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EVALUATION OF HEAVY METAL POLLUTION IN SEDIMENTS OF THE SELANGOR RIVER, MALAYSIA

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Abstract

This study aimed to assess the pollution levels of heavy metals in river sediments collected from ten locations within the Pasir Penambang area in Selangor, which is known for its intensive economic and marine-related activities. The concentrations of Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), and Zinc (Zn) were determined using an Energy Dispersive X-ray Fluorescence (EDXRF) spectrometer. The average concentrations of these metals in the sediments were recorded as follows: Cr (62.46 mg/kg), Cu (21.16 mg/kg), Ni (30.48 mg/kg), Pb (26.77 mg/kg), and Zn (103.54 mg/kg). Pollution levels were evaluated using the Index of Geoaccumulation (I_{geo}), Enrichment Factor (EF), Contamination Factor (CF), and Pollution Load Index (PLI). Results indicated that the sediments were generally classified as uncontaminated to moderately contaminated, primarily with respect to Pb and Zn. EF analysis indicated minor enrichment for Cr, no to minor enrichment for Cu, moderate enrichment for Zn, and significant enrichment for Ni and Pb. CF and PLI values further supported the presence of low overall pollution levels, with minor pollution observed at a few locations in proximity to aquaculture activities. The elevated concentrations of Pb and Zn, together with the significant enrichment of Ni and Pb, suggest localized anthropogenic influence and highlight the need for continued environmental monitoring. These findings highlight the need for targeted pollution control measures and long-term sediment monitoring programs.

Keywords: Heavy metal, sediment, Selangor river, pollution, EDXRF

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Introduction

Selangor River is the third largest river basin in Selangor, stretching approximately 110 km from Fraser's Hill to the coast of Kuala Selangor. It serves as a major source of raw water for domestic, industrial, and irrigation purposes and plays a vital role in supporting regional socio-economic development (Bahar, 2022). Due to its strategic importance, disruptions to the river's water supply may affect commercial, residential, and industrial properties valued at approximately RM 459.04 billion. The basin continues to face increasing pressure from pollution, urbanisation, and water supply demands, highlighting the need for effective river basin management (Raihan et al., 2023; Farid Ahmed et al., 2023).

Kuala Selangor is one of the ten sub-basins of the Selangor River. In Pasir Penambang, Kuala Selangor, the river is surrounded by fisheries-related activities, including fishing, wet markets, boating, and jetties. These economic activities may contribute to river degradation through the discharge of pollutants originating from domestic, commercial, and industrial sources (Lim et al., 2021; Omar et al., 2022; Othman et al., 2018; Rahim & Kasmuri, 2020). Despite the numerous activities taking place on and around the Selangor River, monitoring sediment contamination is essential because river sediments act

as both a sink and a secondary source of heavy metals, reflecting the long-term accumulation of contaminants in aquatic environments (Förstner & Salomons, 1980; Wang et al., 2025).
Heavy metals accumulated in sediments may subsequently be taken up by benthic organisms and transferred through the aquatic food web via bioaccumulation, posing potential ecological and human health risks (Copaja et al., 2023; Nnaji et al., 2023). Furthermore, contaminated sediments may release accumulated heavy metals back into the water column when disturbed by hydrological processes or anthropogenic activities, thereby deteriorating river water quality and threatening aquatic ecosystems (Liu et al., 2023; Wang et al., 2025). Therefore, continuous monitoring of sediment quality is essential for understanding long-term pollution trends and supporting effective river basin management in the Selangor River.

Pollution assessment methods commonly used to evaluate sediment contamination include the Geoaccumulation Index (I_{geo}), Enrichment Factor (EF), Contamination Factor (CF), and Pollution Load Index (PLI) (Hakanson, 1980; Muller, 1969). Therefore, this study aimed to evaluate the pollution levels of heavy metals in the sediments of the Selangor River using these pollution assessment indices. The findings will help identify potential sources of heavy metal contamination and provide scientific evidence to support pollution control strategies, river basin management, and long-term environmental monitoring in the Selangor River.

Materials and Methods

Sampling location and sample collection

Pasir Penambang is a district comprising fishing villages, commercial areas, fishing jetties, small-scale aquaculture farms, seafood wet markets, food stalls, and residential settlements. Located within the downstream estuarine zone of the Selangor River, the area is influenced by cumulative pollutant inputs transported from upstream catchments as well as local anthropogenic activities. Therefore, ten (10) sampling points were strategically selected to provide representative spatial coverage of the study area, encompassing the dominant land-use characteristics and potential pollution sources, including estuarine zones, aquaculture areas, fishing jetties, fish landing facilities, commercial areas, and seafood processing activities. The sampling locations were selected based on field reconnaissance and the surrounding land-use characteristics to evaluate the spatial variation of heavy metal accumulation in river sediments.

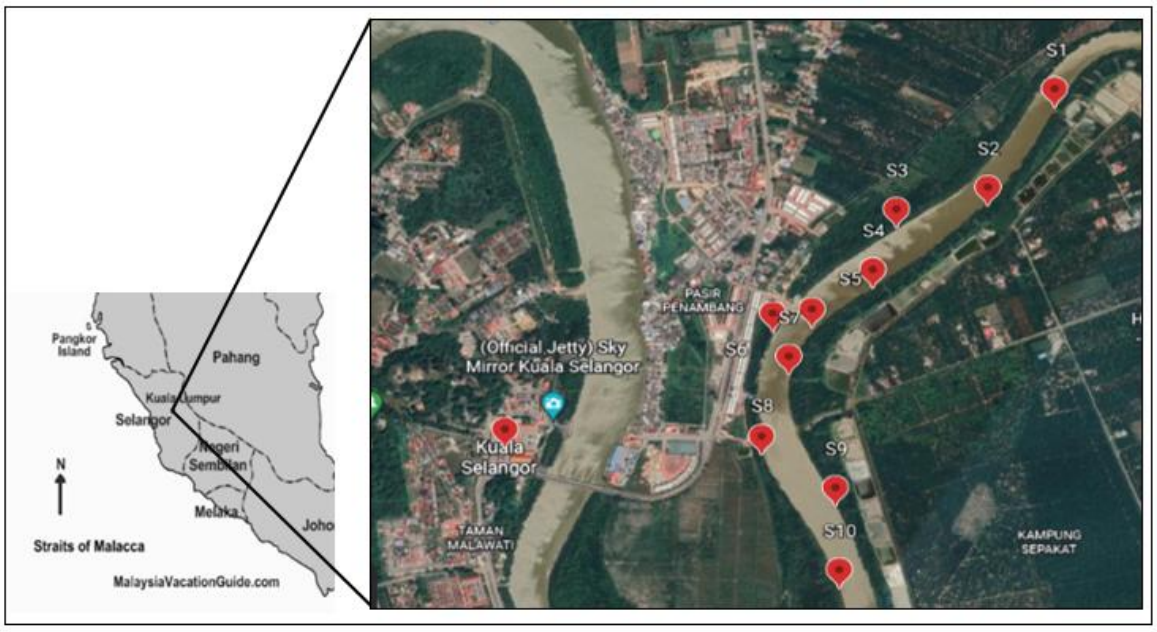


Figure 1. Location of sampling points in the Pasir Penambang area.
(Source: Google Earth, 2024)

Table 1 presents the coordinates and descriptions of the ten sampling locations selected in this study.

Surface sediment samples were collected using a grab sampler from a depth of approximately 5–10 cm below the riverbed surface. The samples were transferred into clean polyvinyl chloride (PVC) containers to minimise contamination during transportation to the laboratory for subsequent preparation and analysis. Sampling was conducted along an approximately 500 m stretch of the river, with adjacent sampling stations located at intervals of about 50 m to ensure representative spatial coverage of the study area. A Global Positioning System (GPS) receiver was used to determine and verify the geographical coordinates of each sampling station. The locations of the ten sampling points are shown in Figure 1.

Table 1. Sampling locations in Pasir Penambang along the Selangor River and their dominant land use

Sampling Location	Longitude	Latitude	Dominant Land Use
S1	101.2605232°	3.3636161°	Estuarine zone (river mouth)
S2	101.2603275°	3.3593897°	Small-scale aquaculture ponds and seafood processing activities
S3	101.2579921°	3.3567279°	Estuarine zone adjacent to fishing village and residential area
S4	101.2583487°	3.3537614°	Mixed residential and commercial area
S5	101.2572468°	3.3503307°	Small-scale aquaculture ponds, seafood processing activities and residential area
S6	101.2557767°	3.3508907°	Fish landing facilities, fishing jetties and commercial activities
S7	101.2573356°	3.3490526°	Estuarine waterfront with fishing and boating activities
S8	101.2577479°	3.3461929°	Commercial area comprising seafood-related businesses and fish landing facilities
S9	101.2617689°	3.3449654°	Downstream estuarine zone with natural vegetation
S10	101.2634106°	3.3422534°	Downstream estuarine zone (river mouth)

Sample treatment and analysis

The sediment samples were oven-dried at 100°C, ground using a mortar, sieved through a 63 μm sieve, and stored in desiccators until analysis. The concentrations of heavy metals (Cr, Cu, Ni, Pb, and Zn) were quantified using a benchtop PANalytical Epsilon3-XL Energy Dispersive X-ray Fluorescence (EDXRF) spectrometer (Apaydın et al., 2022). All sediment samples were analysed in triplicate to improve measurement precision and reduce analytical uncertainty. Instrument performance was verified using certified reference materials (CRMs) and routine quality control procedures prior to sample analysis.

Pollution assessment tools

The pollution level of the river sediments was evaluated using pollution assessment tools, namely the Geoaccumulation Index (I_{geo}), Enrichment Factor (EF), Contamination Factor (CF), and Pollution Load Index (PLI) (Abdul Hakim et al., 2020; Lim et al., 2021; Sefie et al., 2021).

Geoaccumulation Index (I_{geo})

The Geoaccumulation Index (I_{geo}), developed by Muller (1969), is widely used to assess heavy metal contamination in sediments by comparing current concentrations to pre-industrial baseline values. This index is commonly applied in pollution studies as a reference for evaluating the extent of contamination. Table 2 summarises the classification of I_{geo} values and their corresponding contamination levels, while Equation (1) shows the formula used to calculate the index.

Table 2. Classification of I_{geo}

I_{geo} class	I_{geo} value	Contamination level
0	$I_{geo} \leq 0$	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

Source: Muller (1969)

$$I_{geo} = \frac{\log_2 Ci}{1.5 \times Bi} \quad (1)$$

Where:
Ci = measured concentration of heavy metal "i" in the sediment sample
Bi = Geochemical background value of metal "i" in uncontaminated sample. The constant 1.5 is used to account for natural variations in background concentrations resulting from lithological differences.

Enrichment Factor (EF)

The Enrichment Factor (EF) is commonly used to assess the extent of anthropogenic influence on metal concentrations in sediments (Sholkovitz, 1978; Sutherland, 2000). Iron (Fe) is typically employed as the reference element (normaliser) to minimise the influence of mineralogical composition and grain size variability in sediments (Lim et al., 2021; Ng et al., 2021). Table 3 presents the standard classification of EF values and their corresponding enrichment levels. The EF was calculated using Equation (2).

Table 3. Classification of Enrichment Factor (EF)

EF value	Status
EF< 1	No enrichment
1<EF<3	Minor enrichment
3<EF<5	Moderate enrichment
5<EF<10	Moderately severe enrichment
10<EF<25	Severe enrichment
25<EF<50	Very severe enrichment
EF>50	Extremely severe enrichment

Source: (Sholkovitz, 1978; Sutherland, 2000)

$$EF = \frac{(Cx/Cref)\ Sample}{(Cx/Cref)\ Background} \quad (2)$$

Where:
Cx = Measured concentration of heavy metal
Cref = Concentration of the reference element

Contamination Factor (CF)

The Contamination Factor (CF), proposed by Hakanson (1980), is a widely used index for assessing the degree of heavy metal contamination in sediments by comparing the concentration of each metal in the sediment with its corresponding background concentration (Turekian & Wedepohl, 1961). CF for each metal was calculated using Equation (3).

$$CF = Ci/Cb \quad (3)$$

Where:
Ci = Measured concentration of the heavy metal in the sediment sample
Cb = Geochemical background concentration of corresponding heavy metal

CF provides an indication of the contamination level for each individual metal. The Pollution Load Index (PLI) was subsequently calculated to evaluate the overall level of contamination from all analysed metals.

Pollution Load Index (PLI)
The Pollution Load Index (PLI), introduced by Tomlinson et al. (1980), is a widely used index for assessing the overall level of heavy metal contamination in sediments. It provides a simple comparative means to determine whether the concentration of multiple heavy metals in a sediment sample exceeds background levels. PLI was calculated using Equation (4).

$$PLI = (CF1 \times CF2 \times \ldots CFn)1/n \quad (4)$$

Where:
CF = Contamination factor
n = Number of analysed heavy metal

Table 4 presents the standard classification for the Contamination Factor (CF), and Pollution Load Index (PLI) used in assessing heavy metal contamination in sediment.

Table 4. Classification of sediment contamination based on CF and PLI value

Range of CF	Description	Range of PLI	Class of PLI	Description
CF < 1	Low degree of sediment Contamination	PLI ≤ 1	1	No pollution
1 ≤ CF < 3	Moderate degree of sediment contamination	1<PLI ≤3	2	Slight pollution
3 ≤ CF < 6	Considerable degree of sediment contamination	3<PLI ≤6	3	Moderate pollution
CF ≥ 6	Very high degree of sediment contamination	PLI > 6	4	Heavy pollution

Source: Tomlinson et al. (1980)

Result and Discussion

Heavy metal concentration in river sediment

Table 5 presents the mean and standard deviation of five heavy metals (Cr, Cu, Ni, Pb, and Zn) in sediment samples collected from the Selangor River (mg/kg dry weight). The concentrations ranged from 51.48–74.59 mg/kg for Cr, 18.10–21.16 mg/kg for Cu, 27.96–35.31 mg/kg for Ni, 23.02–30.91 mg/kg for Pb, and 79.22–130.08 mg/kg for Zn, with the overall abundance following the order of Zn > Cr > Ni > Pb > Cu. Sampling Point 2 recorded the highest concentrations of Cr, Ni, Pb and Zn, whereas the highest Cu concentration (23.20 mg/kg) was observed at Sampling Point 7. This may be associated with the combined influence of small-scale aquaculture, seafood processing, residential discharges, surface runoff, and contaminant transport from upstream catchments.

Similar findings have been reported in riverine environments where mixed anthropogenic activities contribute to elevated heavy metal concentrations in sediments (Rahman et al., 2023; Hasan et al., 2024). In contrast, Sampling Points 1, 3, 4, 9 and 10, which are located within the estuarine zone, generally

exhibited lower heavy metal concentrations, whereas Sampling Points 5–8 showed intermediate concentrations, reflecting the influence of nearby aquaculture, fish landing facilities, commercial activities and residential settlements. These spatial variations suggest that both local land use and upstream contaminant transport influence the distribution of heavy metals in the river sediments.

Table 5. Heavy metal concentrations in river sediments (mg/kg dry weight)

Sampling Point	Heavy Metal (mg/kg)					Ref.
	Cr	Cu	Ni	Pb	Zn	
1	69.26	22.54	33.21	30.24	122.45	Present study
2	**74.59**	21.85	**35.31**	**30.91**	**130.08**	
3	61.92	18.10	29.23	24.67	95.54	
4	65.96	20.92	31.48	28.34	115.60	
5	57.20	21.27	28.45	25.81	95.10	
6	60.46	20.76	29.64	25.37	93.37	
7	54.33	**23.20**	27.96	23.47	79.22	
8	56.01	20.14	29.01	25.80	99.27	
9	51.48	21.27	26.61	23.02	81.38	
10	73.35	21.54	33.88	30.06	123.42	
Max	74.59	23.20	35.31	30.91	130.08	
Min	51.48	18.10	27.96	23.02	79.22	
SD	8.06	1.39	2.85	2.90	18.08	
Mean	62.46	21.16	30.48	26.77	103.54	
*TEL, Threshold effect level	37.3	35.7	18	35	123	Macdonald et al. (2000)
*LEL, Lowest effect level	26	16	16	31	120	Persaud et al. (1993)
MET, Minimal effect threshold	55	28	35	42	150	Saulnier & Gagnon (2006)
ERL, Effect range low	80	70	30	35	120	Long et al. (1995)

** TEL = Threshold Effect Level; LEL = Lowest Effect Level; MET = Minimal Effect Threshold; ERL = Effect Range Low.*

When compared with the Lowest Effect Level (LEL) proposed by Persaud et al. (1993), the mean concentrations of Cr, Cu and Ni exceeded their respective threshold values of 26, 16 and 16 mg/kg, respectively. In contrast, the mean concentrations of Pb and Zn remained below the corresponding LEL values of 31 and 120 mg/kg. The exceedance of the LEL for Cr, Cu and Ni suggests the potential for adverse biological effects on sediment-dwelling organisms and indicates the need for continued environmental monitoring.

Table 6 compares the concentrations of heavy metals in river sediments from the present study with those reported in previous studies conducted in Malaysia. Overall, the concentrations of Cr, Cu and Ni in the present study were generally higher than those reported in several Malaysian rivers, whereas Pb and Zn concentrations were comparable to or lower than those reported in some previous studies. When compared with the average shale values reported by Wedepohl (1995), only Pb and Zn exceeded their respective background concentrations, whereas Cr, Cu and Ni remained below the average shale values. The elevated Pb concentrations may be associated with anthropogenic sources related to fishing, boating, fish landing operations, and jetty activities, where fuel combustion, lubricant leakage, and vessel maintenance may contribute to Pb accumulation in river sediments (Ng et al., 2021; Nyangon et al., 2019; Yap et al., 2022).

Table 6. Comparison of heavy metal concentrations in river sediments from the present study and previous studies in Malaysia

Author	Location	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
Present study	Pasir Penambang, Kuala Selangor	51.48-74.59	18.10-21.16	27.96-35.31	23.02-30.91	79.22-130.08
Sefie et al. (2021)	Lower Klang River	n/a	n/a	n/a	0.20-0.27	0.18-0.25
Ng et al. (2021)	Kuala Langat	0.86-2.26	3.45-22.91	n/a	56.14-307.17	29.88-73.89
Lim et al. (2021)	Pinang River Basin	0.86-17.05	n/a	0.22-1.76	0.11-4.69	1.45-5.84
Abdul Hakim et al. (2020)	Pahang River	15.6-30.0	11.6-30.0	10.2-28.4	17.2-35.6	47.8-67.9
Wedepohl & H.K (1995)	Kombo-Laka, Cameroon (Average shale)	126	25	56	14	65

**n/a = Data not available in the referenced study.*

Relationship among heavy metals in sediments

Table 7 presents the Pearson correlation matrix for heavy metal concentrations in sediment samples collected from the Selangor River. Strong positive correlations were observed between Cu and Ni (r = 0.79), Cu and Pb (r = 0.79), and Ni and Pb (r = 0.88). These strong correlations suggest that these metals may share similar sources or exhibit comparable geochemical behaviour, reflecting the influence of common anthropogenic activities and/or natural geological inputs. Pearson correlation coefficients of r ≥ 0.70 are highlighted in bold to indicate strong positive relationships.

Table 7. Pearson correlation analysis between heavy metals in sediment samples.

	Cr	Cu	Ni	Pb	Zn
Cr	1.00				
Cu	0.34	1.00			
Ni	0.49	**0.79**	1.00		
Pb	0.43	**0.79**	**0.88**	1.00	
Zn	0.60	0.20	0.29	0.26	1.00

Sediment contamination assessment

Sediment contamination was evaluated using four commonly applied pollution indices, namely the Geo-accumulation Index (I_{geo}), Enrichment Factor (EF), Contamination Factor (CF), and Pollution Load Index (PLI). These indices were used to assess the degree of heavy metal contamination and to distinguish between natural and anthropogenic contributions in the study area.

Geo-accumulation Index (I_{geo})

Figure 2 illustrates the I_{geo} values for heavy metals in the Selangor River sediments. The contamination classes, ranging from unpolluted to extremely polluted, were interpreted according to the classification criteria presented in Table 2. The I_{geo} is widely used to evaluate the extent of sediment contamination resulting from anthropogenic activities.

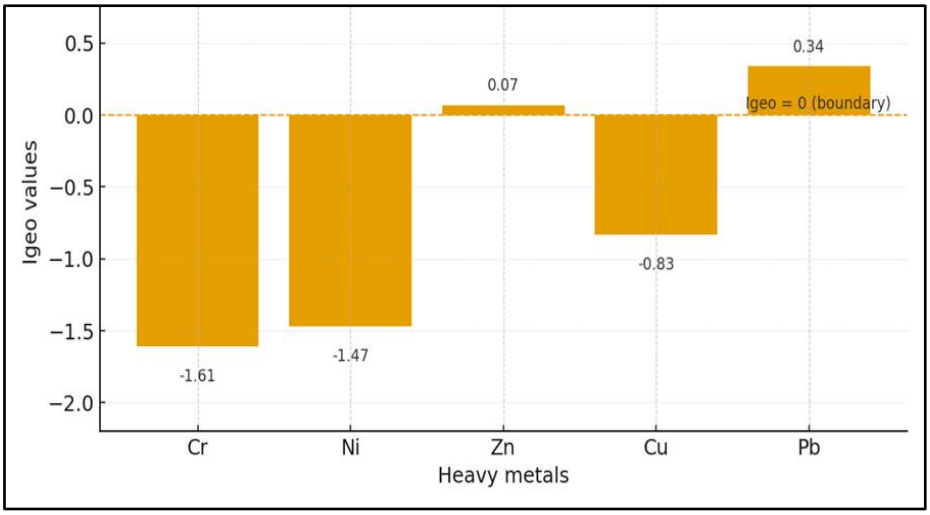


Figure 2. I_{geo} values of metals in Selangor River sediments

The I_{geo} values for the analysed metals decreased in the order of Pb > Zn > Cu > Ni > Cr (Figure 2). According to the I_{geo} classification presented in Table 2, Pb and Zn were classified as Class 1 ($0 < I_{geo} < 1$), indicating that the sediments were uncontaminated to moderately contaminated. In contrast, Cr, Cu and Ni remained within Class 0 ($I_{geo} \leq 0$), indicating uncontaminated sediments. The relatively higher I_{geo} values for Pb and Zn suggest greater anthropogenic influence in the study area. The surrounding land use, including aquaculture activities, fishing jetties, commercial areas, seafood markets and food stalls, together with frequent fishing and boating activities, may have contributed to the accumulation of these metals in the sediments. Similar observations were reported by Lim et al. (2022b), who found that fishing-vessel operations and port maintenance contributed to elevated heavy metal concentrations in sediments, while Masykury et al. (2023) reported that aquatic environments adjacent to ports and areas of intensive human activity commonly exhibit increased heavy metal accumulation in sediments.

Enrichment Factor (EF)

Figure 3 presents the enrichment factor (EF) values for heavy metals in the Selangor River sediments at Pasir Penambang. Based on the classification presented in Table 3, the enrichment order of the analysed metals was Pb > Ni > Zn > Cr > Cu. Chromium (Cr) and copper (Cu) exhibited EF values ranging from 1.21 to 1.93 and 0.60 to 1.40, respectively, indicating minor enrichment and suggesting that these metals were largely influenced by natural lithogenic sources with limited anthropogenic contribution. Zinc (Zn) showed moderate enrichment, with EF values ranging from 3.05 to 4.10. Nickel (Ni) and lead (Pb) exhibited significant enrichment, with EF values ranging from 6.09 to 10.12 and 15.24 to 20.50, respectively, indicating substantial anthropogenic influence.

Among the analysed metals, Pb recorded the highest mean EF value (17.21), suggesting that anthropogenic activities have played a dominant role in its accumulation within the river sediments. The elevated enrichment of Pb may be associated with cumulative anthropogenic inputs, including urban runoff, fishing and boating activities, vehicular emissions, historical mining activities, and industrial discharges within the Selangor River basin. Similar findings have been reported by Lim et al. (2022b) and Wang et al. (2025), who observed elevated Pb concentrations in sediments from fishing ports and coastal environments subjected to intensive vessel traffic.

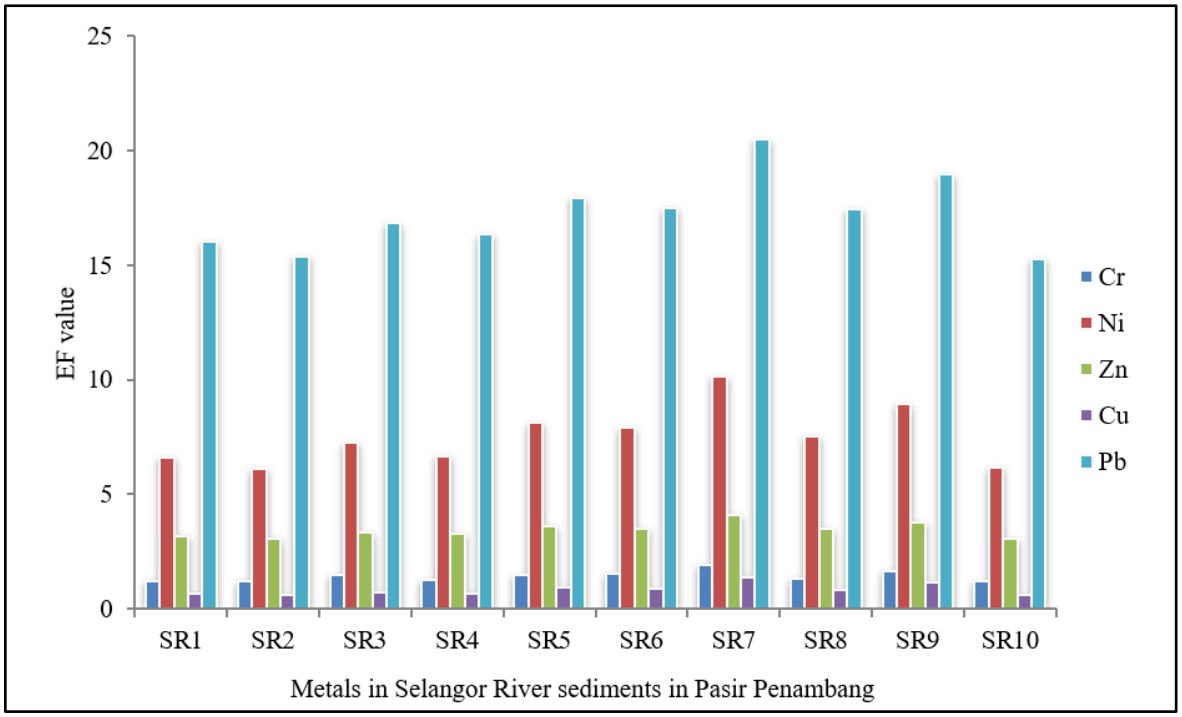


Figure 3. Enrichment Factor (EF) values of heavy metals in Selangor River sediments at Pasir Penambang

Contamination Factor (CF) and Pollution Load Index (PLI)

Based on the contamination factor (CF) values illustrated in Figure 4, Pb exhibited the highest mean CF across all sampling points (1.67), followed by Ni (1.52), Zn (1.42), Cu (1.41), and Cr (0.99). Spatial analysis indicated that Sampling Point 2 recorded the highest CF values for Pb (1.93) and Zn (1.78). Similarly, Ni and Cr also exhibited their highest CF values at this site. Although Sampling Points 5 and 6 were located within areas characterised by similar land uses, including aquaculture, fishing, and commercial activities, the lower CF values observed at these locations suggest that heavy metal accumulation was influenced not only by surrounding land use but also by local hydrodynamic conditions, sediment deposition patterns, proximity to contaminant inputs, and the cumulative transport of contaminants from upstream areas (Förstner & Salomons, 1980; Hakanson, 1980). Consequently, Sampling Point 2 exhibited greater metal accumulation than the adjacent sampling locations, indicating stronger localized anthropogenic influence.

Cu demonstrated its highest CF at Sampling Point 7 (1.66), suggesting localized Cu enrichment that may be associated with intensive fishing and boating activities. The use of copper-containing antifouling paints, engine components, lubricant leakage, and routine vessel maintenance may contribute to Cu accumulation in the surrounding sediments (Ng et al., 2021; Nyangon et al., 2019; Yap et al., 2022). Overall, Cr, Cu, and Ni were classified as having low contamination, whereas Pb and Zn were categorized as exhibiting moderate contamination, indicating relatively greater anthropogenic influence.

The elevated CF values of Pb and Zn may be attributed to urban runoff, aquaculture activities, seafood processing, fishing and boating activities, and fuel combustion residues from maritime operations, which contribute to the introduction of metals into the fluvial system (Farid Ahmed et al., 2023; Lim et al., 2022b; Wang et al., 2025). Lead (Pb) has a high affinity for adsorption onto sediment particles, resulting in greater accumulation than many other metals (Förstner & Salomons, 1980). These CF values were subsequently used to calculate the Pollution Load Index (PLI), providing an overall assessment of cumulative sediment contamination. These findings are consistent with previous studies reporting heavy metal accumulation in tropical river sediments influenced by urbanization, aquaculture, maritime activities, and port operations (Wang et al., 2025; Raihan et al., 2023; Ahmed et al., 2023; Lim et al., 2022a; Tan et al., 2021).

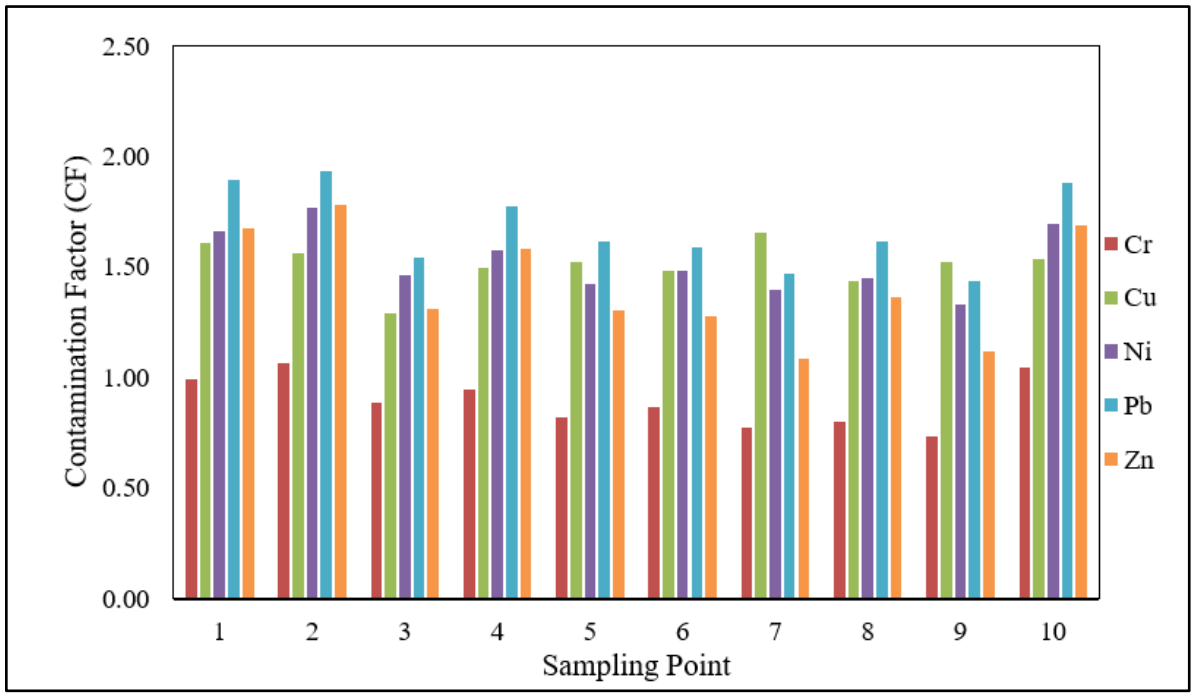


Figure 4. Contamination Factor (CF) values of heavy metals in sediments from the Selangor River at Pasir Penambang.

According to the PLI classification presented in Table 4 (Figure 5), sampling points with PLI values below 1 are classified as unpolluted, whereas those with PLI values between 1 and 3 are considered to be minorly polluted (Tomlinson et al., 1980; Lim et al., 2021). The results showed that most sampling points had PLI values below 1, indicating unpolluted conditions. However, Sampling Points 1, 2, and 10 recorded PLI values between 1 and 3, suggesting minor pollution at these locations. The relatively higher PLI values may be associated with anthropogenic inputs from surrounding land-use activities, including aquaculture, seafood processing, fishing and boating activities, as well as the cumulative transport and deposition of contaminants from upstream areas (Förstner & Salomons, 1980; Ng et al., 2021; Yap et al., 2022). These findings indicate localized metal enrichment rather than widespread sediment contamination and are consistent with previous studies reporting that localized anthropogenic activities and sediment transport processes influence heavy metal accumulation in estuarine sediments (Farid Ahmed et al., 2023; Lim et al., 2022b; Wang et al., 2025).

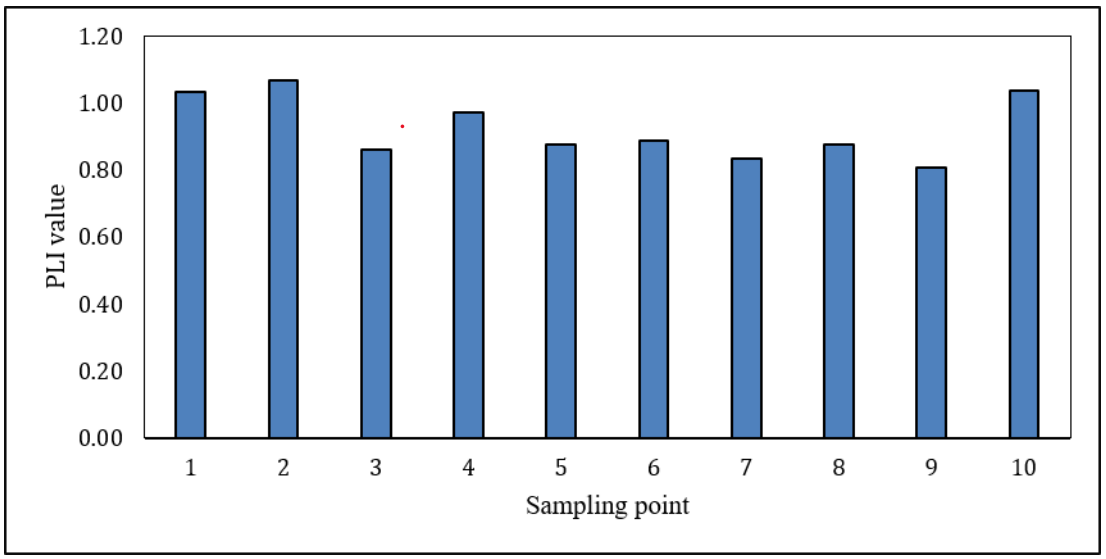


Figure 5. PLI values of metals in Selangor River sediments in Pasir Penambang

Conclusion

This study evaluated the spatial distribution and contamination status of selected heavy metals (Cr, Cu, Ni, Pb and Zn) in the sediments of the Selangor River at Pasir Penambang, Kuala Selangor. Among the analysed metals, Zn recorded the highest mean concentration, followed by Cr, Ni, Pb and Cu. Comparison with average shale values indicated that Pb and Zn exceeded their respective background concentrations, suggesting anthropogenic enrichment. The pollution assessment using Igeo, EF, CF and PLI consistently demonstrated that the sediments were generally characterised by low to moderate contamination. While Igeo classified the sediments as uncontaminated to moderately contaminated, EF indicated minor to significant enrichment depending on the metal, with Pb exhibiting the highest enrichment. CF further showed moderate contamination for Pb and Zn, whereas PLI indicated that most sampling points were unpolluted, except for Sampling Points 1, 2 and 10, which were classified as minorly polluted.

The spatial variation observed in this study suggests that localized anthropogenic activities, including aquaculture, seafood processing, fishing, boating and commercial activities, together with contaminant transport from upstream areas, may have contributed to the accumulation of heavy metals in the sediments, particularly Pb and Zn. These findings provide important baseline information for long-term sediment quality monitoring in the Selangor River estuary and support environmental management by identifying locations that require continued monitoring and targeted pollution control measures. Furthermore, this study contributes to the limited knowledge of heavy metal contamination in the estuarine sediments of the Selangor River and provides a scientific basis for future sediment quality monitoring, environmental risk assessment, and sustainable river basin management.

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Author Contribution

Nadasofa Mohd Saidi contributed to the conceptualization, methodology, data curation, and writing of the original draft. Sabarina Md Yunus was responsible for supervision, validation, and writing – review and editing. Dayang Nurhaziqah Binti Awang Daramat carried out formal analysis, investigation, and visualization. Nik Azlin Nik Ariffin contributed to resources, validation, and writing – review and editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration on the Use of Generative AI

The authors declare that generative artificial intelligence (AI) tools, including ChatGPT, were used only to enhance the clarity of language and improve grammar during manuscript preparation. No AI tools were used for data analysis, interpretation, or generation of scientific content. The authors take full responsibility for the originality, accuracy, and integrity of the work reported in this manuscript.

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