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Geochemical Assessment and Spatial Distributions of Trace Elements in the Surface Sediments of the Strait of Malacca

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Abstract
The Strait of Malacca is one of the major shipping routes in naval logistics linking Indian and Pacific Oceans, which later these activities contributed to the trace metal accumulation in the Strait of Malacca. To assess the source of geochemical elements along with several factors affecting the concentrations in the surface sediments, five surface sediments were collected for physiochemical studies along the Strait of Malacca. The study revealed that the average of the clay, silt, and sand fraction was 10.93, 37.99, and 51.08 % respectively. The average concentrations of Al, Fe, Cr, Mn, and Mg, which were incorporated into seabed sediments through primary deposition from several sources were 5.88 ± 0.63 %, 2.78 ± 0.41 %, $5.73 \times 10^{-3} \pm 1.02 \times 10^{-4}$ %, $9.32 \times 10^{-3} \pm 5.83 \times 10^{-4}$ %, $4.72 \times 10^{-2} \pm 4.61 \times 10^{-3}$ %, and 2.19 ± 0.21 % respectively. According to the results, the comparison of these elements with sediment quality guideline revealed that Cr contents were higher than the low range of the interim sediment quality guidelines (ISQG), suggesting that Cr may pose an environmental hazard. The average enrichment factor (EF) showed as minor and moderate enrichment for all elements while the contamination factor revealed that seabed sediments were affected by moderate level of Cr and Mg contamination. The pollution load indices (PLI) showed that only one sampling station N106 were affected by several sources of geochemical elements in its vicinity. Thus, the coastal area of Strait of Malacca may require further mitigation measure to contain the pollutant levels across the straits.

Keywords: Strait of Malacca; Heavy metal; Sediment; Pollutant; Enrichment factor

1. Introduction

As an important shipping route linking the Indian Ocean and Pacific Ocean, the Strait of Malacca is situated between east coast of Sumatra Island at the southeast end and connected with Strait of Singapore (Thia-Eng *et al.,* 2000). The Strait of Malacca is located at the Equator, and thus has a tropical climate with an annual precipitation of 3000 mm/yr, resulting in severe weathering and monsoonal seasons. The hydrological current in Strait of Malacca is dominated by monsoonal forces, while having a semi-diurnal tidal cycle, with low to medium high turbidity along with a water transparency ranging from 10 to 30 m (Haditiar *et al.,* 2020). The drainage basins adjacent to the Strait of Malacca contribute several nutrient inputs towards its shallow coastal zones, leading to primary productivity being geographically influenced and constant throughout the year (Tan *et al.,* 2006).

The Strait of Malacca is also affected by the wind surges from the Northern and Southern Hemisphere, which leads to the monsoonal seasons. The northeast monsoon occurs from November to March while the southwest monsoon begins in May and ends September, which later causes a corresponding change of kinetic energy in sea currents, variations of precipitation and alters the weathering and sinking processes within the Strait of Malacca (Aboobacker 2017). This results in the Strait of Malacca acting as main contributor for sediment mobilization towards the outer shelf of the Andaman Sea through the hydrodynamic differences driven by monsoonal seasons (Schwab *et al.,* 2012). In previous decades, several environmental issues have been raised such as river pollution where sanitary infrastructures did not keep up with population growth, leading to a deterioration of water quality. Meanwhile, land reclamation, sand mining, and deforestation are common anthropogenic problems that are fast becoming an environmental concern (Saili and Mohamed 2021). Furthermore, monsoon-induced events in highlands can cause severe soil erosion and combined with anthropogenic inputs, result in severe damages to the nearby population (Rahim *et al.,* 2019). These hazards also elevate the concentration of geochemical elements and sedimentation. Previous studies regarding environmental issue in Straits of Malacca has been recorded by (Alina *et al.,* 2012; Khandaker *et al.,* 2015; Ismail *et al.,* 2016), reveals that high level of trace metals originated from anthropogenic inputs (shipping, urbanization and industrial activities) which in turn would pose a biological hazards in the marine environments.

Sediments are a main contributor to environmental quality since the characteristics of sediments determine their ability to affect ecosystem health and biodiversity communities in aquatic environments. Constant deposition through natural and anthropogenic sources would lead to bioaccumulation and bioamplification in marine biodiversity through the source and sink processes of sediments (Woelfl *et al.,* 2006). In theory, monsoonal seasons are the catalyst for magnifying the concentration of pollutants present in the Strait of Malacca through intense physical and hydrological processes. The objective in this study was to assess the source of geochemical elements in the Strait of Malacca along with several factors that affecting the concentration of these elements. Thus, this paper investigates the pollution concentration along with physical attributes of sediment and its influences in geochemical concentration within the Strait of Malacca.

2. Materials and Methods

Five surface sediment samples (Figure 1) with water depths ranging from 15.5 to 67.8 m were obtained using a Veen Van Grab sampler on at western coast of Peninsular Malaysia on August 2017 and May 2018 during the expedition of the UKM-FIO scientific cruise. The methods described by Rahim *et al.,* (2019) were used for the geochemical analyses. The dry and homogenized 60µm sediment samples were mixed with 10 mL nitric acid (HNO_3), 5 mL perchloric acid ($HClO_4$), and 1 mL hydrofluoric acid (HF) for 2 hr in a Teflon beaker and heated to 120 °C. The digested sample was then diluted with 0.5 M nitric acid and 0.5 g boric acid before being subjected to inductively coupled plasma mass spectrometry (ICP-MS) for further analysis of the Al, Fe, Ti, Mn, Mg and Cr content. A standard reference material (NIST 1633b) was used with five replicates for quality assurance; yields between 88 to 92 % of the concentrations were obtained, where the recoveries for each elements producing average yield results of 89% for Al, 89% for Fe, 88% for Ti, 90% for Mg, 92% for Mn and 91% for Cr.

The sediments were texturally analyzed according to the procedures described in (Miller *et al.,* (1987) and Miller, (1993). The organic matter and $CaCO_3$ content were determined with the loss of ignition (LOI) method following Santisteban et al., (2004) was used. In marine environments, the ability of sediments to retain fluids is based on several parameters such as physico-chemical conditions which control the precipitation and dissolution of metals within sediments as their prominent sinks. Sediments can provide a record of the source of pollutants through continuous sinks from adjacent drainage basins which marks the degree of pollution. Thus, a contamination factor (CF) are considered effective tools for monitoring pollution over a period of time, given the site of metal concentrations and their background values (Gopinath *et al.,* 2010).

$$CF = {}^{M_C}/_{B_C}$$

Where M_c is the measured concentration of the metal and B_c is its background concentration. In the meantime, other indices such as the pollution load index (PLI) were used to compare evaluate the degree of heavy metal pollution in marine sediments (Wojciechowska *et al.,* 2019).

$$PLI = (CF_1 \times CF_2 \times \ldots \times CF_N)^{1/N}$$

Where CF is the contamination factor described in the equation above and N is the number of the elements studied. PLI < 1 represents the prefect sediment quality, PLI = 1 corresponds to the baseline level of pollutant presents in the sediment while PLI > 1 indicates degradation of sediment the respective regions (Wojciechowska *et al.,* 2019).

Table 1. Sediment texture and other parameters at the Strait of Malacca

Station	Longitude	Latitude	Sampling Date	Depth (m)	Clay (%)	Silt (%)	Sand (%)
N95	99.9606	6.0069	1/5/2018	39.5	7.23	21.98	70.79
N99	99.9811	5.4428	2/5/2018	40.8	11.30	15.09	73.61
N103	100.44	4.9433	2/5/2018	15.5	13.24	65.70	21.06
N106	100.4561	4.3733	2/5/2018	22	11.44	83.43	5.12
N108	100.4828	3.8247	2/5/2018	67.8	11.41	3.77	84.81
Average					10.93	37.99	51.08

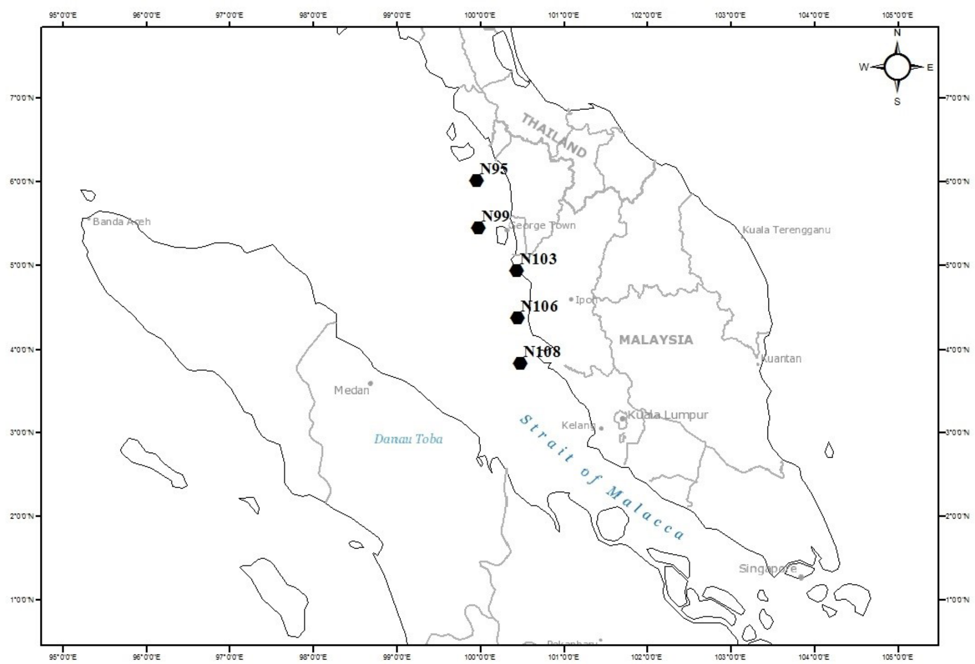

Figure 1. Sampling station for surface sediments in the Straits of Malacca off the west coast of Peninsular Malaysia [Data source: Rahim et al., (In press)]

3. Results and Discussion

The studied sediments consisted of an average of 10.93% clay, 37.99% silt and 51.08% sand. Differences in sedimentary textures were apparent between samples obtained from stations N108 and N95, high silt contents were observed for N95 while N108 was represented by high proportions of clay and sand (Table 1). The increase of clay contents in sediments would suggest the remobilization in the surficial sediment at station N108, where the adjacent river was contributing a significant and sudden input of clay due to weathering and precipitation (Othman *et al.,* 2015). In addition, the tides and waves extending along with Ekman transport generate a net motion from the Andaman Sea towards the Strait of Malacca; this phenomenon is influenced by the severity of monsoonal seasons resulting in mass migration and remobilization and thus contributing towards the increase of silt in station N95 (Weijer *et al.,* 2015; Mandal *et al.,* 2021).

Among the nutrients present in the sediments along the Strait of Malacca, the average values of organic matter and $CaCO_3$ were 6.05 ± 0.14 % and 8.24 ± 0.32%, respectively. The exposure of the adjacent shelf surrounding Peninsular Malaysia leads to hydrological shifts in the magnitude of wave currents, ebb and tides along the Straits of Malacca resulting in different $CaCO_3$ (8.24%) and organic matter (5.41%) content between stations N95 and N108. Furthermore, monsoonal seasons also contribute to the difference in nutrient content where the rate of removal is higher in accordance with diffusion rates in the seabed sediment (Mohamed *et al.,* 2019).

Figure 2 below reveals the spatial distribution of the studied elements along the Straits of Malacca. Further investigation showed that the average concentrations acquired for each element were 2.88 ± 0.34% (Fe), 5.00 ± 0.5% (Al), 1.92 ± 0.18% (Mg), $5.62 \times 10^{-2} \pm 4.20 \times 10^{-3}$ % (Mn), $9.46 \times 10^{-3} \pm 6.4 \times 10^{-4}$ % (Cr) and $5.14 \times 10^{-3} \pm 9 \times 10^{-5}$ % (Zn). Stark differences were observed between the Fe and Zn concentrations in Straits of Malacca and off the east coast Peninsular Malaysia where these levels were 44% (Fe) and 10% (Zn) higher. This suggests that sources from the adjacent shelf contributed to the differences in concentration levels (Shaari *et al.,* 2015). In meantime, the monsoonal season played an important role for higher precipitation rates, which eventually elevated the weathering rates within the drainage basin thus increasing the discharge rates.

Coincidentally, cross shelf inputs and bottom current trajectories may have been affected by the depth difference between The Strait of Malacca and the Andaman Sea, resulting in diminished trans-boundary mobilization and leading to lower rates of remobilization of seabed sediments. This process was due to the difference in dynamic uplift in both water masses (i.e., shallow depth and deeper depth) leading to differences in nutrient transports, and thus low nutrient contents in the shallower shelf (Väli *et al.,* 2011). According to Haditiar *et al.* (2019), the Strait of Malacca enable a small water mass exchange with the Andaman Sea compared to the east coast of Peninsular Malaysia which is influenced by the monsoon which generate a lower transport dynamic between the two coasts. Nevertheless, anthropogenic inputs from urbanization and industrialization along the respective stations also leads to the elevated level of geochemical content.

Correlation analysis was used to determine the relationship between the different geochemical element (Table 2). The correlation matrix revealed that Cr content were positively correlated with Al ($r = 0.917$; $p < 0.05$) and Fe ($r = 0.949$; $p < 0.05$), while positive relation was present between Al and Fe ($r = 0.993$; $p < 0.05$). The strong positive correlation between Al and Fe suggesting the weathering from the parent rock, which is granitic rocks that present in the Western Belts of Peninsular Malaysia (Yaraghi *et al.,* 2020). On the other hand, the positive relation of Fe and Al towards Cr suggested an association of secondary oxides during weathering which exhibit a release behaviour of Cr^{3+} to that of Al^{3+} and Fe^{3+} (Gamaletsos *et al.,* 2017; Yang *et al.,* 2019).

In the meantime, some sediment attributes exhibited a positive correlation with the studied elements. For example, Zn content were correlated with silt ($r = 0.887$; $p < 0.05$), suggesting that absorption-desorption taken place in silt during positive cation exchange capacity processes, reflecting the high level of Zn within the silts. According to Aloupi *et al.,* (2002), several internal parameters of oxyhydroxides, organic matter and carbonates play an important role in the development of the specific surface area of particle which eventually affect the rate of absorption and desorption of sediments, following the Zn contamination of sediments.

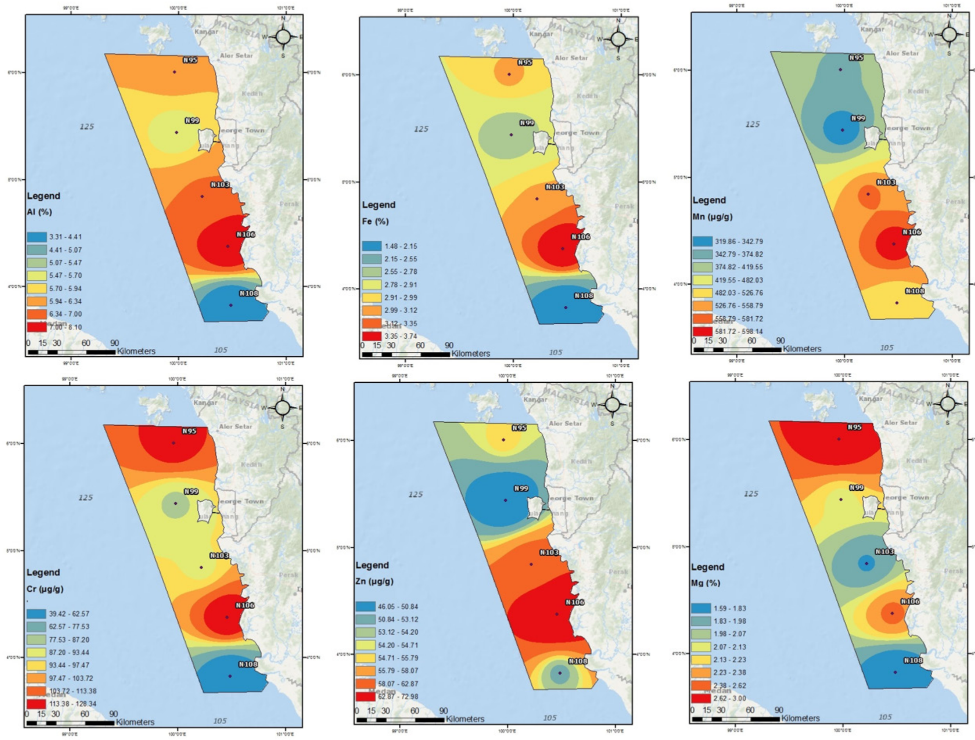

Figure 2. Spatial distribution of selected geochemical elements in the surface sediments of the Strait of Malacca

Table 2. Pearson correlation for all the variables present in the Strait of Malacca

	Clay	Silt	Sand	OM	$CaCO_3$	Al	Fe	Zn	Cr	Mn	Mg
Clay	1										
Silt	0.396	1									
Sand	-0.448	**-.998****	1								
Om	-0.675	0.211	-0.163	1							
$CaCO_3$	**-.938***	-0.46	0.506	0.747	1						
Al	0.012	0.87	-0.848	0.654	0.008	1					
Fe	-0.069	0.814	-0.788	0.718	0.108	**.993****	1				
Zn	0.173	**.887***	-0.874	0.229	-0.358	0.746	0.675	1			
Cr	-0.379	0.641	-0.6	0.866	0.385	**.917***	**.949***	0.584	1		
Mn	0.567	0.73	-0.746	-0.377	-0.786	0.332	0.228	0.814	0.053	1	
Mg	-0.829	0.133	-0.078	**.941***	0.811	0.544	0.615	0.223	0.83	-0.341	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

a. Listwise N=5

Occasional spills of crude oil along with the usage of galvanized anticorrosion products may affect the quality of sediments in the Strait of Malacca, resulting in elevated Zn levels in bulk sediments (Rahman and Ishiga 2012). On the other hand, a positive relationship was noted between Mg and organic matter suggesting the decomposition of organic matter in hemipelagic sediments, which in turn will lead to the accumulation of ammonium ion in sediments (von Breymann *et al.,* 1990). The displacement of Mg^{2+} occurred during ammonium ion uptake during organic matter breakdown is because of the greater affinity of NH^{4+} from sediment particle surface via ion exchange(Jorgensen and Weatherley 2006). Furthermore, weathering due to precipitation may increase the Mg levels as the leached granitic rocks may become a primary source for elevated Mg contents through terrestrial surface runoff, resulting high in organic matter and Mg levels (Kopáček *et al.,* 2017).

3.1 Accumulation of geochemical elements

Based on the average composition of shale presented by Turekian *et al.,* (1961), the average CF values fluctuated as several geochemical elements were present in higher concentrations than others (Table 3). The CF value for Cr suggested moderate levels of Cr contamination ($1 \geq CF \geq 3$) at station N95, N103 and N106. For Mg, the CF value reflected its moderately availability, and presence at all stations. Coincidentally, Al contamination was only recorded at station N106, which will be discussed later. The high CF value of Mg at all stations suggests that the pollutant originated from the industrialization sources. According to Forsido *et al.,* (2020), the generation of highly toxic Mg-bearing materials from industrial and atmospheric fallout, result in the aquatic environment becoming inhabitable for marine lifeforms. Furthermore, a recent study by Wang *et al.,* (2020) revealed that the smelting industry and fertilizers for agriculture are becoming a primary contributor of elevated Mg content in soils; Mg slags can be present in the form of industrial solid waste or used as fertilizers due to their high concentrations of Ca, Mg, and Si which can later be mobilized through runoff towards drainage basins.

The high CF of Cr at stations N95, N103 and N106 also represent anthropogenic inputs of shipyard was prevalent at N95, while N103 and N106 received Cr inputs through terrestrial runoff or wastewater discharges. Rauff *et al.,* (2020) revealed that the deterioration of water quality was apparent surrounding the reclaim area, resulting in elevated Cr levels at station N95. In turn, stations N103 and N106, saw a rise in the Cr concentration due to terrestrial runoff and industrialization which happen along the Perak River and Sangga Besar River (Rauff *et al.,* 2020). A similar study by Rahim *et al.,* (2019) showed that the elevated Cr was due to anthropogenic inputs from terrestrial runoff, finally affecting the elemental concentrations of riverbed sediments, resulting in the deterioration of sediment quality. In the meantime, the dominant CF values of Al suggested the bioaccumulation of pollutants present within the sampling sites, resulting in acidic conditions in the aquatic environment and while Al was being used for the precipitation of phosphorus (P), the bioaccumulation

Table 3. Contamination factor (CF) and pollution load index (PLI) values of the sampling stations in the Strait of Malacca

	Al	Fe	Zn	Cr	Mn	Mg	PLI
N95	0.76	0.64	0.58	1.35	0.44	2.01	0.83
N99	0.69	0.57	0.48	0.95	0.38	1.40	0.67
N103	0.80	0.64	0.63	1.02	0.66	1.21	0.80
N106	1.01	0.79	0.77	1.43	0.70	1.63	1.00
N108	0.41	0.31	0.55	0.44	0.59	1.06	0.52
Average	0.74	0.59	0.60	1.04	0.56	1.46	0.77

of Al eventually elevated the P content and drove away the ecological population surrounding the region of interest (García-García *et al.,* 2012). Research by Gensemer *et al.,* (1999) demonstrated that the rise of Al as a pollutant rather than a biologically essential metal into acidic environments would likely affect aquatic organisms largely in terms of toxicity rather than deficiency, since the Al must satisfy the metabolic requirement of organisms, but have low enough concentration to prevent toxicity.

The PLI values of the selected geochemical elements in this study was presented in Table 3. The PLI values were found to be at baseline level (PLI =1) at station N106, indicates the minimum pollution present in the station N106 (Tomlinson *et al.* 1980; Redwan and Elhaddad 2022). Although the minimum pollution were present in N106 as the coastal regions, the adjacent source of the Manjung River would pose a hazard due to continuous anthropogenic inputs channeling out through Manjung River (Abdullah *et al.,* 2015). According to enrichment factor (EF) values, all selected geochemical element contributed to the sum of the total of pollutants present in the sediments, with the highest total contribution at station N95. As a result, as shown by the PLIs obtained in the surface sediments within the Strait of Malacca, the sediment quality was worst at station N106 at the time of sampling due to the primary deposition of pollutants from its main river, therefore require immediate action from appropriate authorities.

The ranges of geochemical concentrations presented in this study were compared with those of other studies reported within Malaysia and internationally along with sediment quality guidelines (Table 4). In comparison with studies conducted in Malaysia, the Fe concentration were found to be comparable with those reported by Talukder *et al.,* (2021), but higher than those reported by Tavakoly Sany *et al.,* (2013) and lower than the concentration presented in Soon *et al.,* (2016) and Shazili *et al.,* (1997). The Zn, Cr and Mn contents observed in this study were also higher than those reported in previous studies by Tavakoly Sany *et al.,* (2013) and Talukder *et al.,* (2021). However, in comparison to international studies, the Al contents measured here were lower than in studies conducted in the Mediterranean Sea (El-Sorogy and Attiah 2015). However they were comparable to those obtained by Keshav *et al.,* (2015) and Kim *et al.,* (2016), as the ranges observed here were in between the concentrations obtained from the Bay of Bengal and Baixada Santista. In the meantime, the Fe concentrations were comparable to those of the Bay of Bengal and Baixada Santista (Keshav *et al.,* 2015; Kim *et al.,* 2016), but the Zn values were only comparable to those obtained from the Bay of Bengal (Keshav and Achyuthan 2015), while lower concentrations of Zn were reported for the Mediterranean Sea (El-Sorogy and Attiah 2015). The comparison of the Cr, Mn, and Mg contents measured here against those obtained from international water bodies showed that the Cr concentration in the Bay of Bengal were comparable to those obtained in this study (Keshav and Achyuthan 2015). On the other hand, the Mn concentrations obtained here were comparable with those measured in Baixada Santista and the Mediterranean Sea (Kim *et al.,* 2016; El-Sorogy *et al.,* 2015). Comparisons of Zn and Cr contents could be made with the Hong Kong ISQG reported by Chapman *et al.,* (1999). This revealed that the concentrations obtained in this study were higher than the threshold level for Cr set by the ISQG-low level. A similar comparison with those of Canadian sediment quality guidelines showed that the Cr concentrations were above the threshold limits (Salam *et al.* 2019). This translates to the severe biological effects which were not expected to be occurred frequently since the probable effect level (PEL) was a level above that at which severe biological effect is expected to occurred very often (Salam *et al.* 2019). The PEL is commonly used by different associates involved in coastal management activities as a screening tool for assessing sediment quality. In turn, Cr is known for its toxicity and bioaccumulation in ecology communities, which later affect their biodiversity in the respective region. Therefore, it is advised for proper mitigation to be conducted within the sampling location.

Table 4. Comparison of the selected geochemical elements from the coastal areas surrounding Malaysia, international examples, and sediment quality guidelines

Location	Al (%)	Fe (%)	Zn (μg/g)	Cr (μg/g)	Mn (μg/g)	Mg (%)	References
Local							
Port Klang coastal area, Selangor, Malaysia	14.7	6.5	51.05	46.4	231.43	-	(Tavakoly Sany *et al.*, 2013)
Setiu Wetland, Terengganu, Malaysia	0.1374 - 16.44	0.0388 - 7.3	0.03 - 23.40	1.49 - 46.20	5.40 - 332.00	-	(Talukder *et al.*, 2021)
Marudu Bay, Sabah, Malaysia	2.14 - 3.81	0.88 - 1.33	42.77 - 89.3	-	93.71 - 318.22	-	(Soon *et al.*, 2016)
East coast of Peninsular Malaysia	3.04	2.03	76.3	74	-	-	(Shazili *et al.*, 1997)
International							
Cuddalore coast, Bay of Bengal, India	7-9	4.18-7.98	53.7-89.7	112-170	0.05-0.09	-	(Keshav and Achyuthan 2015)
Baixada Santista, Southeastern Brazil	1.69 - 42.81	1.53 - 43.79	5.81 - 133.64	2.75 - 40.23	11.03 - 927.38	-	(Kim *et al.*, 2016)
Andaman Islands	0.33-0.42	0.508 - 3.93	10.4 - 27.72	5.76 - 9.56	23.18 - 524.8	-	(Nobi *et al.*, 2010)
Mediterranean Sea	240	18.96 - 19.81	298.50 - 394.11	0.23–0.29	600–640	0.0530 – 0.0590	(El-Sorogy and Attiah 2015)
Sediment quality guidelines							
Canadian sediment quality guideline (PEL)	-	-	315	90	-	-	(Salam *et al.*, 2019)
Hong Kong (ISQG-low)	-	-	200	80	-	-	(Chapman *et al.*, 1999)
Hong Kong (ISQG-high)	-	-	410	370	-	-	(Chapman *et al.*, 1999)
This study	2.57 - 8.11	1.48 - 4.44	31.85 - 73.09	39.42 - 128.35	319.86 - 971.02	1.39 - 3.01	

4. Conclusion

The geochemical inputs to the coastal regions of the Strait of Malacca coastal were revealed by the EFs of selected elements (Al, Fe, Zn, Cr, Mn, and Mg) derived mainly from natural and anthropogenic sources which promoted their elevated concentrations in the vicinity of the sampling stations. Based on PLIs and geoaccumulation indices, the sediments along the Strait of Malacca are unpolluted to moderately polluted, and would later deteriorate, potentially impacting the aquatic life in the Strait of Malacca. Therefore, the coastal areas of the Strait of Malacca require further attention to mitigate their contamination. Finally, the data presented in this study will contribute to Malaysia's ISQG data source as it provides a baseline study with detailed contamination assessment indices for surface sediments in the coastal regions of the Strait of Malacca.

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