry. Further, sodium selenite was shown to ameliorate this oxidative stress [17]. Marine macroalgae, the primary producers in aquatic environments, are also susceptible to oxidative stress caused by heavy metal contamination. Heavy metal pollution affects the marine food web by slowing macroalgal growth, tempering membrane integrity, and lessening efficiency of photosynthesis [19]. Therefore, such metals exposed in animals of aquatic origin, Pb2+ and Cu2+, also cause cellular oxidative injury, archaeosystem disruption [20]. Although they contribute to the maintenance of the marine food chain, exposure to these heavy metals would hinder their ability to grow, harms their membranes, and reduces their photosynthetic activity. Therefore, confirming the ecological and biological effects of heavy metal pollutants requires understanding their propensity for oxidative stress.

Industrial, mining, urban, and agricultural activities, along with runoff water and atmospheric deposition, redound heavy metal mobilization in rivers, coastal areas, and estuaries (sea). When heavy metals enter coastal environments, they move to sediments by adsorbing suspended substances, composition, and water chemistry. Sediments are reservoirs for various pollutants (heavy metals) and play a vital role in water systems through both natural and anthropogenic processes. Natural phenomena, such as wind, waves, and current, have the potential to release heavy metals from sediments and cause their accumulation in aquatic mammals, fish, birds, plankton, macrobenthos, and even humans [13].

Industrial activities dominate the study area, with wastewater flowing into the rivers and reaching the sea. Seaweed production is a strategic fishery commodity in Central Sulawesi Province, Indonesia. However, the expansion of mining in the Morowali Regency, Central Sulawesi, is progressing without appropriate control. The destruction of mangrove forest areas along the coast is underway, as previously reported [12]. Plans are in place to utilize this land as a nickel-loading port. The Bahodapi coastal area towards South Bungku is anticipated to emerge as a significant nickel hotspot, leading to substantial alterations in ecology and natural functions.

According to Central Sulawesi Province Regional Regulation No. 6 of 2018, concerning the industrial Development Plan for Central Sulawesi Province for 2018-2038, nickel mining activities in the Morowali Regency, Central Sulawesi, are increasingly developing, making Indonesia the largest nickel producer in the world. Potential nickel mines with an area of 237,245 ha are spread across the districts of Central Bungku, West Bungku, East Bungku, South Bungku, Coastal Bungku, Menui Islands, Bahodapi, Bumi Raya and Witaponda. The expanding Ni industry is responsible for environmental damage, deforestation, pollution, and sedimentation, from upstream to downstream. These factors can negatively affect fishermen's livelihoods along the Morowali coast [12]. The disposal of tailings and water from mining sites is channeled into rivers and empties into the sea, resulting in the accumulation of heavy metals in sediments, water, and marine ecosystems (fish, coral reefs, mangroves, seaweeds, and other aquatic biota).

The seawater in Bahodapi, Morowali Regency, contains Cd, Cu, Pb, Ni, and Zn, which are categorized as unsafe for coastal aquatic biota. Meanwhile, the heavy metal concentrations of Pb, Cu, Cd, Ni, and Zn in sediments are hazardous to marine organisms. According to Hasnia et al. [21], the waters surrounding the Bahodapi settlement in the Morowali Regency surpass the seawater quality standards for Port Areas established by the Indonesian Government, exhibiting elevated levels of Pb, Cd, Cu, Zn, and Ni. This research is needed because of the region's significant industrial and mining activities, which are estimated to produce waste discharged into the water and accumulate in the sediments.

Assessment of heavy metal contaminants is key to reducing environmental risks and preventing the negative impacts of pollution caused by industrial and mining activities. Contamination indices and assessments are appropriate for evaluating the heavy metal content and sediment quality in aquatic environments [22]. The aims of this study were 1) to determine heavy metal concentrations in sediment, 2) assess the level of contamination using a contamination index, and 3) identify potential sources of heavy metal contamination using multivariate analysis.

2. Materials and Methods

2.1. Studied area

The Morowali Regency is between 01031'12" South Latitude and 03046'48" South Latitude and between 121002'24" East longitude and 123015'36" east longitude. The Morowali Regency region covers an area of 5.472 km2 of land. The Morowali Regency is one of the four districts on Sulawesi Island with large nickel reserves. The nickel mining industry in the Morowali Regency is progressing rapidly. The broadest potential for mineral and rock resources in the El potential is in the Districts of West Bungku, Central Bungku, East Bungku, Bungku Pesisir, and Bahodopi [23].

2.2. Sediment sampling

The work was conducted from September to December 2023, and sediment samples were collected from nine locations in the Morowali Regency, Central Sulawesi. Figure 1 shows the locations of the sediment sampling points. Sediment sampling was conducted in a seaweed cultivation zone. The water was removed from the sediment, placed in clear plastic, given 1 ml of 90% formalin preservative for 500 g of sediment, and labeled.

The sediment samples were analyzed for heavy metals at the Aquatic Productivity and Environment Laboratory, IPB University, using the acid extraction method outlined in the APHA-AWWA-WEF (2017). The heavy metals included in the analysis were As, Ni, Hg, Cr, Pb, Cd, Cu, and Sn.

2.3. Sediment pollution assessment indices

The equations used for evaluating heavy metal pollution in sediments, such as the geo-accumulation index (I-geo), Contamination Factor (Cf), Contamination degree (Cdeg), and Pollution Load Index (PLI) were derived from various sources, including [24, 25], and are presented in Table 2. The classification levels of contamination in the sediments are listed in Table 3.

Table 1. Geographical coordinates of sediment sampling in Morowali Regency, Central Sulawesi, Indonesia.

Station	Location	Latitude	Longitude
W1	Moahino, Wita Ponda	2°10'42.499" S	122°36'09.568" E
W2	Umbele, Bumi Raya	2°09'29.152" S	122°39'15.880" E
W3	Ungkaya, Wita Ponda	2°-9'40.388" S	122°34'54.058" E
BH1	Fatufia, Bahodapi	2°48'20.901" S	122°09'23.533" E
BH2	Lalampu, Bahodapi	2°46'40.751" S	122°04'41.145" E
BS1	Kaleroang, South Bungku	3°03'28.114" S	122°23'28.243" E
BS2	Kaleroang, South Bungku	3°04'41.436" S	122°22'45.688" E
BS3	Pado-pado, South Bungku	3°01'17.032"S	122°21'27.595" E
BS4	Padabale, South Bungku	3°01'44.009" S	122°21'53.604" E

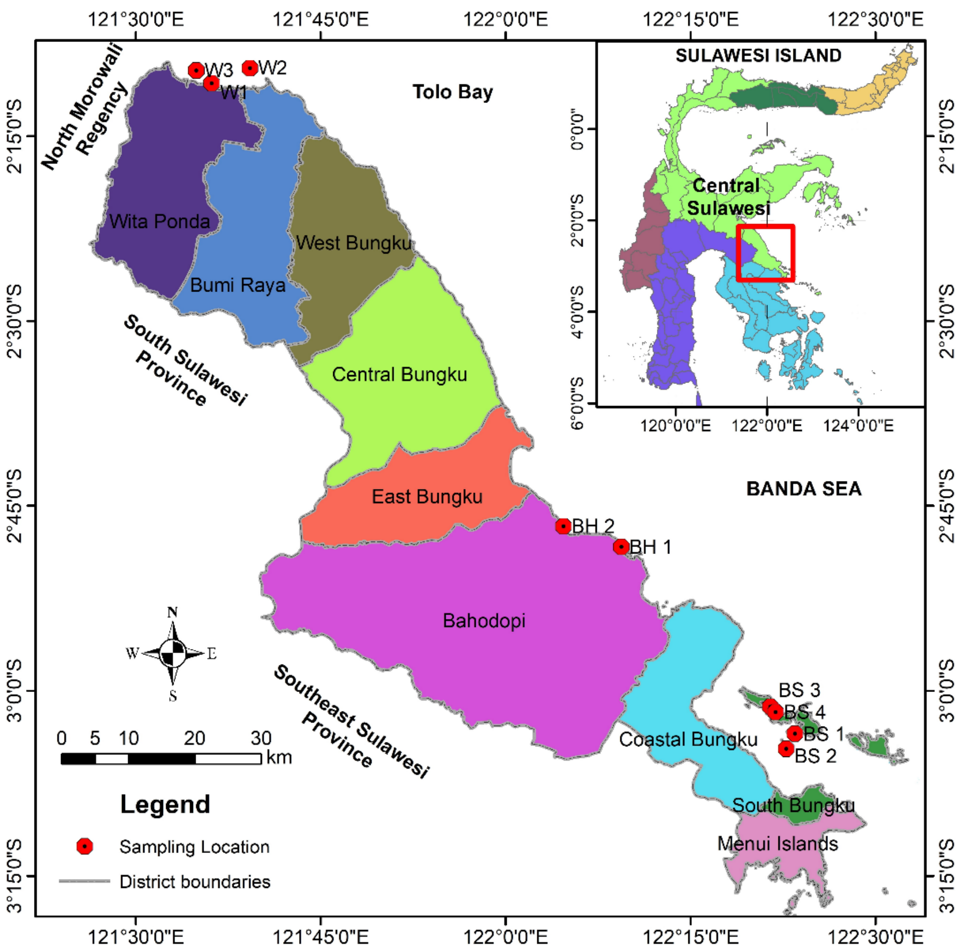


Figure 1. Location of sediment sampling in Morowali Regency, Central Sulawesi, Indonesia.

Table 2. Various pollution index formulas are employed in the current work.

Index	Formula	References
Single indices of pollution		
Geoaccumulation Index (I-geo)	I-geo = $\log_2 \left(\frac{Cn}{1,5 \, x \, Bn}\right)$	Muller (1988); Alharbi *et al.* (2019)
Contamination factor (Cf)	$Cf = \frac{Ci}{Bi}$	Hakanson (1980)); Kumar *et al.* (2022)
Total complex indices		
Contamination degree (Cdeg)	$Cdeg = \sum_{i=1}^{n} Cf$	Mookan *et al.* (2023); Sayom *et al.* (2023)
Pollution load index (PLI)	$PLI = \sqrt[n]{Cf1 \, x \, Cf2 \, x \, Cf3 \, x \ldots Cfn}$	Tomlinson *et al.* (1980); Hossain *et al.* (2021); Asare *et al.* (2022)

Abbreviations: Cn: Concentration of metals in sediment; Bn: Geochemical background value representing the average shale; factor of 1.5 is a correction factor that lithogenic sources may cause; Cf: Contamination factor; Ci: Metal ion concentration in sediment; Bi: The background value of metal concentration in sediments where there is no anthropogenic input; n: The number of analyzed metals; Cdeg: Contamination degree; PLI: Pollution load index.

Table 3. Level of used indices for heavy metals in the current work.

Value	Sediment quality
I-geo ≤ 0	Uncontaminated sediment
0 < I-geo ≤ 1	Uncontaminated to moderately contaminated sediment
1 < I-geo ≤ 2	Moderately contaminated sediment
2 < I-geo ≤ 3	Moderately to heavily contaminated sediment
3 < I-geo ≤ 4	Heavily contaminated sediment
4 < I-geo ≤ 5	Heavy to extremely contaminated sediment
I-geo ≥ 5	Extremely contaminated sediment
Cf < 1	Low
1 ≤ Cf < 3	Moderate
3 ≤ Cf < 6	Considerable high
Cf > 6	Very high
Cdeg < 8	Low
8 < Cdeg < 16	Moderate
16 < Cdeg < 32	Considerable high
Cdeg > 32	High
0 < PLI < 1	Uncontaminated
PLI > 1	Contaminated sediment

Abbreviation: Index geo-accumulation (I-geo), Contamination Factor (Cf), Contamination degree (Cdeg), and Pollution Load Index (PLI).

2.4. Data analysis

Heavy metal concentrations (As, Cr, Hg, Ni, Cd, Cu, Pb, and Sn) were statistically analyzed by determining the minimum, maximum, mean, and standard deviation (SD) values. Zhang et al. [26] employed Pearson correlation analysis and Principal Component Analysis (PCA) with characteristic value rotation to analyze the data and discern the sources of heavy metal contamination in sediments. Statistical analyses were conducted using Minitab 16.0. Additionally, multivariate techniques such as PCA and cluster analysis (CA) have been used to identify pollutant sources and elucidate the relationship between elements. The Varimax rotation method was used to rotate the heavy metals in the sediment as a factor variable. This process reselected the proportion of variance explained by each factor, resulting in a rotated factor loading matrix. Varimax rotation facilitates enhanced differentiation between common factors, thereby improving the interpretation of factor meaning and underlying structure as well as the practical significance of the variables [27].

3. Results and Discussion

3.1. Heavy metals concentration in sediment of morowali regency, central sulawesi

The mean concentrations of heavy metals in the sediment samples were Ni > Pb > Sn > Cu > Cr > Cd > Hg > As. Ni concentration 73.20 + 79.20 mg kg-1; Pb 21.11 + 14.03 mg kg-1; Sn 10.62 + 3.10 mg kg-1; Cu 8.07 + 10.17 mg kg-1; Cr 4.84 + 4.26 mg kg-1; Cd 4.82 + 3.71 mg kg-1; Hg 0.108 + 0.05 mg kg-1; and As 0.023 + 0.005 mg kg-1. The metals Hg, As, Cr, Cu, and Pb met the sediment quality standards according to ANZECC. The metal concentrations of Cd and Ni were above the ISQG value, according to ANZECC and ERL [28]. The concentrations of Hg, As, Cr, Cu, and Pb were still below the background values according to Turekian and Wedepohl [29], except for Cd, Sn, and Ni, whose concentrations were above the BV value of 0.3 mg kg-1, 6.0 mg kg-1, and 68 mg kg-1, respectively. The background values of the heavy metals were established based on the underlying rock makeup and the region's prevalent weathering processes. These values represent typical levels of potentially harmful substances in natural soils without human-induced influence.

The results in Table 4 show that the highest concentrations of the heavy metals Sn and Ni were found in the Bahodapi district, morowali regency, and central sulawesi. At station BH1, the concentration of Sn was 13.94 mg kg-1 and Ni was 161.1 mg kg-1. Meanwhile, at station BH2, Sn and Ni were 17.43 mg kg-1 and 239.37 mg kg-1, respectively, because Bahodapi is a mining and industrial area based on nickel and various derivative industries with an area of + 1,200 ha. This location is also strategic on the international trade route along the coast of central sulawesi and is adjacent to port development plans.

Table 4. Descriptive statistic of metal concentrations (mg kg^{-1}) of sediment samples.

No.	Sampling station	Heavy metals (mg kg^{-1})							
		Hg	As	Cr	Cu	Pb	Cd	Sn	Ni
1	W1	0.151	0.021	3.16	12.01	5.10	1.60	10.3	57.81
2	W2	0.045	0.031	3.28	7.58	10.6	2.08	9.10	57.78
3	W3	0.059	0.031	3.49	3.96	8.86	1.29	8.57	55.51
4	BS1	0.131	0.023	5.97	2.05	10.96	2.04	7.62	72.64
5	BS2	0.075	0.013	2.21	2.49	39.43	9.68	9.64	4.59
6	BS3	0.173	0.023	2.31	1.20	37.33	9.41	9.19	4.75
7	BS4	0.052	0.024	1.94	1.20	38.27	9.76	9.79	4.91
8	BH1	0.132	0.025	5.61	8.95	25.10	4.49	13.94	161.1
9	BH2	0.158	0.022	15.55	33.20	14.37	3.06	17.43	239.37
	Minimum	0.045	0.013	1.94	1.20	5.10	1.29	7.62	4.59
	Maximum	0.173	0.031	15.55	33.20	39.43	9.76	17.43	239.37
	Mean	0.108	0.023	4.84	8.07	21.11	4.82	10.62	73.20
	SD	0.050	0.005	4.26	10.17	14.03	3.71	3.10	79.20
	ISQG-Low[a)]	0.15	20	80	65	50	1.5	-	21
	ERL[b)]	0.15	8.2	81	34	46.7	1.2	-	20.9
	BV[c)]	0.4	13	90	45	20	0.3	6.0	68

a) Interim sediment quality guideline values according to ANZECC (2000).
b) Effect range-low, according to Long et al. [30].
c) Background value by Turekian and Wedepohl [29].

3.2. Contamination indices of sediment

There are many approaches to assess the sediment quality of heavy metal contaminants. The assessment methodologies used in this study included I-geo, Cf, Cdeg, and PLI. The assessment approaches used in this work were the geoaccumulation index, contamination factor, contamination degree, and pollution-load index.

The mean I-geo value of heavy metals at all sediment sampling stations ranges from -10.55 to 4.44. The results showed the following order: Cd > Ni > Sn > Pb > Cu > Hg > Cr > As (Figure 2). The I-geo values for Hg, Cr, Cu, and As were negative (< 0), indicating that the area was not contaminated. In contrast, Pb and Sn suggested that the sampling location was uncontaminated to moderately contaminated. The sampling locations were classified as either not contaminated or moderately contaminated with Sn. Meanwhile, Cd is heavy to highly contaminated, as indicated by the I-geo value. In the Bahodapi District (BH1 and BH2), nickel ore processing industries are spread upstream to downstream, causing high concentrations of Sn and Ni. Wastewater runoff from a coal power plant in the industrial area of Bahodapi pollutes the nearby coast. The disposal of waste makes the water conditions more turbid. The disposal of nickel mining waste into the sea adversely affects marine environments, resulting in reddish discoloration of the water, substantial fish mortality, and elevated levels of heavy metals in sediments, water, and aquatic organisms.

The Contamination Factor (Cf) of cadmium (Cd) metal exceeded that of other heavy metals. Based on the average Cf values, from highest to lowest, Cd > Sn > Ni > Pb > Hg > Cu > Cr > As. The heavy metals Hg, As, Cr, and Cu were in the low-contamination category because their average CF values were < 1. In contrast, Pb, Sn, and Ni were categorized as moderately contaminated with Cf values between 3-6. The sediment category with very high contamination at the sample location was Cd, because the Cf value exceeded 6. The increased presence of Cd metal in the Bahodapi District (BH1 and BH2) has many mining areas and nickel processing industries, whose waste flows and accumulates in the South Bungku sub-district (BS2, BS3, and BS4).

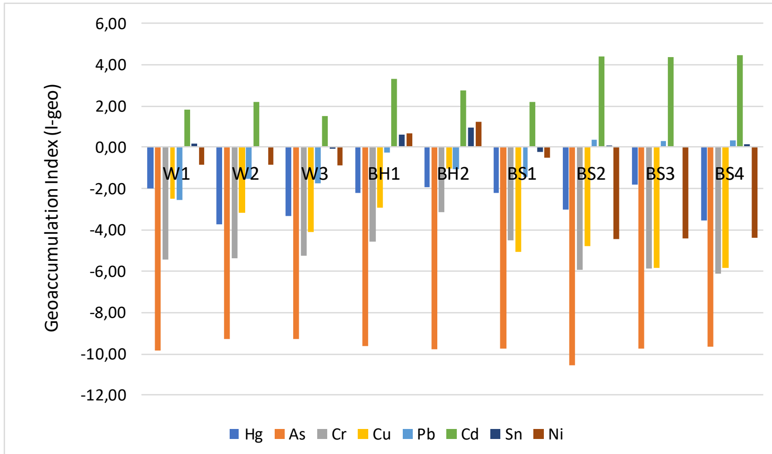


Figure 2. I-Geo value of heavy metals in the sediment sampling location.

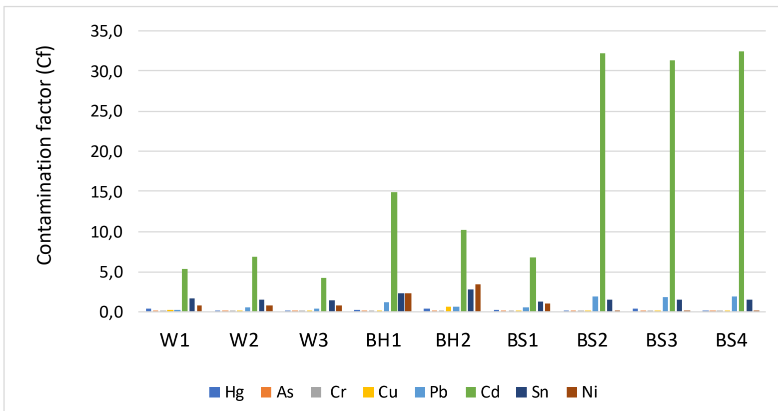


Figure 3. Contamination Factor (CF) of heavy metals in the sampling location.

The integrated contamination index is a multielement approach that is calculated based on a single contamination index. This study used the degree of contamination (Cdeg) values and the pollution load index (Table 5). The degree of contamination (Cdeg) reflects the cumulative impact of various Contamination Factors (CFs), and indicates the overall heavy metal contamination level. We conducted a linear regression analysis between the degree of contamination and concentration of heavy metals in the sediment, as illustrated in Figure 4. Cdeg ranges from 7.26 - 36.33, showing a level of contamination ranging from low to high. The Cdeg value also indicated a low contamination level in sediment samples of 11% (Cdeg < 8), a moderate level of contamination of 33% (Cdeg between 8-16), a considerable contamination level of 22% (Cdeg of 16-32), and a high contamination level because the Cdeg value was > 32 (33%) in South Bungku (BS2, BS3, and BS4). The sediment quality map (degree of contamination) is shown in Figure 6B.

The PLI value was used to ascertain the contamination level of all the observed heavy metals within the sediment samples across the coastal area of the morowali regency. Additionally, we performed a linear regression analysis between the pollution load index and the concentration of heavy metals in the sediment to determine whether the heavy metal concentrations increased with increasing contamination degree and pollution load index, as shown in Figure 5. The PLI value is between 0.18 - 0.53 because the average PLI value is <1, so it can be said that the sediment is uncontaminated with Cr, Cu, Pb, Hg, As, Ni, Sn, and Cd at all sampling locations. A sediment quality map (pollution load index) is shown in Figure 6A.

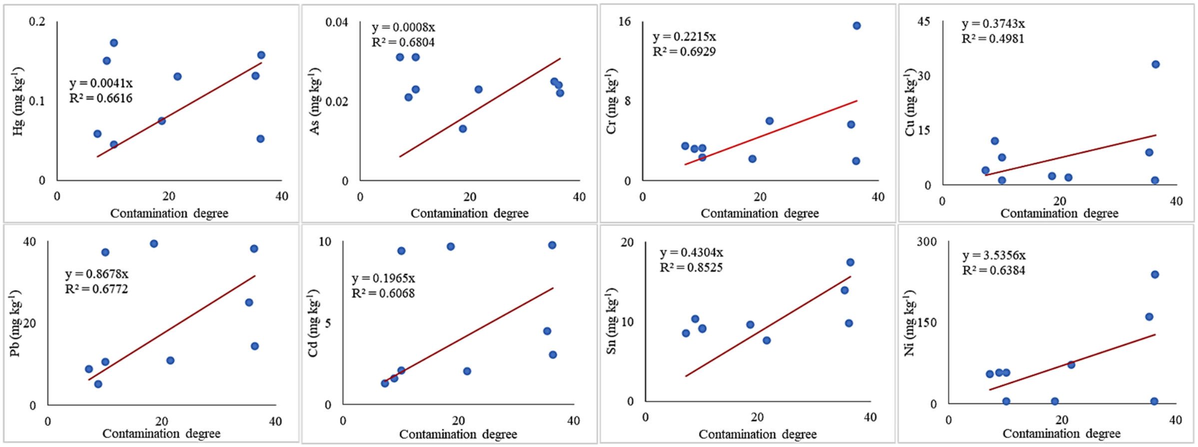


Figure 4. Linear regression analysis for the concentration of heavy metal within contamination degree (a) Hg (b) As (c) Cr (d) Cu (e) Pb (f) Cd (g) Sn (h) Ni.

Table 5. Values of Cdeg and PLI in sampling location.

Sampling station	Cdeg	Classification of Cdeg	PLI	Classification of PLI
W1	8.84	Moderate	0.24	Uncontaminated
W2	10.15	Moderate	0.23	Uncontaminated
W3	7.26	Low	0.20	Uncontaminated
BH1	21.51	Considerable high	0.41	Uncontaminated
BH2	18.65	Considerable high	0.53	Uncontaminated
BS1	10.13	Moderate	0.23	Uncontaminated
BS2	36.18	High	0.19	Uncontaminated
BS3	35.32	High	0.21	Uncontaminated
BS4	36.33	High	0.18	Uncontaminated

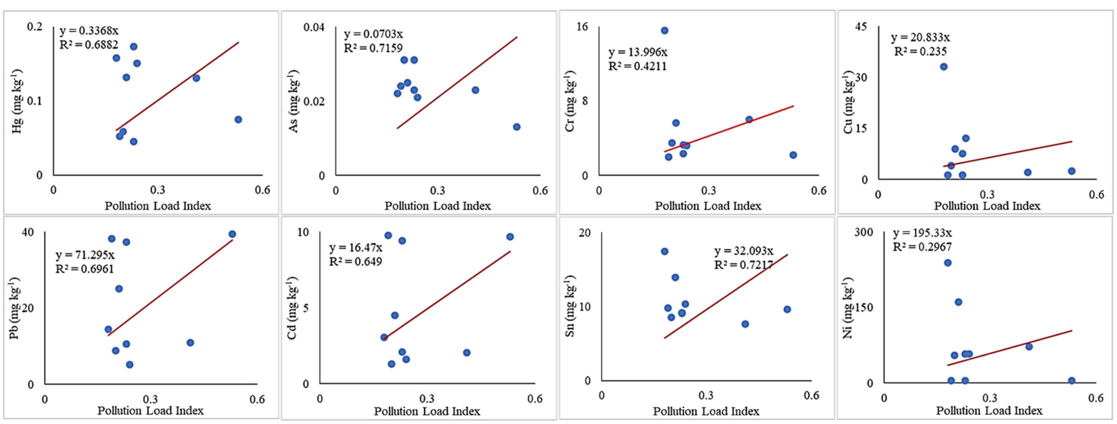
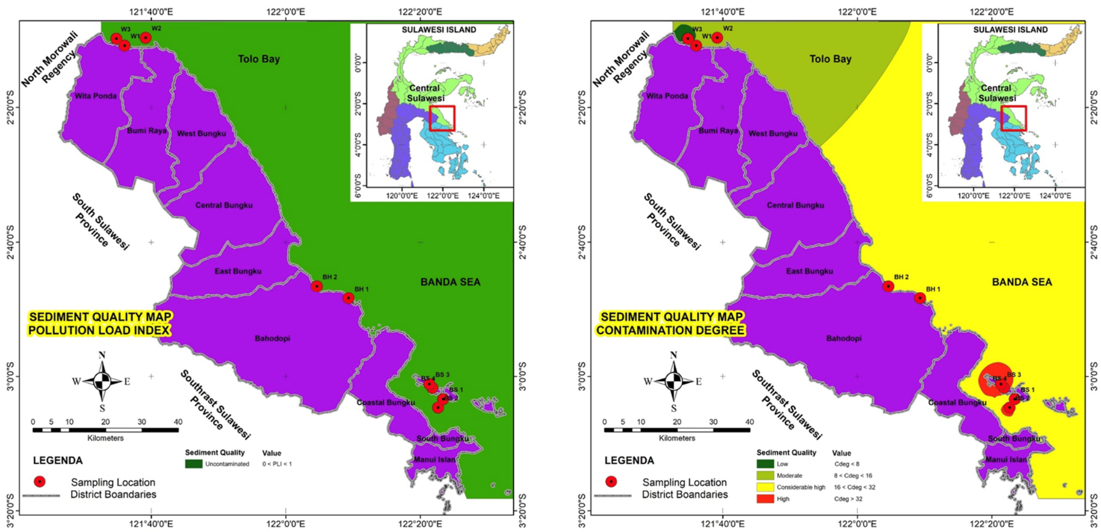


Figure 5. Linear regression analysis for the concentration of heavy metal within pollution load index (a) Hg (b) As (c) Cr (d) Cu (e) Pb (f) Cd (g) Sn (h) Ni.

Based on the findings of Tanjung et al. [31], the heightened operations of agricultural and aquaculture practices, mining industry, and other activities did not exert a significant impact on the contamination levels of heavy metals (Pb, Cu, Hg, and Cd) in the coastal waters of the Mimika Regency. The quality of the ecological environment, influenced by aquaculture, ports, and urban rivers in South Sumatra, also remains safe for environmental risk assessment [32].

3.3. Pearson correlation analysis

The relationship between heavy metals in aquatic sediments provides essential information regarding their sources and pathways [33]. Table 2 presents the outcomes of the Pearson correlation analysis, elucidating the significance level and strength of the correlation among the heavy metal parameters. The p-value indicates the level of significance of the correlation matrix and the strength of the correlation between the parameters. Pearson correlation analysis revealed strong positive correlations between various metal pairs: Cr-Cu (r = 0.908), Cr-Sn (r = 0.818), Cr-Ni (r = 0.915), Cu-Sn (r = 0.878), Cu-Ni (r = 0.869), Pb-Cd (r = 0.985), and Sn-Ni (r = 0.82) at a 99% confidence level. Such solid and positive correlations suggest a shared source of pollutants, that is, heavy metals, across sediment samples from several locations. Multivariate analysis with PCA was used to elucidate intricate interconnections among the metals.



A **B**

Figure 6. Sediment quality map in morowali regency, central sulawesi, Indonesia; (A) Pollution load index and (B) contamination degree.

Table 6. Matrix of Pearson's correlation for the several metal concentrations.

Heavy metals	Hg	As	Cr	Cu	Pb	Cd	Sn	Ni
Hg	1							
As	-0.327	1						
Cr	0.441	-0.031	1					
Cu	0.406	-0.043	0.908**	1				
Pb	-0.073	-0.497	-0.334	-0.389	1			
Cd	-0.061	-0.537	-0.367	-0.388	0.985**	1		
Sn	0.417	-0.143	0.818**	0.878**	-0.033	-0.084	1	
Ni	0.415	0.115	0.915**	0.869**	-0.414	-0.489	0.872**	1

**Correlation of significance at the 0.01 level

3.4. Multivariate statistical analysis

Principal Component Analysis (PCA) was employed to identify the main components associated with the present sources in the sediment samples from several locations in the morowali regency. PCA was adopted for feature extraction to analyze the metal element parameters of the sediments [26, 34]. The factor extraction results with rotation were easier to describe. Therefore, the varimax rotation method was applied to the extracted matrix to enhance its interpretability and scientific relevance. This approach facilitates a more precise understanding of the results and improves their utility for scientific interpretation.

The PCA results showed that the two components had eigenvalues greater than 1.0, explaining 81.1% of the data variance. The two components, namely the first component (F1) and second component (F2), have eigenvalues of 4,236 and 2,249, respectively. If there is an eigenvalue less than one, components such as F3-F8 cannot explain the variable well; therefore, they are not included in the formation of the variable. These two components summarize the main factors that shape the distribution of heavy metals in the sediments.

These components also help identify the primary sources of heavy metals in sediments. F1 accounted for 52.9% of the total variance in both the components, whereas F2 accounted for 28.1% (Table 3). PCA results obtained by applying varimax rotation to the elements and their components. The factor loadings of the PCA were categorized as strong, moderate, or weak based on loading values > 0.75, range 0.75-0.50, or range 0.50-0.30 [35]. F1 contributed 49.2% of the total variance and contained parameters in the strong category, namely, Cr, Cu, Sn, and Ni, with values of 0.930, 0.929, 0.932, and 0.910, respectively. Hg was also included in the F1 component, with a loading value in the medium category (0.608).

The metals included in PC1, namely Cr, Cu, Sn, Ni, and Hg, originated from the same source as the natural geological background. The morowali regency has five mineral resource commodities that have the potential to be superior: nickel, chromite, marble/limestone, manganese, and iron ore. Laterite nickel ore is a typical mineral resource associated with many metals, particularly Mn, Co, Fe, Mg, and Ni [36]. In addition, in the morowali regency, there are many nickel mining locations and nickel ore processing industries [12], as well as aquaculture activities such as seaweed cultivation, which use chemical fertilizers to support its growth and pesticides to prevent disease/pathogens [29], which cause heavy metal contamination in the area.

The F2 contributed 28.1% of the total variance. Pb and Cd strongly influenced the F2 component, with values of 0.919 and 0.934, respectively, as the metal negatively affected F2 at 0.778. Pb and Cd showed opposite relationships with As. These three elements originate from anthropogenic sources, such as industry and mining, agriculture and aquaculture activities, ports, and household waste. Mining operations near the sea are often linked to doctors and ports. Activities that cause environmental pollution, such as shipbuilding, ship traffic, and ship pollution, are usually conducted in port areas. Heavy metal levels in sediments usually occur because of accumulation from deposition and dilution processes, which are influenced by tidal current patterns.

Table 7. Explanation of total variance and PCA matrix.

Explanation of total variance						
Component	Initial eigenvalues			Square loading rotation sums		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative %
1	4.2357	52.9	52.9	3.9374	49.2	49.2
2	2.2492	28.1	81.1	2.5475	31.8	81.0
3	0.8168	10.2	91.3			
4	0.4408	5.5	96.8			
5	0.1338	1.7	98.5			
6	0.1209	1.5	100			
7	0.0020	0.0	100			
8	0.0009	0.0	100			

Matrix of component			The matrix of components rotated		
	F1	F2		F1	F2
Hg	0.487	0.412	Hg	0.608	0.191
As	0.106	-0.799	As	-0.212	-0.778
Cr	0.932	0.184	Cr	0.930	-0.191
Cu	0.939	0.166	Cu	0.929	-0.211
Pb	-0.543	0.769	Pb	-0.203	0.919
Cd	-0.577	0.771	Cd	-0.234	0.934
Sn	0.828	0.436	Sn	0.932	0.081
Ni	0.962	0.061	Ni	0.910	-0.316

a >Method of extraction: PCA

B Method of rotation: Varimax with Kaiser normalization

CA has been widely used to monitor aquatic environments in coastal areas, lakes, reservoirs, and river basins [37, 38]. This CA provides a good overview of the efficient and effective design of observation locations according to the water characteristics of all research locations.

CA was employed to assess the similarity levels among groups of aquatic environmental characteristics at nine sediment sampling locations. According to the dendrogram generated from the CA results, the nine sampling locations were classified into two clusters (Figure 7). Cluster 1 consisted of seven sampling locations (1-3, and 6-9), namely W1, W2, W3, BS1, BS2, BS3, and BS4, which are areas in Witaponda, Bumiraya, and South Bungku Districts. This cluster describes coastal regions, which from a fisheries and marine perspective, include ports, ponds, mariculture activities, and fish auction sites. Morowali regency's seaweed production covers the Witaponda, South Bungku, and Menui Islands [39]. South Bungku is designated a Minapolitan area and a buffer area (hinterland) with seaweed (Kappaphycus alvarezii) as a commodity.

Cluster 2 consisted of sampling locations 4 and 5 and BH1 and BH2. This cluster area is included in the Bahodapi sub-district, which is a nickel mining and industrial area. Hasnia et al. [21] reported that the damage caused by nickel ore mining in the Bahodapi Sub-district, Morowali Regency, was in the severe damage category for abiotic and biotic components. Mining industrial areas close to coastal waters causes heavy metals from piles of topsoil, overburden, and saprolite, which are easily eroded by rainwater and wind, transported to coastal waters, and then settled in river estuaries and the seabed.

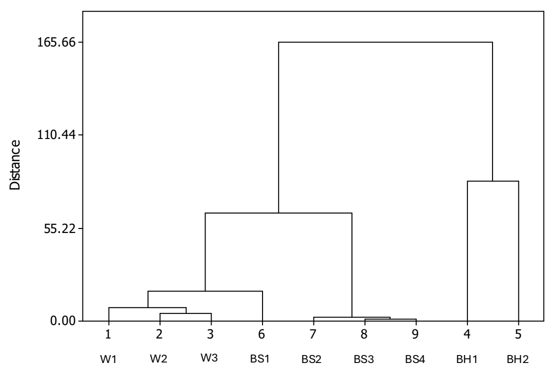


Figure 7. The dendrogram shows the clustering.

The high Ni and Sn contents in this study were the result of the spread of the nickel mining industry in the Bahodapi area. The Ni content of bottom sediments in Fatufia Village, Bahodapi Sub-district, Morowali District, Central sulawesi, is 778 - 1564 µg/g because the sampling location is close to the end of the port, which is a place for storing and transporting nickel to ships. The high Ni concentration in the sediment is also caused by the condition of the area, which is quite calm, relatively closed, and close to the nickel ore reservoirs.

3.5. Implications for environmental risk and policy-making

These results suggest that the presence of heavy metal contamination in sediments of the morowali regency is at certain levels of severity. However, adopting these findings in policy applications is only possible with a complete environmental risk assessment. Environmental Risk Assessment (ERA) is a very important area in the sustainable management of the environment as it is intended to assess in much detail possible threats posed by heavy metals to ecosystems, human health, and socioeconomic activities [2,40]. The absence of a detailed risk evaluation significantly reduces the likelihood of policymakers adopting focused and effective mitigation methods [41].

Bioavailability assessments carry out toxicity assessments of heavy metals and are major elements for determining their actual environmental impact [7, 42]. Even though the Pollution Load Index (PLI) and Contamination degree (Cdeg) provide some insight into contamination levels, neither of these indicators allows biological uptake and eventual accumulation in the organisms inhabiting the ocean to be accounted for. Therefore, future research should integrate sediment quality guidelines (SQGs) to determine if their heavy metal concentrations are above the thresholds considered safe for the environment, and phytoremediation strategies should be used to mitigate the effects of contamination [43].

From a more appealing policy perspective, pollution source identification through multivariate statistical analysis, particularly principal component analysis (PCA) and cluster analysis (CA), shows great potential for obtaining insightful information on anthropogenic inputs into heavy metal contamination [44]. Identifying sources alone does not help establish effective environmental governance. This goes beyond risk-based regulatory framework integration into resource management for sustainable practices. According to recent studies, artificial intelligence (AI) has been used for pollution monitoring and remediation in green mining, which is gaining attention [45]. Real-time environmental monitoring and decision-making can be facilitated by the use of AI-driven models that have demonstrated efficacy in forecasting the spatial distribution of heavy metal contamination in mining regions. This is the case of the latest study towards which most current literature delves into the green aspect of mining, where Artificial Intelligence (AI) can be applied for pollution monitoring and remediation in the morowali regency [43].

This is reflected in the nickel mines and industries, which are also seen as pollutants in the addition of heavy metals to the annals. Morowali regency's nickel mines and associated industries are a major source of heavy metal pollution, underscoring the necessity of stringent environmental laws, effective waste management plans, and sustainable land-use policies [46]. The adoption of multi-criteria decision-making (MCDM) methods will expose ground stakeholders to trade-offs against the environment and direct them toward sustainable alternatives for resource use [47, 48]. Efforts must also be made to Strengthen Corporate social Responsibility (CSR) frameworks to ensure that mining industries actively contribute to the sustainability of ecosystems and the welfare of communities, in which they operate [49].

Awareness-raising campaigns on the adverse effects and mitigation strategies regarding heavy metals can enhance cooperative efforts between local communities, industry, and policymakers [50-52]. In summary, while this work represents a necessary baseline contribution toward comprehending heavy metal contamination in coastal sediments, the consideration of advanced environmental risk assessment methods along with sustainable development paradigms will make this research more relevant to policymakers. Pollions might deploy evidence-based strategies to mitigate environmental risks and achieve sustainable development in the morowali regency using these advanced technologies in green mining, phytoremediation, and the establishment of resilient regulatory frameworks.

4. Conclusions

This research provides information on heavy metal concentrations, assessment of contamination levels, and possible sources in sediment samples collected in the morowali regency, central sulawesi, Indonesia. The Hg, As, Cr, Cu, and Pb concentrations were still below the guideline values for the sediment quality. Based on the accumulation index value, the sediment sampling area was uncontaminated for Hg, Cr, Cu, and As; the categories were uncontaminated to moderately contaminated for Sn and Ni and moderate to highly contaminated for Cd. The Cf value shows that the sediment had low contamination for Hg, As, Cr, and Cu, moderate contamination (Sn, Ni, and Pb), and high Cd contamination. Cdeg sediments ranged from low to high levels of contamination. A pollution load index (PLI) value below 1 indicated that the sediment remained uncontaminated with heavy metals (Hg, As, Cr, Pb, Cu, Cd, Ni, and Sn) across all sampling locations. Furthermore, results from the multivariate analysis (PCA, CA, and matrix of Pearson correlation) show that heavy metals, such as Hg, Cr, Cu, Sn, and Ni, originate from natural geological sources. Three elements (Pb, Cd, and As) originate from industry, mining, agriculture and aquaculture activities, ports, and household waste.

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References

[1]. Pouresmaieli, M., Qarahasanlou, A. N., & Ataei, M. (2024). An evolution in sustainable development: Integrating new semi-quantitative assessment model with strategic management (Insights from the mineral sector). *Case Studies in Chemical and Environmental Engineering, 10*, 100983.

[2]. Pouresmaieli, M., Ataei, M., Forouzandeh, P., Azizollahi, P., & Mahmoudifard, M. (2022). Recent progress on sustainable phytoremediation of heavy metals from soil. *Journal of Environmental Chemical Engineering, 10*(5), 108482.

[3]. Selamoglu, Z. (2011). Orun, I., Talas ZS, Alkan, A. Modulating Effect of Selenium on Gills of Fish Exposed to Heavy Metals. *Fresenius Environmental Bulletin, 20*(1), 104-108.

[4]. Saadat, S. (2022). Evaluating a Sediment Pollution using Contamination Indices and Risk Assessment in Mineralized Zones, Eastern Iran. *Journal of Mining and Environment, 13*(4), 1239-1253.

[5]. Ghadimi, F., Hajati, A., & Sabzian, A. (2020). Assessment of heavy metal contamination in waters due to mineral salts company from Mighan playa/lake, Arak, Iran. *Journal of Mining and Environment, 11*(1), 171-184.

[6]. Caglar, M., Canpolat, O., & Selamoglu, Z. (2019). Determination of some heavy metal levels in three freshwater fish in Keban Dam Lake (Turkey) for public consumption. *Iranian Journal of Fisheries Sciences, 18*(1), 188-198.

[7]. Salehi, S., Pouresmaieli, M., & Qarahasanlou, A. N. (2025). A sustainable way to prevent oral diseases caused by heavy metals with phytoremediation. *Case Studies in Chemical and Environmental Engineering*, 101106.

[8]. Luo, Y. and Jia, Q. (2021). Pollution and risk assessment of heavy metals in the sediments and soils around Tiegelongnan copper deposit, Northern Tibet, China. *Journal of Chemistry, 2021*(1), 8925866.

[9]. Saidon NB, Szabó R, Budai P, Lehel J. (2024). Trophic transfer and biomagnification potential of

environmental contaminants (heavy metals) in aquatic ecosystems. *Environmental pollution, 340*, 122815.

[10]. Orun, I., Talas, Z. S., Ozdemir, I., Alkan, A., & Erdogan, K. (2008). Antioxidative role of selenium on some tissues of (Cd2+, Cr3+)-induced rainbow trout. *Ecotoxicology and Environmental Safety, 71*(1), 71-75.

[11]. Talas, Z. S., Orun, I., Ozdemir, I., Erdogan, K., Alkan, A., & Yılmaz, I. (2008). Antioxidative role of selenium against the toxic effect of heavy metals (Cd+ 2, Cr+ 3) on liver of rainbow trout (Oncorhynchus mykiss Walbaum 1792). *Fish Physiology and Biochemistry, 34*, 217-222.

[12]. Syarifuddin, N. (2022). The influence of the nickel mining industry on maritime environmental conditions in Morowali Regency. *Jurnal Riset & Teknologi Terapan Kemaritiman, 1*, 19-23.

[13]. Zhang, S., Fu, K., Gao, S., Liang, B., Lu, J., and 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).

[14]. Sevindik, M., Akgül, H., Bal, C., & Selamoglu, Z. (2018). Phenolic contents, oxidant/antioxidant potential and heavy metal levels in Cyclocybe cylindracea. *Indian Journal of Pharmaceutical Education and Research, 52*(3).

[15]. Selamoglu Talas, Z., Pinar Dundar, S., Fuat Gulhan, M., Orun, I., & Kakoolaki, S. (2012). Effects of propolis on some blood parameters and enzymes in carp exposed to arsenic. *Iranian Journal of Fisheries Sciences, 11*(2), 405-414.

[16]. Orun, I., & Selamoglu Talas, Z. (2008). Antioxidative role of sodium selenite against the toxic effect of heavy metals (Cd+2, Cr+3) on some biochemical and hematological parameters in the blood of rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792). *Iranian Journal of Fisheries Sciences, 17*(4): 1242-1246.

[17]. Ates, B., Orun, I., Talas, Z. S., Durmaz, G., & Yilmaz, I. (2008). Effects of sodium selenite on some biochemical and hematological parameters of rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) exposed to Pb 2+ and Cu 2+. *Fish physiology and biochemistry, 34*, 53-59.

[18]. Sevindik, M., Akgül, H., Bal, C., & Selamoglu, Z. (2018). Determination of antioxidant, antimicrobial, DNA protective activity and heavy metals content of *Laetiporus sulphureus*. 1946-1952.

[19]. Sevindik, M., Akgül, H., Bal, C., & Selamoglu, Z. (2018). Determination of antioxidant, antimicrobial, DNA protective activity and heavy metals content of *Laetiporus sulphureus*. DNA 25: 26.

[20]. Sevindik, M., Rasul, A., Hussain, G., Anwar, H., Zahoor, M. K., Sarfraz, I., & Selamoglu, Z. (2018). Determination of antioxidative, antimicrobial activity, and heavy metal contents of Leucoagaricus leucothites. *Pakistan journal of pharmaceutical sciences.*

[21]. Hasnia, Gunawan, T. and Herumurti, S. (2019). Research of environmental damage due to nickel mining activity in Bahodopi District, Morowali Regency, Central Sulawesi Province. *Globethics Net*, 0-12.

[22]. El-Amier, Y. A., Bonanomi, G. and Abd-ElGawad, A. M. (2023). Assessment of heavy metals contamination and ecological risks in coastal sediments of the Mediterranean seashore. *Regional Studies in Marine Science, 63*, 103017.

[23]. Statistic Regency of Morowali. (2023). Morowali Regency in figure 2023. Statistic of Morowali Regency.

[24]. Statistic Regency of Morowali. (2023). Morowali Regency in figure 2023. Statistic of Morowali Regency.

[25]. Kumar, V. V., Rimjhim, S., Garagu, A. S., Valappil, N. N. and Rakhavan, P. R. (2022). Heavy metal contamination, distribution, and source apportionment in the sediments from Kavvayi Estuary, southwest coast of India. *Total Environment Research Themes, 3*, 100019.

[26]. Zhang, Z., Juying, L. and Mamat, Z. (2016). Sources identification and pollution evaluation of heavy metals in the surface sediments of Bortala River, Northwest China. *Ecotoxicology and environmental safety, 126*, 94-101.

[27]. Li, W., Zhang, S., Gao, F., Chen, Z., Jiang, J. and Sun, G. X. (2024). Spatial distribution, sources apportionment, and risk assessment of heavy metals in the Changchun black soil area, China. *Journal of Hazardous Materials Advances, 13*, 100402.

[28]. Vu, C. T., Lin, C., Shern, C. C., Yeh, G., Le, V. G., & Tran, H. T. (2017). Contamination, ecological risk and source apportionment of heavy metals in sediments and water of a contaminated river in Taiwan. *Ecological indicators, 82*, 32-42.

[29]. Long, E. R., Macdonald, D. D., Smith, S. L. and Calder, F. D. (1995). Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental management, 19*, 81-97.

[30]. Turekian, K. K. and Wedepohl, K. H. (1961). Distribution of the Elements in Some Major Units of the Earth's Crust. *Geological society of America bulletin, 72*(2), 175-192.

[31]. Tanjung, R. H. R., Hamuna, B. and Yonas, M. N. (2019). Assessing heavy metal contamination in marine sediments around the coastal waters of Mimika Regency. *Journal of Ecological Engineering, 20*(11).

[32]. Rozirwan, Az-Zahrah SAF, Khotimah NN, Nugroho RY, Putri WAE, Fauziyah, Melki, Agustini 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 Sumatera. *Journal of Ecological Engineering, 25*(1), 303-319.

[33]. Astatkie, H., Ambelu, A. and Mengistie, E. (2021). Contamination of stream sediment with heavy metals in the Awetu Watershed of Southwestern Ethiopia. *Frontiers in Earth Science, 9*, 658737.

[34]. Xu, M., Wang, R., Yang, X. and Yang, H. (2020). Spatial distribution and ecological risk assessment of heavy metal pollution in surface sediments from shallow lakes in East China. *Journal of geochemical exploration, 213*, 106490.

[35]. Çil, E. A., Uncumusaoğlu, A. A., Ergen, Ş. F. and Gürbüzer, P. (2023). Evaluation of water and sediment quality of İnaltı Cave (Northern Türkiye) by using multivariate statistical methods. *Environmental monitoring and assessment, 195*(6), 667.

[36]. Gao, J., Du, Z., Ma, S., Cheng, F. and Li, P. (2021). High-efficiency leaching of valuable metals from saprolite laterite ore using pickling waste liquor for the synthesis of spinel-type ferrites MFe2O4 with excellent magnetic properties. *Journal of Materials Research and Technology, 10*, 988-1001.

[37]. Nguyen, T. G. and Huynh, T. H. N. (2022). Assessment of surface water quality and monitoring in southern Vietnam using multicriteria statistical approaches. *Sustainable Environment Research, 32*(1), 20.

[38]. El-Rawy, M., Fathi, H., Abdalla, F., Alshehri, F. and Eldeeb, H. (2023). An integrated principal component and hierarchical cluster analysis approach for groundwater quality assessment in Jazan, Saudi Arabia. *Water, 15*(8), 1466.

[39]. Ya'la, Z. R. (2008). Seaweed Development Prospects. Universitas Tadulako. 15(2), 144-148 P.

[40]. Pouresmaieli, M., Ataei, M., & Qarahasanlou, A. N. (2023). A scientometrics view on sustainable development in surface mining: Everything from the beginning. *Resources policy, 82*, 103410.

[41]. Sakizadeh, M., Sattari, M. T., & Ghorbani, H. (2017). A new method to consider spatial risk assessment of cross-correlated heavy metals using geo-statistical simulation. *Journal of Mining and Environment, 8*(3), 373-391.

[42]. Safari Sinegani, S., Abedi, A., Asghari, H., & Safari Sinegani, A. A. (2015). *Using Trifolium alexandrinum* for phytoremediation of some heavy metals in tailings dam in Anjir-Tange coal washing plant, Mazandaran, Iran. *Journal of Mining and Environment, 6*(2), 141-150.

[43]. Pouresmaieli, M., Boroumand, Y., Habibi, M., Maleki, R., Ataei, M., & Qarahasanlou, A. N. (2025). Green mining with artificial intelligence: A path to sustainability. *Artificial Intelligence in Future Mining,* 309-354.

[44]. Otari, M., & Dabiri, R. (2015). Geochemical and environmental assessment of heavy metals in soils and sediments of Forumad Chromite mine, NE of Iran. *Journal of Mining and Environment,* 251-261.

[45]. Bayatzadeh Fard, Z., Ghadimi, F., & Fattahi, H. (2017). Use of artificial intelligence techniques to predict distribution of heavy metals in groundwater of Lakan lead-zinc mine in Iran. *Journal of Mining and Environment*, *8*(1), 35-48.

[46]. Ifelola, O. E. (2019). Evaluation of background geochemical speciation of heavy metals in overburden topsoil of bituminous sand deposit area, Ondo state, Nigeria. *Journal of Mining and Environment*, *10*(4), 869-882.

[47]. Pouresmaieli, M., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2024). Building ecological literacy in mining communities: A sustainable development perspective. *Case Studies in Chemical and Environmental Engineering, 9*, 100554.

[48]. Tabasi, S., Hassani, H., & Azadmehr, A. R. (2018). Field study on Re and heavy metal phytoextraction and phytomining potentials by native plant species growing at Sarcheshmeh copper mine tailings, SE Iran. *Journal of Mining and Environment*, *9*(1), 183-194.

[49]. Pouresmaieli, M., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2024). Corporate social responsibility in complex systems based on sustainable development. *Resour. Policy*, *90*, 104818.

[50]. Pouresmaieli, M., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2024). Multi-criteria decision-making methods for sustainable decision-making in the mining industry (A comprehensive study). *Journal of Mining and Environment, 15*(2), 683-706.

[51]. Zendelska, A., Trajanova, A., Golomeova, M., Golomeov, B., Mirakovski, D., Doneva, N., & Hadzi-Nikolova, M. (2022). Comparison of efficiencies of neutralizing agents for heavy metal removal from acid mine drainage. *Journal of Mining and Environment*, *13*(3), 679-691.

[52]. Dabiri, R., Bakhshi Mazdeh, M., & Mollai, H. (2017). Heavy metal pollution and identification of their sources in soil over Sangan iron-mining region, NE Iran. *Journal of Mining and Environment*,*8*(2), 277-289.

ارزیابی آلودگی فلزات سنگین در رسوبات ساحلی ناشی از فعالیت‌های استخراج نیکل در منطقه مورووالی، سولاوسی مرکزی، اندونزی

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چکیده:

این کار برای تعیین غلظت فلزات سنگین در رسوبات انجام شد. ارزیابی سطح آلودگی با استفاده از یک شاخص آلودگی و شناسایی منابع بالقوه آلودگی فلزات سنگین با استفاده از تجزیه و تحلیل چند متغیره. این کار از شاخص‌های آلودگی برای ارزیابی سطوح آلودگی رسوبی استفاده کرد. غلظت فلزات سنگین با تعیین مقادیر حداقل، حداکثر، میانگین و انحراف استاندارد (SD) مورد تجزیه و تحلیل آماری قرار گرفت. با توجه به فاکتور آلودگی (Cf)، کادمیوم سطوح آلودگی بسیار بالایی را نشان داد، در حالی که Ni ،Sn و Pb آلودگی متوسط را نشان دادند. As ،Hg، Cr و Cu به عنوان دارای سطوح آلودگی پایین طبقه بندی شدند. درجه آلودگی (Cdeg) از کم تا زیاد در سراسر سایت‌های نمونه‌برداری شده متغیر بود که منعکس کننده سطوح مختلف شدت آلودگی است. تجزیه و تحلیل های آماری چند متغیره، از جمله تجزیه و تحلیل اجزای اصلی (PCA)، ماتریس همبستگی پیرسون، و تجزیه و تحلیل خوشه ای (CA)، برای شناسایی منابع بالقوه آلودگی فلزات سنگین استفاده شد. مس، قلع، نیکل، جیوه و کروم به فرآیندهای زمین‌شناسی طبیعی نسبت داده می‌شوند، در حالی که سرب، کادمیوم، و As به فعالیت‌های انسانی مرتبط هستند که احتمالاً از صنعت معدن نیکل نشات می‌گیرند. در نتیجه، این کار بر تأثیر زیست محیطی پیچیده استخراج نیکل در Morowali تأکید می کند و نیاز به شیوه های مدیریت زیست محیطی سختگیرانه برای کاهش تخریب بیشتر و حفاظت از اکوسیستم های ساحلی در سولاوسی مرکزی را برجسته می کند..

کلمات کلیدی: شاخص آلودگی، فلزات سنگین، تجزیه و تحلیل چند متغیره، استخراج نیکل، رسوب.