



Ecological risk assessment of Polychlorinated Biphenyls (PCB) in the sediment around Langkawi Island, Malaysia

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Abstract

Background : Langkawi Island, a UNESCO Global Geopark in Malaysia, faces increasing vulnerability to organic contamination from persistent pollutants such as polychlorinated biphenyls (PCBs). Owing to their environmental persistence and bioaccumulative properties, PCBs pose potential ecological and human health risks, particularly in coastal and port-influenced environments.. **Objective**: This study aimed to determine the concentrations, spatial distribution, possible sources, and ecological risks of selected PCB congeners in surface sediments surrounding Langkawi Island. **Methodology**: Surface sediment samples were collected from five locations around the island and analyzed for fourteen PCB congeners. Sample preparation and extraction followed United States Environmental Protection Agency (USEPA) standard methods. Quantitative analysis was conducted using gas chromatography equipped with a micro-electron capture detector (GC- μ ECD). Ecological risk was assessed using established sediment quality guidelines and probabilistic risk approaches.

Results : Total PCB concentrations ranged from 42.35 to 151.96 ng/g, with a mean concentration of 60.42 ± 4.31 ng/g. The highest PCB levels were observed at Telaga Harbor, likely associated with intensive maritime activities and vessel maintenance operations. No significant correlation was found between total PCB concentrations and sediment organic content, suggesting multiple or localized contamination sources. High-chlorinated PCB congeners predominated (63%), indicating inputs from port operations, jetties, and waste disposal activities. Ecological risk assessment indicated occasional adverse biological effects, while the probability of severe toxicity to aquatic organisms and risks to human health remained below 50%.. **Conclusion**: Although PCB contamination in Langkawi Island sediments is moderate, localized hotspots associated with harbor activities warrant attention. The dominance of highly chlorinated congeners highlights the influence of maritime-related sources. Continued environmental monitoring and management of ship-related contaminants are recommended to protect the ecological integrity of this geopark.

Keywords: Polychlorinated biphenyls, sediment, Langkawi, Malaysia, Risk assessment, Tourism

1. Introduction

Polychlorinated biphenyls (PCBs) constitute a class of persistent organic contaminants characterized by high toxicity, environmental mobility, lipophilicity, and biomagnification along food webs. Owing to these properties, even low-level exposure to PCBs may induce adverse effects on both wildlife and human health (Moon et al., 2009). In marine systems, sediments act as the primary sink for PCBs, where these compounds can persist for extended periods due to their strong resistance to chemical and biological degradation, thereby serving as indicators of historical pollution inputs. PCB congeners with higher degrees of chlorination (6-9 chlorine atoms) exhibit greater stability and toxicity compared to lower chlorinated congeners (1-5 chlorine atoms), largely due to their reduced susceptibility to biodegradation (Moon et al., 2009 & Nasher et al., 2025).

Although the importation of polychlorinated biphenyls (PCBs) and PCB-containing products has been prohibited in Malaysia since 1995, a considerable number of aging transformers and capacitors filled with PCB-contaminated oils remain in operation (Ibrahim, 2007). In addition, various consumer goods, including certain paints, carbonless copy paper, obsolete fluorescent lighting systems, and electrical equipment containing PCB-based capacitors, are considered potential secondary sources of PCBs in the Malaysian environment (CAOP, 2005). Numerous investigations have reported the presence of PCBs across different environmental compartments in Malaysia, Monirith et al., (2003); Vaezzadeh et al., (2021); Nasher et al., (2025), as well as in human samples, Sudaryanto et al., (2005), indicating widespread and persistent contamination. According to national reports, envi-

ronmental releases of PCBs primarily occur through accidental spills, leakage during chemical transportation, and failures or fires involving transformers and capacitors. Furthermore, PCBs may also be emitted during combustion-related activities such as waste incineration and uncontrolled open burning at landfill sites (CAOP, 2005).

Langkawi Island is located in the Strait of Malacca along the northwestern margin of Peninsular Malaysia (JPDSM, 2007). The Island was designated as a national Geopark in 2006 and subsequently recognized as a UNESCO Global Geopark in 2007. As a result, Langkawi has been promoted primarily as an ecotourism destination and is largely protected from intensive industrial development. However, the Island attracts approximately 2.4 million visitors annually (JPDSM, 2007), and the continuous growth of tourism-related activities is likely to impose increasing environmental pressure, potentially contributing to elevated levels of pollution in both terrestrial and marine ecosystems.

Ecological risk assessments of polychlorinated biphenyls (PCBs) in aquatic sediments have been widely reported in the scientific literatures (Hidayati et al., 2021; Kassegne et al., 2020; Iniahe and Kpomah 2022). In these investigations, measured PCB concentrations were commonly interpreted using sediment quality guidelines (SQGs), particularly the effects range-low (ERL) and effects range-median (ERM) thresholds developed for evaluating sediment-associated contamination. These benchmarks, adopted by the U.S. Environmental Protection Agency (USEPA), categorize contaminant levels into three risk classes: concentrations below the ERL are associated with rare biological effects, values between the ERL and ERM indicate the potential for occasional adverse effects, while concentrations exceeding the ERM are

linked to frequent negative biological impacts (Long et al., 1995). Despite extensive applications of this approach elsewhere, ecological risk assessments of PCB contamination in sediments have not yet been undertaken in this region of Malaysia. Consequently, the present study aims to investigate the concentrations, spatial distribution, potential sources, and ecological risks of fourteen PCB congeners in sediment samples collected from Langkawi Island.

2. Materials and Methods

22.1. Study Area.

Figure 1 presents the positions of five sampling stations surrounding Langkawi Island, including Langkawi Port, Telaga Harbor, Kilim Jetty, Porto Malai Jetty, and Kuah Jetty. The selection of these sites was based on the variation in anthropogenic activities characterizing each location. Detailed descriptions of the associated activities are provided in Nasher et al., (2025).

2.2. Sample Collection and Preparation

Surface sediment samples were obtained using a stainless-steel Van Veen grab sampler. The upper most sediment layer (0–10 cm) was carefully subsampled using a stainless-steel spatula that had been pre-cleaned with n-hexane and acetone to minimize contamination. The collected sediments were immediately wrapped in aluminum foil, sealed in polyethylene (Ziploc) bags, and stored in an ice-filled cooler prior to transport to the laboratory. Approximately 100 g of sediment from each station was transferred into pre-cleaned glass containers, weighed, and freeze-dried using a Labconco Lyph Lock 6 freeze dryer (Model 77530-00). Duplicate samples from each station were prepared and analyzed to ensure data reliability.

2.3. Grain size analysis

Sediment grain size distribution was determined to classify samples into gravel (>1 mm), sand (1–0.063 mm), and silt and clay fractions (<0.063 mm). Grain size analysis was performed using a Vibratory Sieve Shaker AS 300 control. A known mass of wet sediment was freeze-dried for 72 h (Labconco Lyph Lock 6, Model: 77530-00). water content was calculated based on the mass difference before and after drying. The dried sediments were gently homogenized using a mortar to preserve grain characteristics and subsequently sieved through a series of stainless-steel meshes (2, 1, 0.5, 0.25, 0.125, 0.063, and 0.045 mm) for 10 min. The mass retained on each sieve was weighed and expressed as a percentage of the total sieved mass. Sediment fractions ≤ 0.25 mm, consisting mainly of medium to fine sands and coarse silt, were selected for subsequent PCB analysis

2.4 Total organic carbon (TOC) and organic matter (OM)

Total organic carbon (TOC) content in sediment samples was determined following established protocols (Dahle et al., 2003 and Nasher et al., 2013). A fixed mass of sediment was acidified with concentrated hydrochloric acid (HCl) to reduce the pH to ≤ 2 for the removal of inorganic carbon and subsequently oven-dried at 50 °C for 48 h. TOC concentrations were measured using a high-temperature combustion method with a CHNS(O) elemental analyzer (Thermo Finnigan, Italy). Organic matter (OM) content was determined using the loss-on-ignition method. Approximately 2 g of dried sediment from each station was placed in a pre-weighed porcelain crucible and combusted at 550 °C for 6 h in a muffle furnace (Briggs, 1977). The OM percentage was calculated based on the mass difference before and after ignition.

2.5. Chemical Analysis

Polychlorinated biphenyl (PCB) congeners were extracted from sediment samples following USEPA Method 3540C (US EPA 1996a), while sample clean-up was conducted according to USEPA Method 3630C (US EPA 1996b). Briefly, 10 g of freeze-dried sediment was spiked with surrogate standards, including 2,4,5,6-tetrachloro-m-xylene (TCMX) and decachlorobiphenyl (PCB 209), to evaluate extraction efficiency. Samples were extracted using a Soxhlet apparatus with 200 mL of GC-grade acetone and dichloromethane (DCM) (1:1, v/v) for 10 h. The combined extracts were treated overnight with activated copper granules to remove elemental sulfur and subsequently passed through a glass column packed with glass wool. The extracts were con-

centrated to approximately 3 mL using a rotary evaporator (EYELA, Japan; Model N-1001S-W). Solvent exchange was performed by adding 10 mL of hexane, followed by further concentration to 2 mL.

The concentrated extracts were further purified by passing them through a glass chromatography column containing 5 g of deactivated silica gel (5% H₂O) and topped with 1 g of anhydrous sodium sulfate (Na₂SO₄). The PCB fraction was eluted with 25 mL of pentane and concentrated to 2 mL by rotary evaporation. Hexane (10 mL) was added for solvent exchange, and the final extract volume was reduced to 1 mL under a gentle stream of high-purity nitrogen gas. All extracts were stored in amber glass vials at –5 °C and analyzed within one week. The extract (1 µL) was injected into Gas Chromatography (Agilent Technologies, USA) equipped with a micro electron capture detector (µECD).

2.6 Instrumental Analysis

Quantitative determination of PCB congeners was performed using a gas chromatograph (Agilent 6890, USA) equipped with a micro-electron capture detector (µECD). Separation was achieved using a fused silica DB-5MS capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). High-purity nitrogen (99.9%) was used as the carrier gas at a flow rate of 1.0 mL/min, with make-up and purge gas flows of 45 and 30 mL/min, respectively. Detector gas flows were maintained at 450 mL/min for air and 45 mL/min for hydrogen. The GC system was operated in splitless injection mode. The oven temperature program was initiated at 80 °C and held for 3 min, increased to 180 °C at a rate of 20 °C/min, and finally ramped to 280 °C at 3 °C/min with a hold-time of 25 min (Nasher et al., 2025).

2.7 Quality Assurance and Quality Control QA/QC.

Quality assurance and quality control procedures were implemented to ensure the accuracy and reliability of the analytical results. Method accuracy was evaluated by determining the recovery of target PCB congeners in spiked sediment samples after correcting for concentrations measured in unspiked samples. Mean recoveries for the fourteen PCB congeners ranged from 72% to 89%, with relative standard deviation (RSD) values generally below 10%, in accordance with the acceptance criteria of USEPA Methods 3540C and 3630C. Surrogate internal standards (TCMX and PCB 209) were added to all samples to monitor potential losses and contamination during extraction, clean-up, and instrumental analysis. Analytical precision was assessed through the analysis of replicate sediment samples from each station. Procedural blanks were analyzed with every ten sample sets to detect possible contamination from solvents, reagents, surrogate standards, or laboratory glassware. The limits of detection LOD were adjusted to be three times as large as the standard deviation (SD) of the blank values. Limits of detection (LOD) were defined as three times the standard deviation of blank measurements, yielding detection limits ranging from 0.02 to 0.09 ng for PCB congeners. Results below the LOD were excluded from further analysis.

2.8 Data analysis

Chromatographic data acquisition and processing were carried out using Agilent ChemStation software. Quantification of PCB congeners was achieved using an external calibration method based on fourteen PCB standards. Calibration curves showed strong linearity, with correlation coefficients (r) ranging from 0.98 to 0.99. Regression models with r values ≥ 0.99 were considered acceptable according to Environmental Protection Agency guidelines. Pearson correlation analysis was employed to examine relationships between PCB concentrations and sediment characteristics, including TOC, OM, and grain size fractions, as well as inter-congener relationships among sampling stations. Statistical analyses were conducted using SPSS software (version 15.0 for Windows), and statistical significance was defined at p ≤ 0.05, corresponding to a 95% confidence level.

3. Results

3.1 Sediment characteristics

Table 1 summarizes the percentage composition of organic matter (OM), total organic carbon (TOC), and grain-size fractions in

the sediment samples collected from the main port and several jetties surrounding Langkawi Island. The highest TOC and OM values were observed at Kilim Jetty, which can be attributed to its position at the mouth of the Kilim River. This river is bordered by extensive mangrove forests that contribute substantial amounts of organic material to the jetty area (Nasher et al., 2013). Furthermore, leakage from the nearby landfill and direct discharge of municipal waste into the river likely enhance the organic load entering the site. Grain-size distribution indicates that the sediments throughout the Island are predominantly sandy (Table 1), with clay fractions accounting for less than 1% of the total composition. A strong and statistically significant association was identified between OM and TOC contents ($r^2 = 0.80$), while TOC showed a moderate correlation with the proportion of sandy sediment ($r^2 = 0.44$).

Table 1. Percentage composition of OM, TOC, and grain-size fractions in Langkawi Island sediments

Stations	OM%	TOC%	Gravel %	Sand %	Silt+Clay %
Langkawi Port	15.31	1.37	23.19	76.81	
Kuah Ferry	12.95	1.56	5.39	94.61	
Kilim Jetty	16.74	3.10	1.26	98.67	
Telaga Harbor	9.78	0.68	9.91	89.92	0.15
Porto Malai Jetty	14.37	1.25	11.00	89.00	

3.2 Concentrations of PCB in sediment

The concentrations of total PCB congeners ($\Sigma 14$ PCBs) measured in sediment samples from the five sampling stations around Langkawi Island are illustrated in Figure 2. Substantial spatial variation was observed among the stations, with total PCB concentrations ranging from 42.35 ± 3.43 ng/g at Kuah Ferry to 151.96 ± 8.89 ng/g at Telaga Harbour, and an overall mean concentration of 60.42 ± 4.31 ng/g. The highest PCB contamination was recorded at Telaga Harbor, where 13 of the 14 target congeners were detected, indicating diverse and continuous PCB inputs. In contrast, the lowest contamination levels were observed at Kuah Ferry, where only nine congeners were identified. Congener-specific results revealed that PCB 95, 138, 180, and 195 were the dominant compounds, collectively contributing approximately 49% of the total PCB burden. Among individual congeners, PCB 138 exhibited the highest concentration, whereas PCB 52 was detected at the lowest levels.

Elevated PCB concentrations at Telaga Harbor can be attributed to its function as a focal point for recreational yachts, sailing vessels, and privately owned boats, where fueling, servicing, and maintenance activities are routinely conducted. Maintenance operations within the Harbor and adjacent workshops may release PCB-containing materials, such as dielectric fluids, into the aquatic environment (Kassegne et al., 2020). In addition, surface runoff during the rainy season can transport PCB-contaminated soils into harbor waters, further contributing to sediment contamination. The hydrophobic and persistent nature of PCBs, coupled with their strong affinity for suspended particulate matter, promotes their accumulation and long-term retention in bottom sediments.

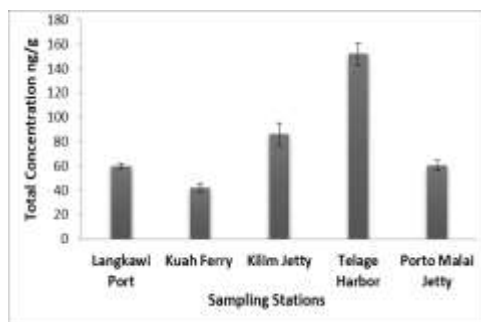


Figure 2. The total concentrations (ng/g) of PCBs for sediment samples of Langkawi Island

Total PCB concentrations at the remaining stations, Kilim Jetty (86.24 ± 8.62 ng/g), Porto Malai Jetty (60.42 ± 5.03 ng/g), and Langkawi Port (59.90 ± 9.98 ng/g), were relatively comparable, suggesting the influence of common contamination sources

and/or similar anthropogenic activities across the Island. The rapid socio-economic development of Langkawi as a major eco-tourism destination over the past two decades has likely intensified activities such as the disposal of obsolete electrical transformers, oil leakage, shipping operations, and municipal effluent discharges. These factors may collectively contribute to the widespread distribution of PCBs in the marine environment of Malaysia and the broader Southeast Asian region (Wurl and Obbard, 2005).

In addition to local sources, regional transport from neighboring industrialized areas, including Penang Island and parts of Thailand, may also influence PCB contamination in Langkawi through seasonal monsoon winds and prevailing sea currents. Elevated PCB concentrations reported in urban and industrial regions of Thailand have been attributed to extensive use of transformers and capacitors, as well as industrial effluents and power plant discharges (Cheevaporn et al., 2005). Similarly, high PCB levels detected in human breast milk from Penang have been linked to municipal and industrial waste disposal sites, with atmospheric transport identified as a major exposure pathway (Sudaryanto et al., 2005). In tropical regions, heavy rainfall can effectively scavenge atmospheric PCBs and deliver them to coastal waters, representing a significant input pathway to marine sediments (Wurl and Obbard 2005). Additional contributions may arise from high-temperature industrial processes on the Island, such as cement production and waste incineration, which are known to generate PCB emissions. A similar PCB input was reported in China by DLH (2014).

The results of regression analyses for the total PCB congeners and their corresponding geochemical parameters (including OM, TOC content and sediment particle size) at each sampling sites revealed that no significant correlations ($p < 0.05$) were found between total PCB congeners and TOC % ($r^2 = -0.30$), OM % ($r^2 = -0.61$), or Sandy sediment ($r^2 = 0.11$), indicating that PCB accumulation in sediments is primarily governed by discrete source inputs and complex transport processes rather than sediment composition alone. These findings are consistent with previous studies, (Ouyang et al, 2006; Fatunsin et al, 2020 and Otim, 2020), and support the conclusion that PCB distributions in sediments are strongly influenced by localized anthropogenic activities such as ferry, jetty, and harbor operations, waste disposal sites, landfills, and emissions from cement production facilities.

3.3 Distribution and source of PCBs in sediment

The distribution patterns of PCB congeners and homologues in environmental media provide valuable insight into their potential sources, transport pathways, and environmental fate (Gao et al., 2013; Kassegne et al., 2020). The homologue composition of PCBs detected in sediment samples from Langkawi Island is illustrated in Figure 3. The following is the decreasing order of the average homologue composition of PCBs: hepta-PCB (24 %) > hexa-PCB (18 %) > octa-PCB (18 %) > penta-PCB (15 %) > tetra-PCB (13 %) > tri-PCB (11 %). The predominance of higher-chlorinated PCB homologues reflects their greater hydrophobicity, persistence, and resistance to biodegradation, which favor their accumulation in bottom sediments.

Telaga Harbour exhibited a relatively high contribution of penta-PCBs, accounting for approximately 31% of the total PCB burden at this site, compared with an average of 15% across all stations. Dominant penta-PCB congeners included CB95, CB101, CB105, and CB118. Previous studies have reported that PCB congeners 105 and 118 are associated with insulating oils used in electrical capacitor manufacturing (Huang et al., 2011). Moreover, commercial PCB mixtures such as Aroclor 1254, which are characterized by a high proportion of penta-chlorinated biphenyls, were historically used in a wide range of applications, including electrical equipment, paints, hydraulic fluids, plasticizers, sealants, inks, and pesticide extenders (ATSDR, 2000; Wischkaemper et al., 2013; Zhao et al., 2019; Hidayati et al., 2021). The detection of penta-PCBs in sediments is therefore considered a fingerprint of commercial PCB sources, likely derived from contaminated soils and transported into aquatic systems through surface runoff (Zhong et al., 2020). Hepta-

chlorinated PCBs were the most abundant homologues at several stations, contributing 39% at Langkawi Port, 25% at Telaga Harbor, and 24% at Porto Malai Jetty, with an overall average contribution of approximately 25% across all sediments (Figure 3). The dominance of hepta-PCB congeners such as CB187, CB180, and CB170 suggests inputs from electrical infrastructure, particularly transformers and capacitors, where highly chlorinated PCBs were extensively used due to their thermal stability and dielectric properties. Similar associations between hepta-PCBs and power generation facilities have been reported in soils near power plants in Nigeria (Aganbi et al., 2019).

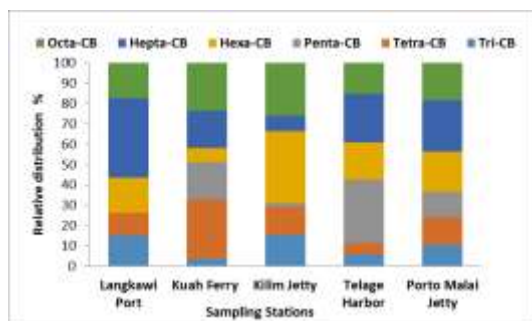


Figure 3. Relative distribution (%) of PCB homologue group in the sediment samples of Langkawi Island.

At Kilim Jetty, hexa-chlorinated PCBs (notably CB128 and CB138) were detected at particularly high levels, accounting for approximately 35% of the total PCB concentration, while the average contribution of hexa-PCBs across all stations was 18%. The landfill located near the Kilim River is considered a major potential source of PCB contamination to the river and adjacent jetty. PCB-128 has been identified as a combustion-related marker (Kim et al., 2004), and elevated levels of hexa-PCBs in sediments have been linked to fuel combustion emissions from boats and ships (Iniaghe and Kpomah, 2022). Consequently, intensive tourist boat traffic and shipping activities at Kilim Jetty likely contribute to local PCB inputs. In addition, relatively high proportions of octa-PCBs, dominated by CB195 (24%), and tri-PCBs, mainly CB18 and CB28 (16%), were also observed at this station. These findings indicate the combined influence of landfill leakage, open waste dumping, and boating activities, identifying Kilim Jetty as a localized hotspot of PCB contamination. In contrast, tetra-chlorinated PCBs, primarily CB52 and CB44, were most prominent at Kuah Ferry, where they constituted approximately 29% of the total PCB concentration, compared with an average of 13% across all sites. Tri-chlorinated PCBs are commonly associated with their use as additives in paints and electrical appliances (Eqani et al., 2013), and may also enter aquatic systems through direct disposal of solid wastes and industrial effluents (Unyimadu and Benson, 2023). The variability in PCB homologue composition among stations highlights the presence of multiple PCB sources across Langkawi Island.

The degree of chlorination plays a crucial role in determining the environmental fate and distribution of PCB congeners. As shown in Figure 4, highly chlorinated PCBs predominated over low-chlorinated congeners in most sediment samples. Highly chlorinated PCBs are more persistent, more lipophilic, and exhibit a stronger affinity for particulate matter, with slower degradation rates, allowing them to accumulate in sediments near their sources (Kassegne et al., 2020). The dominance of these congeners suggests that local point sources, including jetties, ferry terminals, harbors, ports, improper disposal of electrical equipment containing PCB-contaminated oils, and landfill sites, are major contributors to PCB contamination on the Island. Similar source patterns have been reported in other coastal and industrialized regions (Lao et al., 2021; Tang et al., 2020; Zhang et al., 2014; Deng et al., 2020).

In contrast, low-chlorinated PCB congeners are more volatile and mobile, enabling their transport over longer distances via water

currents, tidal exchange, and seasonal wind patterns. Regional industrial areas such as Penang Island and coastal zones of Thailand, where elevated PCB levels have been reported in sediments and marine organisms, may therefore represent boundary sources contributing to PCB inputs in Langkawi Island sediments (Cheevaporn et al., 2005). Overall, the observed PCB distribution pattern, dominated by high-chlorinated congeners (63%) with a substantial contribution from low-chlorinated congeners (37%), reflects the combined influence of local point sources and regional boundary transport processes.

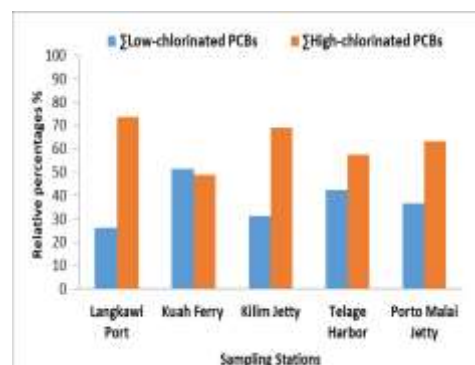


Figure 4. Relative percentages (%) of Σ low-chlorinated PCBs and Σ high-chlorinated PCBs in the sediment of different sampling stations

3.4 Ecological Risk assessment of PCBs

Polychlorinated biphenyls (PCBs) have been classified by the United States Environmental Protection Agency as probable human carcinogens, falling under Group B2, which indicates a medium level of carcinogenic risk (ATSDR, 2014). Exposure to PCBs through environmental pathways such as water, air, and food has been associated with a wide range of adverse health effects, including endocrine disruption, acne-like dermatological conditions in adults, and neurobehavioral and immunological alterations in infants (ATSDR, 2000; Klanova et al., 2007). In addition, long-term exposure to PCBs has been linked to cancer-related illnesses and toxic effects, particularly endocrine and neurotoxic impacts in humans (Kimbrough, 1995; ATSDR, 2000; Klanova et al., 2007). These properties underscore the potential ecological and human health risks posed by PCBs in aquatic environments.

The ecological risk of PCBs in sediments from Langkawi Island was assessed using the effects range-low (ERL; 22 ng/g dry weight) and effects range-median (ERM; 180 ng/g dry weight) sediment quality guidelines established by the U.S. Environmental Protection Agency. The total PCB concentrations measured in this study (42.35–151.96 ng/g dry weight) exceeded the ERL values but remained below the ERM threshold. This concentration range suggests that adverse biological effects on benthic organisms may occur occasionally, but are unlikely to be frequent. Consequently, the probability of negative toxic effects on aquatic organisms, and indirect risks to human health through the consumption of locally sourced fish and seafood, is estimated to be below 50%. Based on these criteria, sediments from Langkawi Island are not expected to pose frequent ecological or human health risks, nor to significantly threaten the local fisheries-based economy.

When compared with PCB concentrations reported in other regions, the levels observed in Langkawi Island sediments were broadly comparable to those measured in Bangladesh (32.17–199.40 ng/g; Habibullah-Al-mamun et al., 2019) and the Pearl River Estuary, China (17.68–169.26 ng/g; Zhao et al., 2016). However, PCB concentrations in this study were higher than those reported for several other aquatic environments, including shrimp ponds in northern Central Java (0.6–3.6 µg/kg), where contamination was attributed to the use of Aroclor 1254 in electrical equipment and to oil and fuel combustion (Hidayati et al., 2021); the Caspian Sea (2.00–53.00 ng/g; Mirzababaei et al., 2024); and the coastal waters of Qingdao, China (6.5–32.9 ng/g; Pan et al., 2007).

In contrast, PCB concentrations in Langkawi sediments were considerably lower than those reported for heavily impacted regions such as Lagos Lagoon, Nigeria (273.46–6757.61 ng/g), where PCB inputs were mainly associated with anthropogenic point sources (Unyimadu and Benson, 2023); the Surabaya coastal area, Indonesia (<DL–420 ng/g), where PCB distribution was strongly influenced by proximity to pollution sources (Mumhammad Ilyas et al., 2010); the central coastal area of Vietnam (9.72–3730 ng/g), where elevated PCB levels were linked to tourism, transportation, and domestic activities (Tham et al., 2019); and Gwangyang Bay, South Korea (average 294 ng/g), where higher concentrations in inner bay sediments indicated land-based pollution inputs (Hong et al., 2011).

Comparison of PCB homologue distribution patterns further supports these findings. The dominance of hepta-PCBs observed in the present study is consistent with results reported for soils near a power plant in the Niger Delta, Nigeria (Aganbi et al., 2019), while the elevated levels of penta-PCBs align with findings from sediment cores collected in the Lagos Lagoon system (Unyimadu and Benson, 2023). Variations in PCB concentrations and homologue profiles among different studies may be attributed to differences in industrial intensity, geographical setting, environmental conditions, sampling season, analytical methodologies, number and type of PCB congeners analyzed, physicochemical properties such as biodegradability and water solubility, and the effectiveness of waste management practices.

5. Conclusion

PCB congeners were detected in sediment samples collected from five locations around Langkawi Island, Malaysia. The highest concentrations occurred at Telaga Harbor, likely driven by intensive yacht and boat traffic as well as routine vessel maintenance operations. The remaining stations exhibited relatively comparable total PCB levels, suggesting the influence of similar local activities, particularly those associated with tourism-related boat movements, and shared point-source inputs. The dominance of highly chlorinated PCB congeners over lower-chlorinated forms can be attributed to their greater environmental persistence and limited degradability. These patterns point toward anthropogenic point sources such as marine vessel operations, yacht terminals, ship maintenance, disposal of PCB-containing electrical components, leakage from nearby landfills, and emissions associated with cement production. The absence of a significant relationship between total PCB concentrations and TOC% further supports the interpretation that human-generated inputs, rather than natural sediment characteristics, are the primary contamination drivers. Ecological risk assessment results indicate that the potential for harmful biological effects arising from PCB concentrations in the Island's sediments is low and unlikely to occur frequently. Nevertheless, systematic monitoring of persistent organic pollutants (POPs), alongside repeated ecological risk evaluations across multiple environmental compartments, is strongly recommended. Such continued surveillance is essential to safeguard the Island's marine ecosystems, which play a vital role in supporting the national economy through tourism and diverse fisheries resources.

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