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Assessment of Heavy Metals Contamination in Estuaries Area of Sungai Kilim, Pulau Langkawi

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ABSTRACT

Heavy metal pollution poses a critical environmental challenge, particularly in estuarine ecosystems such as the Kilim River in Langkawi, Malaysia. This study investigates the distribution of heavy metals (Co, Cr, Fe, Pb, and Zn) in sediment samples collected from 16 locations in Sungai Kilim using the aqua regia closed digestion method. Sediments were processed to prevent contamination, including soaking in 5% nitric acid, drying, pulverizing, and sieving before analysis. Inductively coupled plasma optical emission spectrometry (ICP-OES) was employed for precise analysis, with accuracy validated through reference material testing. The concentrations of heavy metals varied, with Co ranging from 4.50 to 68.49 ppm, Cr from 12.55 to 184.26 ppm, Fe from 0.83% to 4.48%, Pb from 3.42 to 76.55 ppm, and Zn from 11.90 to 75.20 ppm. Enrichment factor calculations showed no significant enrichment for Co (2.354), Cr (2.019), and Zn (1.532), but Pb displayed a moderately severe enrichment (6.198), indicating significant contamination. The findings highlight notable heavy metal concentrations in Sungai Kilim sediments, particularly for lead, suggesting environmental risks exacerbated by industrial and urban activities. These results emphasize the need for targeted environmental management strategies to mitigate contamination and safeguard the ecological health of the estuarine ecosystem.

INTRODUCTION

Heavy metal pollution in aquatic environments, particularly in sediment, is a pressing environmental concern due to its long-lasting and harmful impacts. Sediments act as both sinks and sources of heavy metals, making them critical in determining contamination levels in aquatic systems. Various methods, such as the geo-accumulation index, enrichment factor, contamination factor, and pollution load index, are employed to assess sediment quality [1]. Coastal areas, especially marine sediments, are significant

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reservoirs of heavy metals, which are introduced through natural processes like rock weathering and erosion, as well as anthropogenic activities, including industrial discharge, agricultural runoff, and urban waste [2]. These metals, once deposited in the sediments, can affect aquatic ecosystems over long periods, influencing both abiotic and biotic components. Heavy metals can alter sedimentary bacterial communities, which play a crucial role in nutrient cycling and maintaining ecological balance in ecosystems like mangroves [3]. The ability of bacteria to express heavy-metal resistance genes when exposed to contaminated environments is vital for mitigating the toxicity of these metals. These genes enable microorganisms to detoxify heavy metals through mechanisms such as metal transport, precipitation, and chelation [4]. However, heavy metal pollution can severely disrupt these processes, leading to degradation of ecosystems. This is evident in areas like Langkawi's Kilim Geoforest Park, where the increasing influx of pollutants from nearby industries and agricultural activities poses a serious threat to the mangrove ecosystem [5]. Given its significance as both a tourist destination and a critical ecological site, preserving Kilim Geoforest Park from further degradation is crucial. Monitoring heavy metal levels in sediments aligns with Malaysia's Twelfth Plan and Sustainable Development Goal 14, which targets the reduction of marine pollution by 2025.

Estuaries, like mangrove ecosystems, are dynamic environments that are particularly vulnerable to heavy metal pollution due to their proximity to human activities. Estuaries are transitional zones where freshwater meets seawater, and their unique ecological composition makes them highly susceptible to contamination from industrial, agricultural, and urban sources [6]. Heavy metals, such as Cobalt (Co), Chromium (Cr), Iron (Fe), Lead (Pb) and Zinc (Zn) are of particular concern in estuarine environments because of their toxic effects and persistence in the ecosystem [7]. These metals can accumulate in the sediments, where they pose long-term risks to aquatic organisms and ecosystems. For instance, excessive Cobalt exposure has been associated with severe health impacts, including cancer, organ damage, and respiratory difficulties [8].

The accumulation of heavy metals in estuarine sediments can disrupt key ecological processes, such as nutrient cycling, and harm species essential to the estuarine food web, including fish, mollusks, and other invertebrates. Langkawi, an island known for its rich biodiversity and ecotourism, faces increasing risks of heavy metal pollution in its estuarine regions, such as Sungai Kilim, where some studies have documented contamination in Langkawi's waters, particularly around tourist-heavy areas [9]. Therefore, further research is essential to assess the concentrations of heavy metals in estuarine environments, identify the sources of pollution, and implement appropriate remediation measures to protect these vulnerable ecosystems.

EXPERIMENTAL

Figure 1 shows the study area, Sungai Kilim, which is a dynamic estuarine system influenced by both natural processes and anthropogenic activities, making it a critical site for assessing heavy metal pollution. By focusing on Sungai Kilim, researchers aim to evaluate the impact of industrial and urban activities on metal concentrations within the ecosystem. This estuary serves as a representative site to understand the environmental pressures arising from rapid development in Langkawi, Malaysia.

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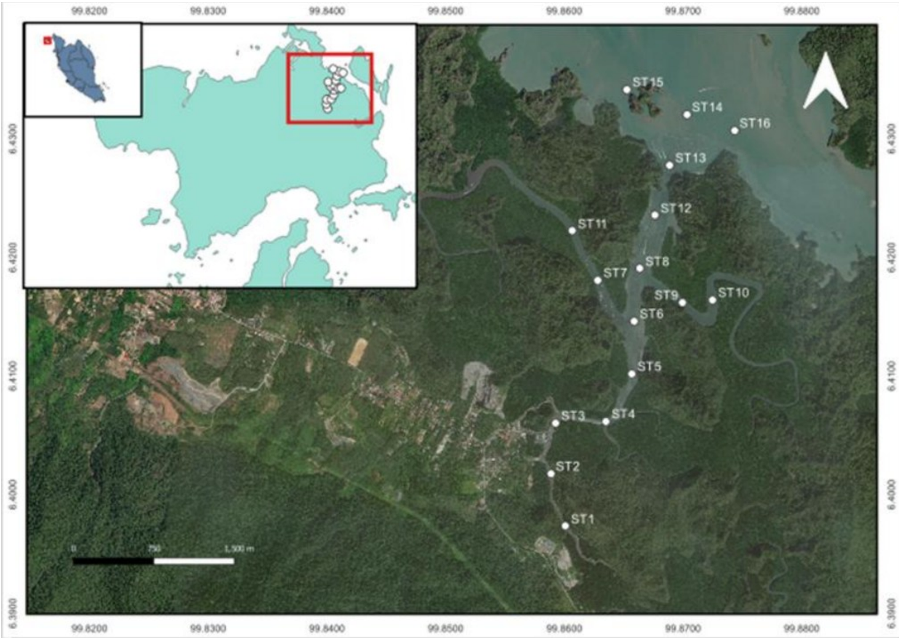

Figure 1. Map of the sampling area, Sg Kilim, Langkawi, Kedah

The research in Sungai Kilim (Figure 1) provides valuable insights into the levels and sources of contamination, helping to distinguish between naturally occurring metal concentrations and those elevated due to human activities. Such investigations are essential for identifying specific pollution sources and assessing their ecological impact. This comprehensive approach informs targeted environmental management and remediation efforts to protect and sustain the estuarine ecosystem [10,11].

Table 1 below provides the geographical locations and coordinates of the 16 sampling stations in Sungai Kilim, which serve as the basis for this study. These stations were strategically chosen to cover various points within the estuary, ensuring comprehensive spatial coverage to capture variations in environmental and pollution gradients. Each station is represented by precise latitude and longitude coordinates, enabling accurate mapping and consistency in sample collection during fieldwork.

For heavy metal assessment, three set of samples were collected using the core sampler. To prevent contamination, sediment samples were packed in plastic bags that had been submerged in 5% nitric acid for 2 to 3 days [12]. The sample bags and plastic containers were arranged in a line and their labelling and numbers were examined. The sediment sample was then placed on plastic trays to air-dry for 2-3 days for sediment characteristic analysis or oven dry for 24 hours at 105°C for heavy metal analysis. For the heavy metal analysis, the samples were thoroughly dried before being pulverised with a mortar and pestle and a 63µm sieve. Priority was paid to precautions against contamination. The samples were then placed in labelled plastic vials and preserved in desiccators until they were analysed in the lab.

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Table 1. Position of sampling stations at Sungai Kilim.

Station No	Latitude (N)	Longitude (E)
K1	6°23'50.52"N	99°51'36.20"E
K2	6°24'6.34"N	99°51'31.87"E
K3	6°24'21.70"N	99°51'33.24"E
K4	6°24'24.90"N	99°51'51.14"E
K5	6°24'37.04"N	99°51'55.68"E
K6	6°24'55.12"N	99°51'54.93"E
K7	6°25'14.24"N	99°51'58.03"E
K8	6°25'29.71"N	99°52'2.93"E
K9	6°24'59.65"N	99°52'10.68"E
K10	6°25'5.86"N	99°52'20.35"E
K11	6°25'3.42"N	99°52'33.68"E
K12	6°24'53.94"N	99°52'29.60"E
K13	6°24'42.66"N	99°52'27.38"E
K14	6°24'40.61"N	99°52'42.62"E
K15	6°24'27.19"N	99°52'44.94"E
K16	6°25'41.89"N	99°52'55.43"E

For heavy metal analysis, a Teflon bomb was filled with 8.0 ml of Aqua Regia (2 mL of concentrated HNO_3 and 6 mL of concentrated HCl were added) for digestion after measuring and adding 0.25 g of sediment that had attained a consistent weight for the heavy metal analysis [13]. To stop silicate gel from forming, the Teflon Bomb jackets were sealed tightly. Samples were added to acid and then heated at 150°C for five hours. The samples were left to cool overnight at room temperature, and then each sample received 3.0 ml of an acid solution made of boric acid and EDTA. Samples were then placed in an oven at 150°C for an additional five hours. Lastly, test tubes containing the supernatants were filled to a capacity of 25.0 ml with Mili-Q water. For every sampling site, the sediment samples were analyzed three times, including a blank sample, to confirm the accuracy of the analytical techniques. Parts of certified reference materials (SRM1646a, estuary sediments) from the National Institute of Standards and Technology (NIST) were analyzed together with each batch of samples in order to verify analytical accuracy [14,15]. The Inductively Coupled Plasma Optical Emission Spectrometer (Perkin Elmer, Optima 8000) was then used to measure the amounts of metals (Co, Cr, Fe, Pb and Zn) in the final digested solutions [16].

The concentration of heavy metals detected in the ICP-OES analysis was then utilized to evaluate the level of heavy metal contamination using the EF, CF, and geo-accumulation index. The enrichment factors (EFs) for each element were calculated based on Equation 1:

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$$\text{Enrichment Factor EF} = \left(\frac{M}{Fe}\right) \text{Sediment sample} \,/\, \left(\frac{M}{Fe}\right) \text{Crust} \qquad (1)$$

where values for the Earth’s crustal elements [9], and M and Fe are the metal concentrations in the sample.

Iron (Fe) is commonly chosen as a normalizer for the enrichment factor (EF) in heavy metal studies due to its abundance, stability, and minimal influence from anthropogenic activities. Fe is one of the most abundant elements in the Earth's crust and its concentration in sediments and waters is generally stable, making it an ideal reference element for comparison with other metals [10]. Its widespread natural occurrence and relatively consistent behavior in the environment mean that it is less likely to be influenced by human-induced factors like industrial pollution, which may skew the concentrations of other metals [11]. This stability allows Fe to serve as a reliable baseline, enabling researchers to differentiate between naturally occurring metal concentrations and those that are elevated due to human activity. Additionally, iron's tendency to co-occur with other metals in sediment samples further supports its use as a normalizer, providing a means to assess relative enrichment and identify potential anthropogenic contamination [17]. By using Fe as a normalizer, researchers can more accurately interpret the ecological impacts of heavy metals in the environment. Table 2 illustrates how the EF values were interpreted.

Table 2. Five pollution categories on the basis of the EF [18]

Enrichment Factor (EF) Value	Contamination Degree
< 2	Deficiency to minimal enrichment
2-5	Moderate enrichment
5-20	Significant enrichment
20-40	Very high enrichment
> 40	Extremely high enrichment

The index of geoaccumulation (I_{geo}) enables the assessment of contamination by comparing current and pre-industrial concentrations. This index can also be applied to the assessment of soil contamination. It is computed using Equation 2:

$$I_{geo} = \text{Log}_2 \frac{\text{Cn}}{1.5\ \text{Bn}} \qquad (2)$$

Where,
Cn : concentration of the examined element in the examined bottom sediment
Bn : geochemical background value in fossil argillaceous sediment knows as average shale
The constant 1.5 allows one to compensate for natural fluctuations in the content of a given substance in the environment and very small anthropogenic influences. Muller [19] has distinguished six classes of the geoaccumulation index (Table 3).

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Table 3. Pollution extent as determined by geoaccumulation index.

Class	Value	Soil quality
0	$I_{geo} < 0$	practically 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

Contamination factor (CF) is commonly used to characterize the degree of metal contamination in sediment. Equation 3 may be used to calculate the quantity of pollution produced by contaminants in an ecological system.

$$CF = (CN\ BN) \qquad (3)$$

where BN represents the background metal concentration in normal shale and CN represents the metal content in the sample. Table 4 below show the pollution classification.

Table 4. Pollution classification of the contamination factor (CF).

	Range	Status
Contamination Factor (CF)	CF < 1	Low contamination
	1 ≤ CF ≤ 3	Moderate contamination
	3 ≤ CF ≤ 6	Considerable contamination
	CF > 6	Very high contamination

RESULTS AND DISCUSSION

As a precision check, certified reference material (SRM1646a) was used for the method validation. With recoveries ranging from 90% to 142.54%, the percentage of recoveries for the certified and measured concentration of those metal was satisfied. The recovery test findings for the SRM 1646a study are displayed in Table 5.

Table 5. Measured value, certified value and the percentage recovery of heavy metal.

Heavy Metal	Sungai Kilim		
	Measured SRM	Certified Value	Recovery (%)
Co	4.50	5.00	90.00
Cr	58.30	40.90	142.54
Fe	2.48	2.01	123.51
Pb	228.75	234.50	97.55
Zn	46.00	48.90	94.07

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In the context of assessing environmental quality, the heavy metal concentrations in Sungai Kilim were measured to provide an analysis of potential contamination in the region. The concentrations of key metals—cobalt (Co), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn)—were recorded at various stations within Sungai Kilim. Notably, the concentrations of aluminum (Al) and iron (Fe) are expressed as percentages, while the other metals are represented in parts per million (ppm). These measurements are crucial for understanding the levels of pollution and their potential impacts on the local ecosystem.

The data presented in Table 6 highlight the variability of heavy metal concentrations across different sampling stations in Sungai Kilim. By analyzing these values, it is possible to assess the relative pollution levels at each location and identify hotspots of contamination, particularly for metals like lead, which may indicate anthropogenic pollution sources. These findings contribute to broader environmental monitoring efforts aimed at safeguarding ecosystem health and informing future pollution control strategies.

Table 6. Heavy metals concentration in each station (the concentration of aluminum (Al) and iron (Fe) is expressed as a percentage (%), whereas the concentrations of other metals are represented in part per million (ppm) for Sungai Kilim.

STATION	Co	Cr	Fe	Pb	Zn
K1	18.04	6.66	1.75	10.77	32.2
K2	2.34	37.22	1.85	10.9	16
K3	6.51	125.45	1.76	14.37	14.67
K4	12.18	67.05	1.72	5.6	12
K5	4.51	66.35	1.66	12.37	35.97
K6	15.51	12.68	1.65	2.7	19.37
K7	17.84	21.38	1.74	7.03	19.93
K8	2.44	23.52	1.82	4.53	14.37
K9	20.64	29.64	1.71	26.37	18.7
K10	8.61	33.37	1.72	12.37	19.1
K11	7.84	46.18	0.44	19.53	36.7
K12	25.58	98.32	0.47	56.17	23.6
K13	22.32	90.75	1.8	20.83	29.07
K14	33.01	39.98	1.38	17.07	22.69
K15	31.44	29.45	1.39	33.03	29.57
K16	59.51	92.93	1.12	33.37	14.73

Table 6 presents the concentrations of five heavy metals—cobalt (Co), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn)—across 16 monitoring stations in Sungai Kilim. The metals cobalt, chromium, lead, and zinc are expressed in milligrams per liter (mg/L), while iron is reported as a percentage (%). The data indicate a varied distribution of metal concentrations across the stations. Station K16 recorded the highest cobalt concentration at 59.51 mg/L, suggesting localized enrichment of this metal, while chromium concentrations peaked at 125.45 mg/L at station K3, highlighting potential pollution sources or geological contributions in the area. Iron concentrations remained consistently low, with the highest level of 1.85% observed at station K2, indicating minimal localized influences on iron levels. Lead concentrations varied significantly, with the highest level of 19.53 mg/L recorded at station K11, potentially linked to anthropogenic activities, such as boating or other waterway uses. Zinc concentrations were highest at station K5, reaching 35.97 mg/L, reflecting possible natural or human-induced inputs. Overall, the data suggest that Sungai Kilim experiences varying degrees of heavy metal contamination,

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with certain stations, such as K3 and K16, showing particularly high levels of chromium and cobalt, respectively. The spatial distribution of cobalt (Co) concentrations in Sungai Kilim is illustrated in Figure 2.

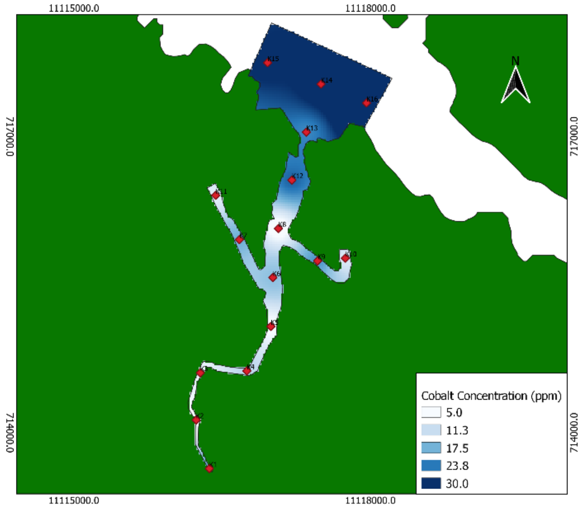

Figure 2. Contour map of Cobalt (Co) concentration (ppm) for Sg. Kilim.

Based on Figure 2, the spatial distribution of cobalt (Co) concentrations in sediment samples from Sungai Kilim provides insight into potential sources and environmental dynamics influencing heavy metal accumulation in this area. Cobalt concentrations are highest in the northern region of Sungai Kilim, with values progressively decreasing downstream. This pattern suggests a point source of cobalt, potentially from natural mineral deposits or anthropogenic activities such as industrial discharge or agricultural runoff upstream [20]. The reduction in cobalt concentration downstream could also result from dilution effects as the metal mixes with incoming sediments, influenced by hydrological factors like water flow velocity and sediment transport [21].

The concentration gradient observed along the river may also reflect deposition processes that trap cobalt in the northern region, where sediment characteristics and hydrological conditions favor accumulation. Conversely, areas with lower cobalt concentrations downstream may be receiving cleaner sediment inputs or experiencing different sedimentation dynamics, such as faster flow rates preventing heavy metal deposition [22].

Comparing the observed cobalt concentrations to sediment quality guidelines reveals that most areas fall within a low to moderate contamination range, with concentrations unlikely to pose significant risks to sediment-dwelling organisms. However, the localized hotspot in the northern part of Sungai Kilim warrants further investigation to determine if the concentrations exceed natural background levels or indicate anthropogenic impacts requiring mitigation [21]. Elevated cobalt levels in this region could have ecological implications, as cobalt is known to bioaccumulate in aquatic organisms, potentially disrupting food webs and posing risks to human health through biomagnification [20]. The spatial distribution of cobalt highlights the need for ongoing monitoring and targeted management to address potential pollution sources in Sungai Kilim.

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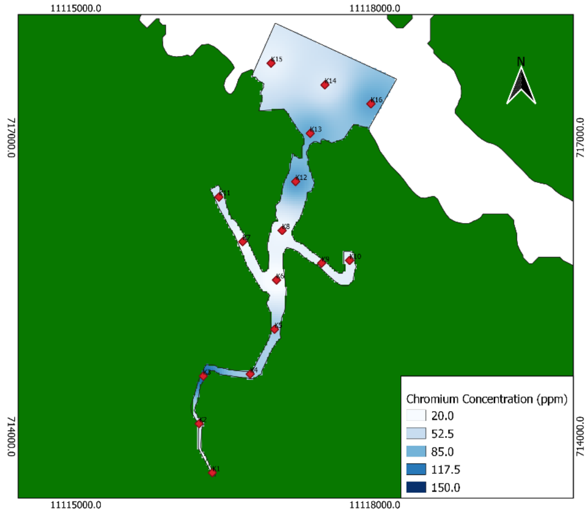

Figure 3. Contour map of Chromium (Cr) concentration (ppm) for Sg. Kilim.

The spatial distribution of chromium (Cr) concentrations in sediment samples from Sungai Kilim, as illustrated in Figure 3, ranges from 20.0 ppm to 150.0 ppm, with a color gradient representing this spread, where lighter blue indicates lower concentrations and darker blue signifies higher concentrations. The pattern reveals that higher chromium concentrations are concentrated in specific northern areas along the waterway, suggesting localized sources of contamination such as industrial activities, urban runoff, or agricultural inputs [20]. The distribution may also be influenced by hydrodynamic factors, as areas with lower water flow can facilitate sedimentation, allowing chromium to settle and accumulate [21].

The observed accumulation pattern could reflect chromium-rich sediment deposition in slower-moving zones of the river, creating environmental "hotspots." These hotspots may pose risks to sediment-dwelling organisms and aquatic ecosystems if concentrations exceed ecological thresholds. The spatial clustering of high chromium levels in the northern region emphasizes the potential role of point sources, such as industrial discharge or mining activities upstream, in contributing to elevated chromium concentrations [22].

Comparing these observations to sediment quality guidelines suggests that while most areas of Sungai Kilim may remain within acceptable ranges for chromium concentrations, localized hotspots could exceed natural background levels and warrant further investigation [21]. These areas may represent potential risks to local ecosystems, particularly as chromium can be toxic to aquatic organisms and may bioaccumulate in food chains, ultimately posing risks to human health [20].

The spatial distribution of chromium concentrations in Sungai Kilim highlights the need for targeted monitoring and management efforts, particularly in the northern regions where concentrations are highest. Further studies should aim to identify specific sources of chromium contamination, assess their impacts, and implement appropriate mitigation measures to protect the aquatic environment and associated ecosystems.

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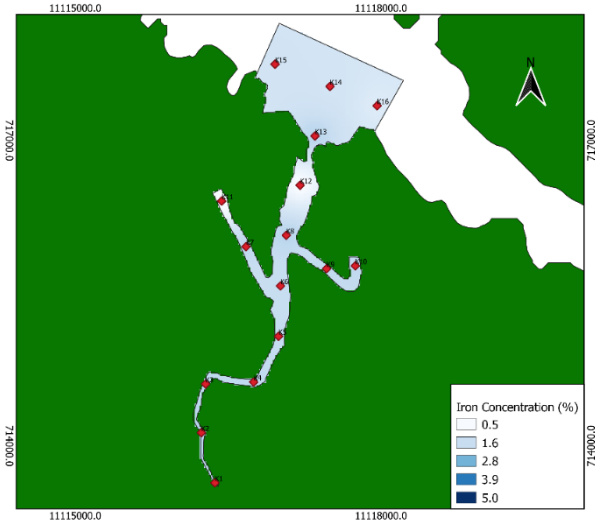

Figure 4. Contour map of Iron (Fe) concentration (%) for Sg. Kilim.

Figure 4 above shows the spatial distribution of iron (Fe) concentrations in sediment samples from Sungai Kilim, reveals concentrations reaching up to 5.0%, with higher levels concentrated in the northern and central sections. This pattern suggests the influence of specific environmental or anthropogenic factors, including runoff from surrounding areas, point sources of contamination, or sediment accumulation driven by water flow dynamics. Elevated iron concentrations in these regions may have ecological implications, as excess iron can alter water chemistry, disrupt species composition, and affect nutrient cycling within the aquatic ecosystem [23].

The localized accumulation of iron in northern and central Sungai Kilim could result from hydrodynamic processes that facilitate sediment deposition in these areas, as well as potential contributions from upstream inputs. Additionally, variations in sediment characteristics, such as organic content or particle size, may influence iron binding and retention in these zones [23]. The high levels observed emphasize the importance of understanding sediment-water interactions and their role in mobilizing or immobilizing iron under varying environmental conditions, particularly in areas prone to low oxygen or anoxic conditions that can enhance iron release from sediments into the water column.

Comparing these concentrations to sediment quality guidelines suggests that most areas remain within acceptable thresholds; however, the elevated levels in the northern and central sections of Sungai Kilim warrant closer investigation to determine whether they stem from natural sources or anthropogenic activities. Iron, while essential for aquatic life, can be detrimental in excess, potentially altering the aquatic ecosystem's structure and function [23].

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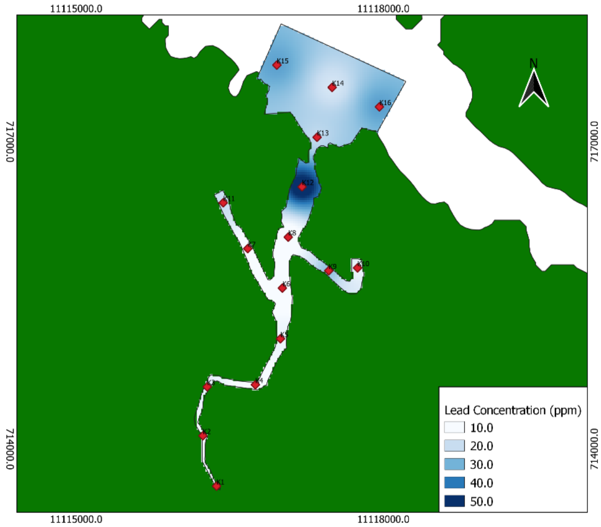

Figure 5. Contour map of Lead (Pb) concentration (ppm) for Sg. Kilim.

The spatial distribution of iron concentrations in Sungai Kilim underscores the need for targeted monitoring efforts and further research to identify specific sources and evaluate their ecological impact. Identifying whether these high concentrations are due to natural processes or external inputs is critical for developing effective management and mitigation strategies. The spatial pattern of lead (Pb) concentrations in sediment samples from Sungai Kilim, as depicted in Figure 5, reveals notable variation, with levels peaking at 50 ppm in certain locations. Elevated lead concentrations are primarily concentrated in specific zones, particularly those influenced by urban development, boating activities, or industrial runoff. These localized contamination sources are typical contributors to pollution in coastal and aquatic systems [24,25]. The uneven distribution of lead inputs across the area results in environmental "hotspots" of contamination. The accumulation of lead in these hotspots may also be driven by hydrodynamic factors, such as reduced water flow in certain sections, which promotes the settling of heavy metals in sediments. Such hotspots pose ecological risks, as lead is toxic to aquatic life and can bioaccumulate in the food chain, potentially affecting marine organisms and human health [26].

The high concentrations of lead identified in Sungai Kilim emphasize the need for focused monitoring and remediation efforts. Determining the specific sources of lead contamination, such as industrial effluents or urban stormwater runoff, is crucial for devising effective measures to mitigate environmental risks and safeguard aquatic ecosystems [27,28]. The distribution of lead in Sungai Kilim highlights the substantial impact of human activities on heavy metal contamination in the area. To mitigate these effects, it is imperative to implement pollution control strategies and promote sustainable land use and industrial practices.

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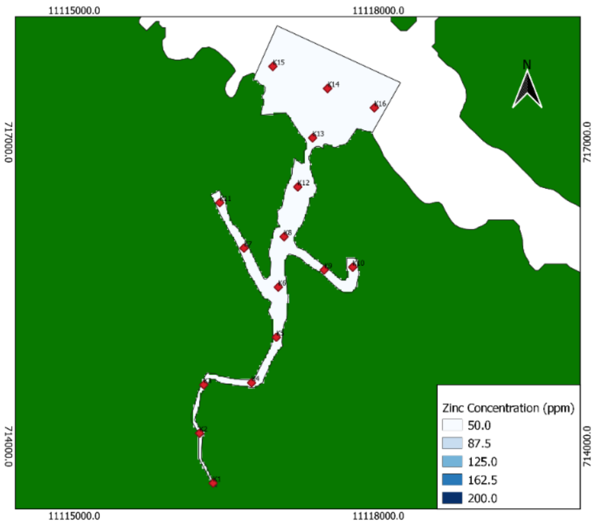

Figure 6. Contour map of Zinc (Zn) concentration (ppm) for Sg. Kilim.

The spatial distribution of zinc (Zn) concentrations in sediment samples from Sungai Kilim, as illustrated in Figure 6, ranges from 50.0 ppm to 200.0 ppm, with a distinct gradient represented by varying shades of blue. Higher zinc concentrations are concentrated in the central and southern sections of the river. These areas of elevated levels suggest localized sources of contamination, which could include industrial runoff, agricultural activities, or urban pollution [25]. Reduced water flow in these sections may facilitate the settling of zinc particles, leading to their accumulation in the sediments [29].

The observed gradient in zinc concentrations highlights the influence of hydrological factors, such as water movement and sedimentation dynamics, on the spatial distribution of heavy metals. Slower water flow in the central and southern parts of the river creates conditions favorable for zinc to settle and accumulate, forming zones of higher contamination. Elevated zinc levels in these areas could pose risks to local aquatic ecosystems, as excessive zinc concentrations may be toxic to aquatic organisms and can disrupt ecological balance [23]

These findings emphasize the need for targeted environmental monitoring and pollution management in Sungai Kilim. Efforts to mitigate zinc contamination should focus on identifying specific pollution sources and implementing appropriate control measures. Sustainable practices in industrial and agricultural sectors, as well as enhanced waste management strategies, are essential to minimize zinc inputs into the river and protect its ecological health [26,30]. The contamination factor in Sungai Kilim is illustrated in Table 7 below.

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Table 7. Contamination Factor of Sungai Kilim.

STATION	Co	Cr	Fe	Pb	Zn
K1	0.57	1.81	0.80	3.67	1.07
K2	2.30	0.72	0.75	2.65	0.86
K3	2.64	0.85	0.72	4.01	0.55
K4	0.41	0.93	0.30	0.58	0.79
K5	0.70	0.88	0.30	5.47	0.66
K6	2.74	0.98	0.50	1.94	0.17
K7	2.45	0.86	0.66	2.15	0.39
K8	1.11	1.06	0.57	3.17	0.99
K9	0.48	1.27	0.60	1.54	0.49
K10	0.74	1.21	0.61	1.35	0.39
K11	0.61	1.40	0.33	0.87	0.51
K12	0.54	0.27	0.28	1.08	0.85
K13	0.90	0.51	0.15	5.05	0.38
K14	0.26	0.43	0.24	0.24	0.37
K15	0.25	0.12	0.26	1.20	0.55
K16	0.42	0.49	0.29	0.53	0.44

Based on the contamination factor (CF) ranges presented in Table 7, the analysis of stations in Kilim reveals significant contamination concerns, particularly for Lead (Pb). Several stations in Kilim exhibit CF values indicating considerable contamination (CF between 3 and 6), highlighting notable environmental threats. For instance, stations K1 (3.673 mg/L), K3 (4.008 mg/L), K5 (5.468 mg/L), and K13 (5.051 mg/L) are particularly concerning due to their elevated Pb concentrations, which pose serious risks to both ecological and human health.

Additionally, Cobalt (Co) levels at stations K3 and K6 also fall within the considerable contamination range, further contributing to the area's pollution profile. Chromium (Cr), Iron (Fe), and Zinc (Zn), on the other hand, generally demonstrate moderate to low contamination levels. However, the high Pb concentrations underscore an urgent need for targeted remediation efforts. The contamination patterns in Kilim suggest a significant anthropogenic influence, likely tied to urban runoff, industrial activities, and other human interventions. Previous studies have identified lead as a persistent and toxic heavy metal linked to these sources [23,29]. Such contamination underscores the need for immediate environmental management and regulatory measures.

In conclusion, Kilim faces severe contamination challenges, particularly from Lead and Cobalt, which necessitate urgent remediation actions to protect environmental and public health. Ongoing monitoring, combined with strategies to identify and mitigate pollution sources, is crucial for reducing contamination levels and preventing future environmental degradation. These measures align with best practices in environmental management to combat localized pollution and ensure sustainable ecosystem health [10].

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Table 8. Enrichment Factor of Sungai Kilim.

STATION	Co	Cr	Pb	Zn
K1	0.72	2.27	4.61	1.35
K2	3.07	0.97	3.54	1.15
K3	3.68	1.18	5.60	0.76
K4	1.35	3.10	1.92	2.61
K5	2.29	2.90	17.96	2.16
K6	5.52	1.97	3.90	0.34
K7	3.69	1.30	3.24	0.58
K8	1.96	1.87	5.59	1.75
K9	0.80	2.13	2.58	0.82
K10	1.22	2.00	2.23	0.65
K11	1.87	4.25	2.65	1.54
K12	1.95	0.99	3.89	3.07
K13	6.10	3.45	34.07	2.57
K14	1.08	1.80	1.02	1.56
K15	0.93	0.47	4.55	2.08
K16	1.43	1.67	1.82	1.52

Table 8 presents the Enrichment Factor (EF) for four heavy metals—Cobalt (Co), Chromium (Cr), Lead (Pb), and Zinc (Zn)—measured across various stations in Kilim. The EF values provide insights into the level of metal contamination, with a color-coded system categorizing the severity of enrichment. The classification is as follows: White indicates no enrichment, Light Blue represents minor enrichment, Green denotes moderately severe enrichment, Yellow signifies severe enrichment, Orange indicates very severe enrichment, and Red represents extremely severe enrichment. This visual system helps easily identify the extent of metal contamination at each station.

In Kilim, Lead (Pb) displays significant contamination at stations K5 and K13, with EF levels reaching Severe and Very Severe Enrichment. Other metals, such as Cobalt and Chromium, generally exhibit Minor to Moderate Enrichment across most stations, suggesting localized but less severe contamination. These findings align with studies that emphasize localized pollution patterns influenced by anthropogenic activities, such as urban runoff and industrial discharges [10,11]. This information is crucial for identifying priority areas in Kilim that require environmental monitoring and remediation efforts to address metal contamination effectively. Such targeted measures are consistent with environmental best practices for mitigating pollution hotspots [14].

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Table 9. Geo-Accumulation Index of Sungai Kilim.

STATION	Co	Cr	Fe	Pb	Zn
K1	-1.39	0.27	-0.91	1.29	-0.48
K2	0.61	-1.05	-1.00	0.82	-0.80
K3	0.81	-0.83	-1.07	1.42	.1.45
K4	-1.89	-0.69	-2.32	-1.38	-0.93
K5	-1.11	-0.77	-2.30	1.87	-1.19
K6	0.87	-0.62	-1.60	0.37	-3.14
K7	0.70	-0.80	-1.18	0.52	-1.96
K8	-0.43	-0.50	-1.40	1.08	-0.59
K9	-1.65	-0.24	-1.33	0.03	-1.62
K10	-1.02	-0.31	-1.31	-0.15	-1.93
K11	-1.29	-0.11	-2.19	-0.79	-1.57
K12	-1.48	-2.46	-2.44	-0.48	-0.82
K13	-0.73	-1.55	-3.34	1.75	-1.89
K14	-2.54	-1.81	-2.65	-2.62	-2.01
K15	-2.61	-3.61	-2.51	-0.33	-1.46
K16	-1.85	-1.63	-2.36	-1.50	-1.76

Table 9 represents the Geo-Accumulation Index (Igeo) for heavy metals such as Cobalt (Co), Chromium (Cr), Iron (Fe), Lead (Pb), and Zinc (Zn) across various stations in Sungai Kilim. The Igeo values provide insight into the pollution levels of these metals at different locations. A color-coding system visually distinguishes between contamination levels, with classifications ranging from virtually unpolluted (blue) to strongly polluted (red). This visual aid facilitates identifying areas that may require environmental attention.

The status key categorizes Igeo values into six distinct pollution levels. Blue (< 0) represents stations that are virtually unpolluted, with no harmful metal concentrations. Light blue (0 to 1) indicates areas that are unpolluted to moderately polluted, reflecting mild contamination. Green (1 to 2) signifies moderately polluted areas, where contamination is noticeable but not severe. Yellow (2 to 3) highlights moderately to highly polluted areas, signaling rising pollution levels needing intervention. Orange (3 to 4) marks strongly polluted zones with significant contamination, while Red (> 5) identifies extremely polluted areas posing serious environmental risks, though no stations in Table 9 fall into this category.

The data from Sungai Kilim indicate that most stations fall into the "virtually unpolluted" or "unpolluted to moderately polluted" categories, suggesting good environmental health in the region. Most metal concentrations measured at these stations show no contamination or minimal pollution, with negative Igeo values for metals such as Chromium (Cr) and Iron (Fe), further emphasizing a relatively clean environment. These findings are promising and reflect the effectiveness of existing pollution control

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measures. They align with trends observed in regions with minimal industrial activity, where pollution levels are generally low, and environmental conditions remain stable [10].

However, localized concerns regarding Lead (Pb) indicate the existence of certain hotspots of contamination within Sungai Kilim. Elevated Lead concentrations at stations K1, K3, K5, K8, and K13 point to more significant contamination in these areas, as evidenced by higher Igeo values. Lead pollution is particularly concerning due to its toxicity, which poses serious health risks to humans and wildlife even at relatively low concentrations. Previous research in coastal and estuarine environments has identified industrial activities, urban runoff, and vehicle emissions as common sources of Lead contamination, which contribute to its increased deposition in sediment and water [11,29].

The identified hotspots of Lead pollution highlight the need for focused and sustained monitoring efforts. Considering the persistence and toxicity of Lead, it is critical to track its concentrations over time and investigate potential contamination sources. Factors such as localized industrial activities, runoff from urban areas, or historical use of Lead-containing materials (e.g., paint or gasoline) could contribute to the problem. Addressing these sources will be essential to mitigating further contamination [31]. This approach aligns with best practices in environmental management, which advocate monitoring, source identification, and targeted interventions to address pollution locally [10]. In summary, while the overall environmental quality in Sungai Kilim is encouraging, the localized contamination of Lead requires a focused approach to environmental management. Regular monitoring, coupled with strategies for identifying and addressing pollution sources, will be key to maintaining ecosystem health and safeguarding public health in this region.

CONCLUSION

The study of metal concentrations in Sungai Kilim reveals significant variability in cobalt (Co), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn), with pollution patterns influenced by local environmental factors. In Kilim, Co and Cr exhibit notable variability, while Pb concentrations vary widely, indicating diverse pollution sources. Zinc levels also fluctuate, whereas consistently high iron levels suggest a common origin or widespread environmental impact. These findings underline the importance of addressing localized pollution through targeted regulatory measures, such as controlling industrial discharges and managing emissions from boating activities. Limitations of the study include potential variability in sampling methods and the influence of unmeasured local factors. The findings highlight the necessity of identifying pollution hotspots, tailoring interventions to specific contaminants, and implementing stringent environmental regulations to mitigate current impacts and prevent future contamination.

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AUTHOR’S CONTRIBUTION

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Mohamad Sajjad carried out the research, wrote and revised the article. Prof. Ts. Dr. Mohd Azlan Mohd Ishak conceptualized the central research idea and provided the theoretical framework. Ts. Dr. Jamil Tajam and Dr. Khairunnisa Ahmad Kamil designed the research, supervised research progress; Prof. Ts. Dr. Mohd Azlan Mohd Ishak and Ts. Dr. Jamil Tajam anchored the review, revisions and approved the article submission.

CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare absence of conflicting interests with the funders.

REFERENCES

[1] Kumar, P., & Fulekar, M. H. (2019). Multivariate and statistical approaches for the evaluation of heavy metals pollution at e-waste dumping sites. *SN Applied Sciences*, *1*, 1506. https://doi.org/10.1007/s42452-019-1559-0.

[2] Tang, Z., Deng, R.-J., Zhang, J., Ren, B.-Z., & Hursthouse, A. (2019). Regional distribution characteristics and ecological risk assessment of heavy metal pollution of different land use in an antimony mining area—Xikuangshan, China. *Human Ecology Risk Assessment: An International Journal*. https://doi.org/10.1080/10807039.2019.1608423.

[3] Zhu, D. H., Song, Q. L., Nie, F. H., Wei, W., Chen, M. M., Zhang, M., & Chen, J. J. (2022). Effects of environmental and spatial variables on bacteria in Zhanjiang mangrove sediments. *Current Microbiology*, *79*(4), 97. https://doi.org/10.1007/s00284-021-02684-5.

[4] Gamal, E. H. O., Hussein, H. A., Khaled, E., Mohammed, R. S., & Iqbal, A. (2019). Recent progress in metal-microbe interactions: Prospects in bioremediation. *Journal of Pure and Applied Microbiology*, *13*(1), 13–26. https://doi.org/10.22207/JPAM.13.1.02.

[5] Blanton, A., Ewane, E. B., McTavish, F., Watt, M. S., Rogers, K., Daneil, R., et al. (2024). Ecotourism and mangrove conservation in Southeast Asia: Current trends and perspectives. *Journal of Environmental Management*, 365, 121529.

[6] Chilton, D., Hamilton, D. P., Nagelkerken, I., Cook, P., Hipsey, M. R., Reid, R., et al. (2021). Environmental flow requirements of estuaries: providing resilience to current and future climate and direct anthropogenic changes. *Frontiers in Environmental Science*, *9*, 764218.

[7] ElTurk, M., Abdullah, R., Mohamad Zakaria, R., & Abu Bakar, N. (2019). Heavy metal contamination in mangrove sediments in Klang estuary, Malaysia: Implication of risk assessment. *Estuarine, Coastal and Shelf Science*. https://doi.org/10.1016/j.ecss.2019.106266.

[8] Meng, S., Peng, T., Pratush, A., Huang, T., & Hu, Z. (2021). Interactions between heavy metals and bacteria in mangroves. *Marine Pollution Bulletin*, 172, 112846.

[9] Tajam, J., & Kamal, M. L. (2013). Marine environmental risk assessment of Sungai Kilim, Langkawi, Malaysia: Heavy metal enrichment factors in sediments as assessment indexes. *International Journal of Oceanography*. https://doi.org/10.1155/2013/482451.

[10] Liao, J., Cui, X., Feng, H., & Yan, S. (2021). Environmental background values and ecological risk assessment of heavy metals in watershed sediments: A comparison of assessment methods. *Water, 14*(1), 51. https://doi.org/10.3390/w14010051.

[11] Mziray, W. A., & Kimirei, I. A. (2016). A review on the accumulation of heavy metals in coastal sediment of Peninsular Malaysia. Environmental Monitoring and Assessment, 188(2), 70. https://doi.org/10.1007/s10661-016-5374-0.

https://doi.org/10.24191/scl.v19i2.6866

[12] Dessie, E. (2022). Determination of selected heavy metal content and its associated health risk in selected vegetables and fruits marketed in Bahir Dar Town, Northwest Ethiopia (Doctoral Dissertation, Department of Pharmacy, Wollo University).
[13] Foo, Y. Z., Ecklyn, F. F. M., Tan, Y. F., Khoo, X. Y., Lee, H. Y., Yong, J. C., & Ong, M. C. (2021). Heavy metals level in the surficial sediment from Perai River of Penang, Malaysia. In *IOP Conference Series: Earth and Environmental Science,* 944(1), p. 012052.
[14] Mokhtar, M., Tajam, J., & Wagiman, S. (2019). Determination of the sediment contamination level in Dangli waters of Langkawi UNESCO Global Geopark, Kedah, Malaysia. *Sains Malaysiana*, *48*(1), 45-49. https://doi.org/10.17576/jsm-2019-4801-06.
[15] Torta, F., Hoffmann, N., Burla, B., Alecu, I., Arita, M., Bamba, T., & Wenk, M. R. (2024). Concordant inter-laboratory derived concentrations of ceramides in human plasma reference materials via authentic standards. *Nature communications*, *15*(1), 8562.
[16] Chand, V., & Prasad, S. (2013). ICP-OES assessment of heavy metal contamination in tropical marine sediments: A comparative study of two digestion techniques. *Microchemical Journal*, *111*, 53-61. https://doi.org/10.1016/j.microc.2012.11.007
[17] Zhou, Y., Jiang, D., Ding, D., Wu, Y., Wei, J., Kong, L., ... & Deng, S. (2022). Ecological-health risks assessment and source apportionment of heavy metals in agricultural soils around a super-sized lead-zinc smelter with a long production history, in China. *Environmental Pollution*, *307*, 119487.
[18] Sutherland, R. A. (2000). A comparison of geochemical information obtained from two fluvial bed sediment fractions. Environmental Geology, 39, 330-341.
[19] Muller, G. 1981. The heavy metal pollution of the sediments of Neckars and its tributary: A stocktaking. Chem. Zeit., 105: 157-164.
[20] Silva, A., Johnson, L., & Torres, M. (2019). *Geochemical patterns in riverine sediments: Case studies*. Environmental Geochemistry Journal, 22(3), 45-67.
[21] CCME (Canadian Council of Ministers of the Environment). (2019). Canadian sediment quality guidelines for the protection of aquatic life: Summary tables.
[22] Li, Y., Pan, S., Wang, L., Jia, F., Lu, F., & Shi, J. (2023). Soil chromium accumulation in industrial regions across China: Pollution and health risk assessment, spatial pattern, and temporal trend (2002–2021). *Toxics*, *11*(4), 363.
[23] Krueger, K. M., Carey, C. C., Gerling, A. B., Doubek, J. P., & Soranno, P. A. (2020). Iron and manganese fluxes across the sediment-water interface in a drinking water reservoir. *Water Research, 182*, 116003.
[24] Chen, M., Ma, L., & Zhang, J. (2018). Heavy metal contamination in coastal sediments of China: Sources and spatial distribution. *Marine Pollution Bulletin, 136*, 187-193.
[25] Li, Y., Wang, S., & Zhang, H. (2016). Urban runoff as a significant source of heavy metals in aquatic environments. *Science of the Total Environment, 557*, 753-761.
[26] Zhang, W., Cheng, Z., & Yu, H. (2020). Assessing heavy metal pollution and sediment quality in coastal ecosystems. *Environmental Pollution, 263*, 114399.
[27] Mao, Q., Yang, Q., & Liu, X. (2021). Spatial distribution and source identification of heavy metals in the coastal sediments of East China. *Environmental Pollution, 268*, 115917.
[28] Torres, C., Figueroa, M., & Pérez, G. (2022). Characterizing the spatial distribution of lead in coastal ecosystems: Implications for marine ecosystem management. *Environmental Pollution,* 285, 117515.
[29] Zhao, X., Huang, J., & Liang, C. (2019). Heavy metals in coastal sediments: Sources, fate, and impact on ecosystems. *Environmental Science and Pollution Research, 26*(12), 12234-12247.
[30] Van, H. T., & Nga, L. T. Q. (2024). Effects of Zn pollution on soil: Pollution sources, impacts and solutions. *Results in Surfaces and Interfaces*, 100360.

https://doi.org/10.24191/scl.v19i2.6866

[31] Mititelu, M., Neacșu, S. M., Busnatu, Ș. S., Scafa-Udriște, A., Andronic, O., Lăcraru, A. E., & Olteanu, G. (2025). Assessing Heavy Metal Contamination in Food: Implications for Human Health and Environmental Safety. *Toxics*, *13*(5), 333.

https://doi.org/10.24191/scl.v19i2.6866