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Spatial distribution and ecological risks of polychlorinated biphenyls in a river basin affected by traditional and emerging electronic waste recycling in South China

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ABSTRACT

With development of e-waste related legislation in China, formal recycling activities are designated in some areas while informal ones are illegally transferred to emerging areas to avoid supervision. However, the resulting environmental impact and ecological risks are not clear. Here, we investigated the discharge of polychlorinated biphenyls (PCBs) to soil and aquatic environments by e-waste recycling activities in the Lian River Basin, China. The study area included a designated industrial park in the traditional e-waste recycling area (Guiyu, known as the world's largest e-waste center), several emerging informal recycling zones, and their surrounding areas and coastal area. A total of 27 PCBs were analyzed, and the highest concentration was found in an emerging site for soil (354 ng g^{-1}) and in a traditional site for sediment (1350 ng g^{-1}) respectively. The pollution levels were significantly higher in both the traditional and emerging recycling areas than in their respective upstream countryside areas (p = 0.0356 and 0.0179, respectively). Source analysis revealed that the traditional and emerging areas had similar PCB sources mainly associated with three PCB technical mixtures manufactured in Japan (KC600) and the USA (Aroclor 1260 and Aroclor 1262). The PCB pollution in their downstream areas including the coastal area was evidently affected by the formal and informal recycling activities through river runoff. The ecological risk assessments showed that PCBs in soils and sediments in the Lian River Basin could cause adverse ecotoxicological consequences to humans and aquatic organisms.

1. Introduction

Before banning electrical and electronic waste (e-waste) import, approximately 70 % of the world's e-waste was shipped to China (Li and Achal, 2020). 47 % of the 1.5 million tons of e-waste imported ended up in Guiyu, Lian River Basin, China (Purchase et al., 2020). It is estimated that by 2030, about 28.4 million tons of e-waste will be domestically generated in China (Fu et al., 2018). During e-waste dismantling and thermo-recycling activities, many hazardous substances, such as polychlorinated biphenyls (PCBs) are released into the surrounding environment (Chakraborty et al., 2021; Liu et al., 2013b; Shi et al., 2020b). The presence of PCBs in the environment leads to a public health concern and wildlife decline since they are highly persistent, bioaccumulative, and potentially toxic (Liu et al., 2009, 2013a; Remili et al., 2021; Taylor et al., 2019). Although PCB production was banned in most countries from 1970 s to 1980 s, their environmental

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concentrations are still high in many areas across the globe (Helou et al., 2019; Weitekamp et al., 2021). Previous studies showed that e-waste recycling were the major source of PCBs that highly accumulated in soils, sediments, local food items, human milk of both residents and recycling workers in Guiyu (Xing et al., 2009; Shi et al., 2019). Therefore, PCBs continue to pose a significant threat to humans and wildlife in the e-waste recycling areas, and understanding their sources, fate, and transport should remain a research priority (Wang et al., 2020).

Facilities for e-waste recycling are often located in densely populated areas, marked by convenient transportation and highly connected river networks (Zhang et al., 2012; Shi et al., 2020a). Hence, e-waste recycling poses a significant threat to the immediate surrounding areas and the whole catchment area downstream (Lu et al., 2021). It is estimated that 75 % of e-waste recycling activities occurs in unregulated informal facilities (Zhang et al., 2012). Since previous studies primarily focused on PCB contamination in areas proximal to traditional e-waste recycling facilities, the contamination in downstream catchment area was overlooked as well as the role of emerging informal e-waste recycling in emission of PCBs (Yang et al., 2012). We hypothesized that the emerging area might be a new emission of PCBs. Therefore, there is a need for investigating the role of emerging informal e-waste recycling as a source of PCBs in the environment. Previous studies demonstrated that homolog distributions were a powerful chemical signature for assessing the source of PCBs in the environment (Li et al., 2009; Li et al., 2020).

The major objective of the present study is to investigate the chemodynamics of PCBs from an intensive e-waste recycling center and its surrounding whole catchment to better understand: i) the role of traditional and emerging informal e-waste recycling on the environmental distribution of PCBs in soils and sediments; ii) the transport pathways from emission points in the river basin to the marine environments; and iii) the potential ecological hazard based on sediment quality guidelines. Results from this study will provide critical insights on the strategies for mitigating pollution arising from e-waste recycling activities.

2. Materials and methods

2.1. Sample collection

Fig. 1 shows the locations where soil (n = 17), river sediment (n = 15), and marine sediment (n = 19) samples were collected in 2016. Briefly, **b**asin **s**oil (BS) and **r**iver **s**ediment (RS) samples were collected along the Lian River Basin and **m**arine sediment (M) samples were collected in the coastal area. The sediments were collected using a stainless-steel Peterson dredger, while soils were collected using a stainless shovel. Five subsamples were mixed in situ for each soil/sediment sample, wrapped with aluminum foil, and then packed into a plastic bag. All samples were put in an icebox, transported to the laboratory, and stored in a freezer at − 20 °C.

2.2. Chemicals

Reagents of pesticide grade such as n-hexane, dichloromethane (DCM), and acetone were purchased from local vendors (Anpel Inc., China). We selected 27 PCBs as target congeners, and these are (IUPAC number) 8, 18, 28, 44, 52, 66, 77, 81, 101, 105, 114, 118, 123, 126, 128, 138, 153, 156, 157, 167, 169, 170, 180, 187, 189, 195, and 206. Tetrachloro-*m*-xylene (TCMX) and decachlorobiphenyl (DCB) purchased from J&K Scientific (AccuStandard, USA) were used as surrogate standards, while 13 C-PCB208 (Smart E International, Wellington, Canada) was used as an internal standard. The purity of the analytical standards was > 95 %. The standard reference material (SRM) 1941b was purchased from the National Institute of Standards and Technology, USA.

2.3. Chemical analyses

Sample extraction and chemical analyses were performed following our previous methods (Shi et al., 2013, 2016a). Briefly, sediment and soil samples (>100 g) were freeze-dried (freeze drier, Songyuan, Inc.) for 5 – 7 days, ground to powder, and then sieved using a 100-mesh sieve. About 10 g of the sample was spiked with the TCMX and DCB surrogate standards before Soxhlet extraction for 18 h at 70 °C, using a

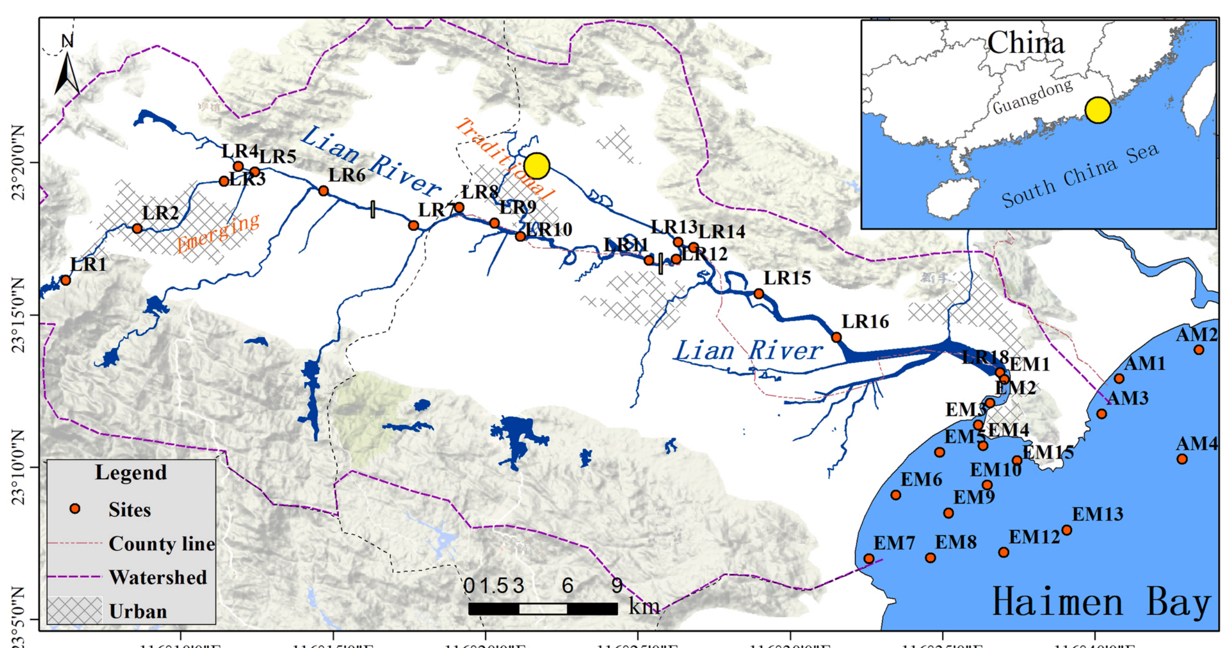

Fig. 1. Sampling locations in Lian River Basin, Guangdong Province, China. In detail, locations for **r**iver **s**ediments (RS1–18) and the adjacent basin soil samples (BS1–18) are designated as LR1–18 on the map (upstream background site, emerging informal e-waste recycling area, midstream traditional recycling area, the other urban and countryside areas, etc.); locations for marine sediment are designated as EM1–15 for estuary and Haimen Bay sediments and AM1–4 for adjacent marine sediments.

solvent mixture comprising acetone, hexane, and DCM (150 mL, 1:1:1, v/v/v). Sulfur was removed from sediment and soil samples using activated copper. The extractant was then concentrated using a rotary evaporator and cleaned up using column chromatography (packed with 2 g of Na_2SO_4, 8 g of silica gel, 5 g of alumina, and glass wool bottom-up). The PCB-containing fractions were eluted using a solvent mixture comprising DCM and hexane (20 mL, 1:1, v/v), followed by DCM (15 mL). The eluant was concentrated to 250 μL using a nitrogen evaporator before quantification using GC-ECD (Agilent 6890, USA), and congener identification using GC/MS (QP 2010 ultra, Japan).

Quantification using gas chromatography was achieved by first separating the analytes using a Rtx-5MS capillary column (30 m × 0.25 mm × 0.25 μm). The oven temperature for GC/MS and GC-ECD was programmed as follows: 110 °C (2 min), 110–180 °C (10 °C/min), 180–250 °C (5 °C/min), 280 °C (20 min). The GC/MS was operated in electron impact/selected ion monitoring mode. The target individual PCBs were quantified using the internal standards calibration method.

2.4. Quality control

Procedural blanks, matrix-spiked blanks, duplicate samples, and a standard reference material for marine sediments (SRM 1941b) were analyzed with every 20 field-sample batches. The recoveries of surrogate standards (TCMX and DCB) were within the 70–130 % range, while the measured spiked concentration ranged 75–125 % in SRM 1941b. Details on method detection limits and recoveries are provided in Table S1 and S2. The standard deviations were less than 15 % among duplicate samples. All the quality control results met the acceptable range for the performance of pollutant analysis in soils and sediments established by USEPA. The hierarchal cluster analysis (HCA) and principal component analysis (PCA) were conducted and visualized via R packages (*pheatmap and ggplot2*).

3. Results and discussion

3.1. PCBs distribution in basin soils, river and marine sediments

The Σ27PCB concentrations in soils from the Lian River Basin were 3.72 – 354 ng g^{-1} (Fig. 2). The average PCB concentration was 39.4 ng g^{-1}, which was comparable to an e-waste recycling site (26.2 ng g^{-1}) in north China; higher than river bank soils from Pakistan, urban soils in Turkey and Rwanda, an industrial park in Northwest China, and heavily higher than Tibetan Plateau, the highest altitude area on earth (0.025 ng g^{-1}) as shown in Tables S6 (Dumanoglu et al., 2017; Hong et al., 2018; Ren et al., 2019; Ullah et al., 2020; Xu et al., 2020). However, the mean concentration was lower than the concentrations detected in soils proximal to a PCB factory in Italy (250 ng g^{-1}) (Bagnati et al., 2019). Evidently, high PCB pollution in some areas of the world directly resulted from the PCB related industry. Hence, the relatively high-level PCB pollution in the Lian River Basin may relate to the e-waste recycling activities.

As shown in Fig. 2, the high concentrations were found in soils from the traditional e-waste recycling area (122 ng g^{-1}) and the emerging informal recycling area (354 ng g^{-1}), while the low concentrations were found in the upstream background area (4.5 ng g^{-1}) and a countryside area (3.72 ng g^{-1}). Statistical analysis showed that the PCB levels were significantly higher in the traditional emerging recycling area than in its surrounding area (88.4 vs 15.2 ng g^{-1}, $p = 0.0462$). Especially the levels were significantly higher in the traditional area than in its upstream and downstream areas ($p = 0.0398$ and 0.0190, respectively). The PCB spatial variations in soils suggested that e-waste recycling might be a major source of PCBs in the Lian River Basin (Shi et al., 2019).

River sediment acts as a sink for PCB contaminants (Lu et al., 2021). Generally, the concentrations were higher than those found in adjacent soils along the Lian River (Fig. 2 and Table S4), ranging from 18.7 to 1350 ng g^{-1}. The average concentration (521 ng g^{-1}) was comparable to the Ase River polluted by e-waste in Nigeria (Irerhievwie et al., 2020); higher than those polluted by industrial and urban emission (Table S7), such as the Lerma River in Mexico, the Delaware River in the USA, the River Clyde in the UK, Scarp River in France, the Brisbane River in Australia, and rivers in Shanghai (Brito et al., 2015; Net et al., 2015; Anim et al., 2017; Vane et al., 2017; Kim et al., 2018; Qadeer et al., 2019; Yang et al., 2019), heavily higher than the Chaobai River (drinking water) and Jiulong River (wetland) in China (Zhang et al., 2019; Yang et al., 2020); but lower than the Escravos River in Nigeria and the Hudson River (2500 ng g^{-1}) in the USA (Chitsaz et al., 2020; Iwegbue et al., 2020). Surficial sediments from the Escravos River were

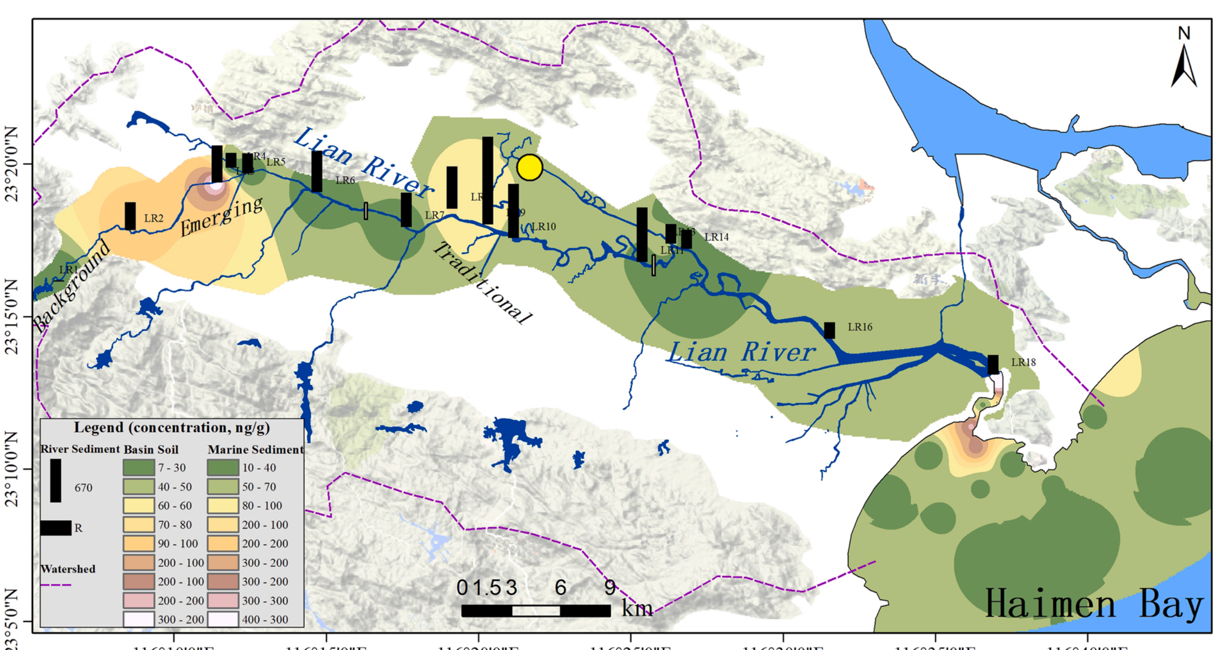

Fig. 2. The PCBs distribution in river sediments, basin soils, and marine sediments in Lian River Basin, Estuary and Haimen Bay, respectively.

exposed to fresh discharges from a crude oil production plant, while sediments from the Hudson River were exposed to historical contamination from capacitor production plants, indicating that the anthropogenic PCB evidence seemed to be sealed in sediments for both emerging (fresh) and traditional (historical) emissions (Butcher and Garvey, 2004; Rodenburg and Ralston, 2017).

Like spatial variations in basin soils, the highest Σ27PCB concentration was found in sediments from the traditional e-waste recycling area (1350 ng g^{-1}), followed by an emerging recycling site (761 ng g^{-1}); while the lowest concentration was found in upstream background area (18.7 ng g^{-1}). The pollution levels were significantly higher in both the traditional and emerging recycling areas than in their respective upstream countryside areas ($p = 0.0356$ and 0.0179, respectively). The results suggest that e-waste activities were probably a major contributor to the PCBs pollution in the Lian River sediments.

The Σ27PCBs concentrations ranged from 7.96 to 426 ng g^{-1} in sediments collected from Haimen Bay (Fig. 2 and Table S5). The average concentration was 61.6 ng g^{-1}, which was similar to the Ross Sea near Antarctica (Deng et al., 2020); higher than those from Persian Gulf, Bangladesh, Kingdom of Bahrain, Santos Estuary in Brazil, Adriatic Sea, and Delmarva ins USA, Bohai Sea and Jiulong River Estuary in China (Table S8) (Wu et al., 2016; de Souza et al., 2018; Kim et al., 2018; Habibullah-Al-Mamun et al., 2019; Jafarabadi et al., 2019; Bersuder et al., 2020; Combi et al., 2020). The comparisons indicated that the extent of PCB pollution in Haimen Bay was probably more severe, compared to the rest of the world.

In the fan-shaped marine area (Fig. 2), high concentration (426 ng g^{-1}) was found in the estuary of Lian River, which is the mixing zone of the river water and seawater, while the low concentrations were found in the outer area. These results suggest that riverine discharge was probably the main source of PCBs in marine sediments (Dinc et al., 2021; Johansen et al., 2021; Olisah et al., 2021). Statistical analysis results show that the mixing zone (estuary) showed significantly high pollution level than the outer area and adjacent marine area ($p = 0.0005$ and 0.0078, respectively). The results suggest that e-waste activities were probably a major contributor to the local marine PCBs pollution and the Lian River might a transport pathway.

3.2. Sources identification based on HCA

Under government intervention, dozens of recycling enterprises concentrated in the designated industrial park of the traditional area with 30-year recycling history, while more facilities were illegally transferred to wider emerging inform areas (Shi et al., 2016b, 2019). Cluster analysis of PCB concentration in soils showed that samples from the emerging and traditional recycling sites formed the same cluster (Fig. 3A, BS3 and 10). The results suggest that PCBs in emerging sites might share a similar source with that in the traditional recycling sites. Previous estimates reported that only 25 % of e-waste recycling occurs at designated centers (Li and Achal, 2020). Evidently, the e-waste

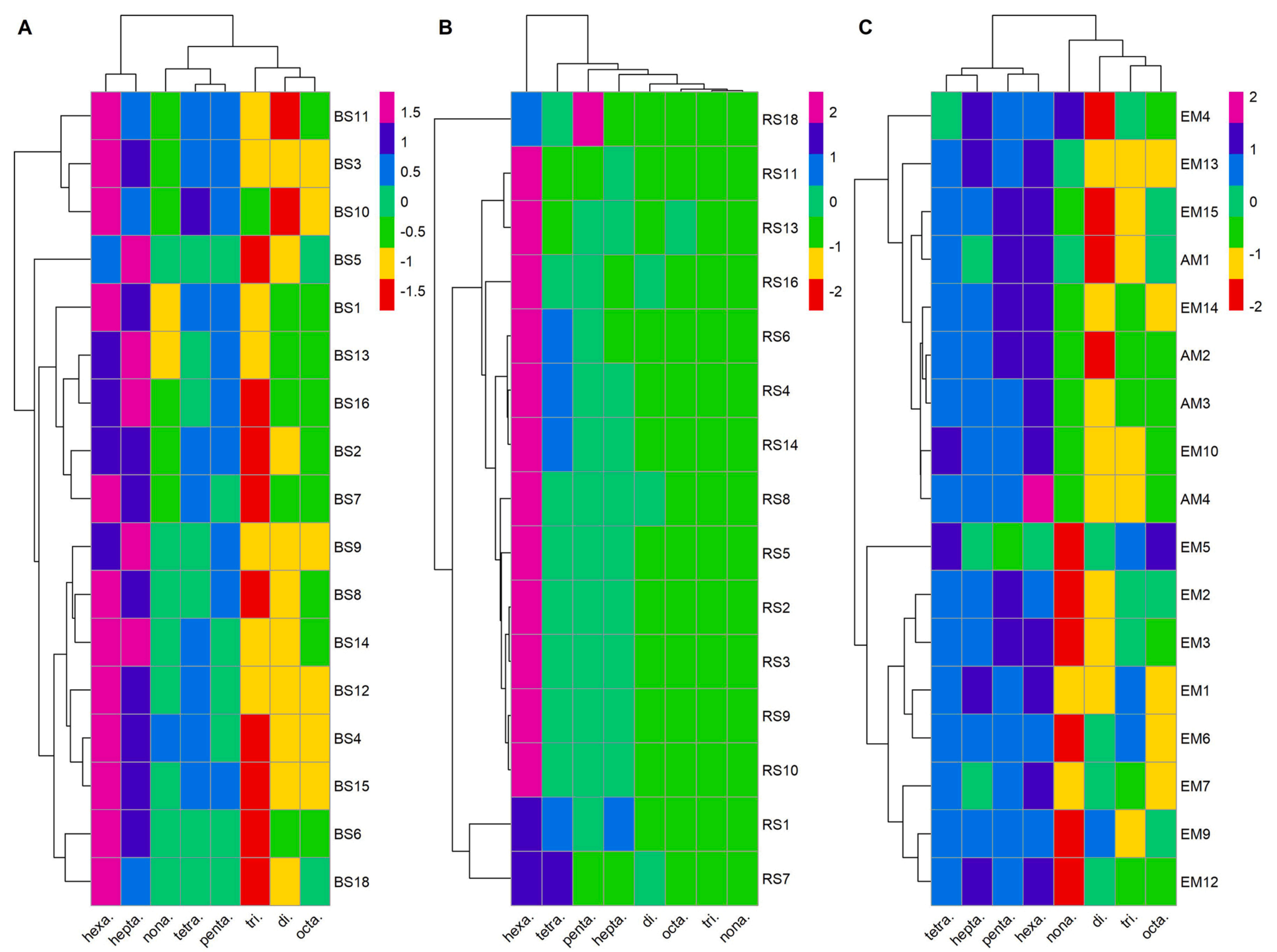

Fig. 3. HCA heatmap of field samples based on their PCB homolog distribution to identify potential pollution sources of basin soils (A), river sediments (B), and marine sediments (C), respectively.

recycling took place in emerging undesignated places illegally as well (Zhang et al., 2012).

The homolog distribution of PCBs among different sites might give more information about the sources and environmental transportation routes (Jin et al., 2020; Lu et al., 2021). The hexa- and hepta-CBs dominated all the soil samples in the Lian River basin. Previous studies found that the tri- and penta-CBs were the dominant congeners in historically contaminated soils in China, since they were the major PCB products prior to the 1980s (Wang et al., 2019). However, a recent study also about Guiyu found that hexa- and hepta-CBs were enriched in soils compared to tri- and tetra-CBs, and this was attributed to unregulated e-waste recycling and disposal (Luo et al., 2020).

Like soil (Fig. 3B), the hexa-CBs were the most dominant homologs in the river sediment. Overall, the median concentration of the PCB homologs in the Lian River sediments were in the order: hexa-CBs > tetra-CBs > hepta-CBs > penta-CBs > octa-CBs > nona-CBs ≈ tri-CBs > di-CBs. The homolog distribution differed significantly from the one obtained in the Yangtze River Estuary, which was impacted by e-waste recycling activities where the median concentrations were in the order: penta-CBs > tri-CBs > hexa-CBs > hepta-CBs > octa-CBs > nona-CBs (Zhao et al., 2019). Before they were banned, PCBs with high proportions of penta- and tri-CBs were manufactured in China. The comparison suggests that the recycling products here might be different from the Yangtze River Estuary.

Like soil, cluster analysis also showed that river sediment samples from the emerging and traditional recycling sites formed the same cluster (Fig. 3A, RS2, 3 and 9, 10). Apart from the upstream background and countryside sites (RS1 and 7), the homologue distribution showed a spatial consistency and continuity. Moreover, spatial variations in PCB concentration and homolog distribution in river sediments can be caused by changes in river flow rate, depth, direction, breadth, and other morphodynamical factors (Li et al., 2020). Overall, the results suggest sediments acted as a sink and surface runoff was a possible migration route of PCBs in aquatic environments.

In the marine sediment, hexa-CBs tetra- and penta-CBs dominated the homologue distribution, which was similar to the river sediment. The Haimen Bay can be classified as estuary area, left half area (mainly affected by the river runoff) and right half area (co-affected by the river runoff and the adjacent coastal current). The cluster analysis also showed that the estuary sites (EM1–3) formed in a same or a slightly bigger group, apart from EM4 (Fig. 3C), while the adjacent marine sites (AM1–4) formed in another different big group. More interestingly, the sites on the left half of the Haimen Bay formed in the same biggest group with estuary sites, while the right half sites of the bay formed in the same with adjacent marine sediment sites, indicating that the PCB pollution in this bay might be co-affected by the Lian River runoff and the adjacent coastal currents.

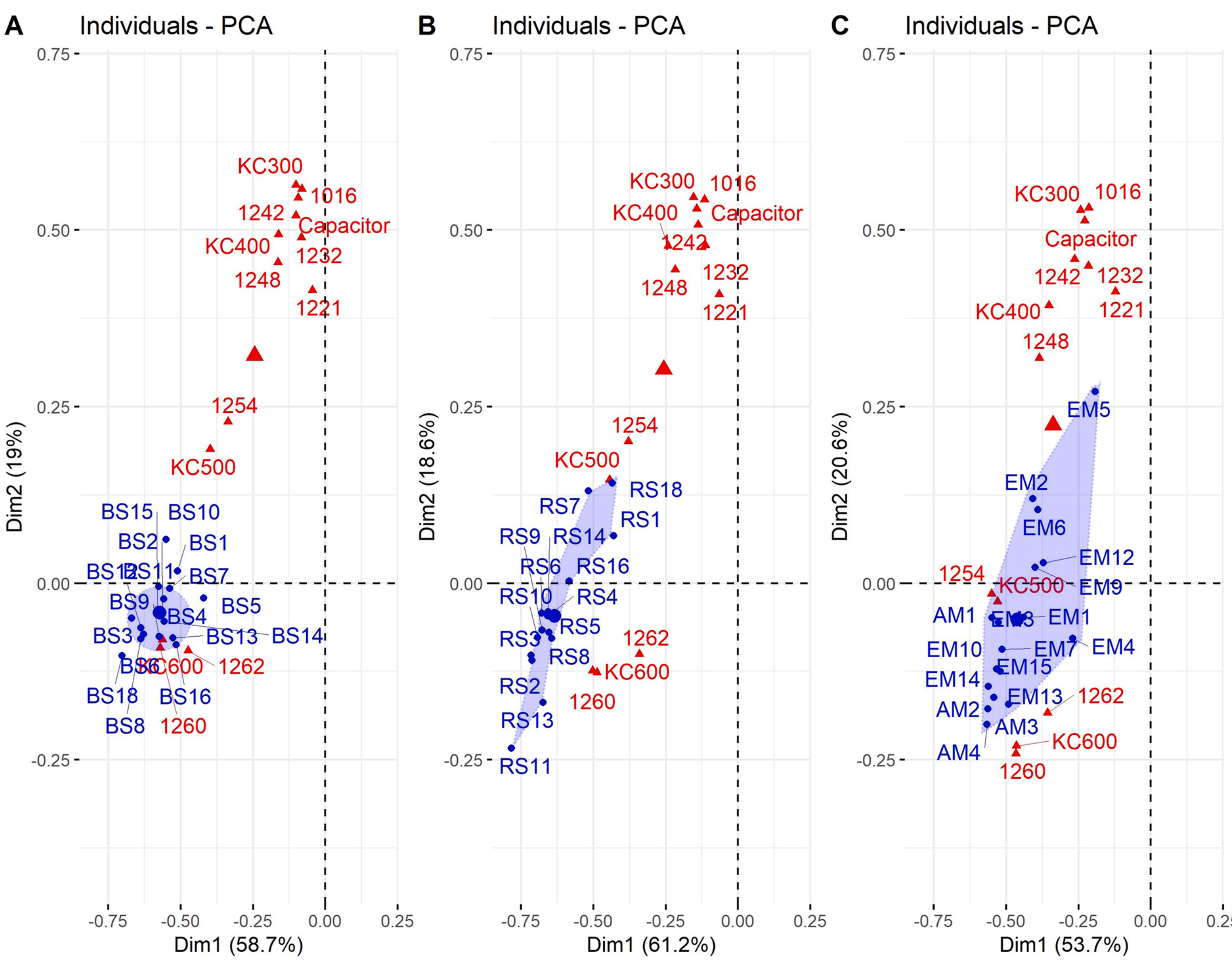

Fig. 4. PCA of commercial PCB products (red) and field samples (blue) based on their homolog distribution to identify the product sources of basin soils (A), river sediments (B), and marine sediments (C), respectively.

3.3. Sources identification based on PCA

The distribution of PCB homologs was further tested using PCA based on homologue distribution of each site, as well as the most used commercial PCB mixtures; namely, Aroclor (1016, 1221, 1232, 1242, 1248, 1254, 1260, and 1262) from USA, Kanechlor (KC300, 400, 500 and 600) from Japan, and capacitor mixtures (tri-PCBs) from China (Li et al., 2021). The first (PC1) and second (PC2) components explained 58.7 % and 19 % in basin soil variance (Fig. 4A), 61.2 % and 18.6 % in the river sediment (Fig. 4B), 53.7 % and 20.6 % in the marine sediment (Fig. 4C), respectively. Interestingly, the soil samples were closely concentrated in a small circle that included Aroclor 1260, 1262, and KC600; the river sediment samples were arranged like a river line, in which the emerging and traditional e-waste recycling sites were also close to the above commercial PCB mixtures; while the marine sediment samples were dispersed but slightly close to more other commercial mixtures, such as Aroclor 1254 and KC500. The PCA results indicated that the emerging and traditional e-waste recycling activities may have contributed to the discharge of PCBs into the terrestrial and aquatic environments in the Lian River Basin, and the influences decreased with distance.

The results demonstrated and supported that Lian River Basin was a global e-waste recycling region and the PCB containing products were mainly manufactured outside China. For example, KC600 was manufactured in Japan, while Aroclor 1260 and 1262 were manufactured in USA, which were mainly used in synthetic resins as plasticizers, and as a de-dusting agent (Faroon and Olson, 2000; Hidayati et al., 2021). However, this was different form another notorious e-waste center, Taizhou in China, featuring transformer and capacitor recycling (Xing et al., 2009). For example, Aroclor 1221 and 1248 were mainly used in capacitors, hydraulic fluids, gas-transmission turbines, vacuum pumps, and adhesives (Faroon and Olson, 2000). Their clusters were far from Lian River samples in PCA results (Fig. 4), further supporting the differences with Taizhou.

3.4. Potential health and ecotoxicological risks

Since PCBs are persistent, highly bioaccumulative, and toxic organic contaminants, evaluating the health and ecological risks of PCBs in soils and sediments is imperative (Brázová et al., 2021; Castro-Jiménez et al., 2021; Teunen et al., 2021; Valizadeh et al., 2021). However, there are currently no harmonized standards in China. For soils, we preliminarily assessed the health risks by comprising the maximum limit (60 ng g^{-1}) enacted by the former Union of Soviet Socialist Republics Ministry of Health (Bobovnikova et al., 1993; Aganbi et al., 2019). Here, 17.6 % of sites, all from the emerging and traditional e-waste areas, exceeded the limit, which may pose high health risks to residents.

We further used the Hakanson's potential ecological risk index (E_r^i) to estimate the ecological risk posed by PCBs, which is often used (Hakanson, 1980; Cui et al., 2016; Baqar et al., 2017). E_r^i is calculated using a toxicity factor of 40, and normalized concentration using PCB background concentration (usually 10 ng g^{-1}). Soils and sediments with $E_r^i < 40$ are considered to have low potential ecological risk, $40 \le E_r^i < 80$ have moderate potential, $80 \le E_r^i < 160$ have considerable potential; $160 \le E_r^i < 320$ have high potential, while $E_r^i \ge 320$ have very high risk. Here, soils from the emerging and traditional areas had a moderate potential to very high ecological risk. In river sediments, all sites posed very high ecological risk except the sites which didn't form in the same cluster with e-waste recycling sites (Fig. 3B).

Ecological risk of PCBs in sediments was further evaluated using sediment quality guidelines [SQG: threshold effect level (TEL), effect range low (ERL), effect range median (ERM), probable effect level (PEL)](Table 1) (MacDonald et al., 2000; Gómez-Gutiérrez et al., 2007; Mehdinia et al., 2021). The results demonstrate that a concerning number of sites had concentrations in the range where a frequent occurrence of adverse effects is expected in river and marine sediments (93.3 % and 70.6 %, respectively). None of the sites exceeded the PEL value for marine sediments. However, SQG have several limitations in assessing the magnitude of anthropogenic chemical pollution and the potential for eliciting adverse biological effects in aquatic organisms (McCauley et al., 2000; Birch, 2018). SQG are based on acute toxicity in invertebrates, which might not be adequate for protecting higher trophic level organisms such as fish, seabirds, and marine mammals (Sanganyado et al., 2021). Using a habitat-based food web model, a previous study found PCB concentrations in marine sediments that could protect killer whales against adverse effects were 0.004 – 0.39 ng g^{-1} (Alava et al., 2012). Based on this criterion, all the marine sediments contained PCB concentrations that could result in bioaccumulation of PCBs above the toxic effect threshold in marine mammals.

Table 1
Sediment water guidelines for PCBs (ng g^{-1} dry weight) and the percentage of incident of effects in the study.

Sediment quality guidelines	Threshold effect concentration		Probable effect concentration	
	TEL	ERL	PEL	ERM
River Sediment[a]				
Guidelines	34.1	50	277	400
Incident	93.3 %	93.3 %	80.0 %	53.3 %
Marine Sediment[b]				
Guidelines	21.6	22.7	189	180
Incident	70.6 %	70.6 %	17.6 %	17.6 %

[a] Sediment quality guidelines for freshwater sediments (MacDonald et al., 2000).
[b] Sediment quality guidelines for marine sediments (Gómez-Gutiérrez et al., 2007).

4. Conclusion

The highest PCB concentrations were detected in sediment and soil samples from e-waste recycling areas in the Lian River Basin, Guangdong Province, China. Moreover, source identification using HCA and PCA revealed that equipment containing commercial PCBs, such as KC600, Aroclor 1260, and Aroclor 1262, were imported into the recycling areas and the pollution in the other areas of the basin were affected by the recycling activities to varying degrees. Considering that only 25 % of e-waste recycling occurs in designated centers of the traditional area, the results of this study suggest that emerging informal e-waste recycling might be contributing to PCB contamination in the Lian River Basin. The results suggest surface runoff was a major route PCBs entered Lian River and that the physicochemical characteristics of the PCB homologs influenced their environmental fate and transport. An ecological risk assessment of the environmental samples revealed that there was a need for controlling PCB pollution in the Lian River Basin.

Overall, the whole basin PCB investigations revealed that curbing informal or unregulated e-waste recycling in emerging areas was imperative to reduce PCB pollution. Soil and sediment clean-up and remediation, upgrading of e-waste recycling procedures could help minimizing the discharge of contaminants into the environment. There are numerous micropollutants and their transformation products associated with e-waste (e.g., halogenated flame retardants, rare earth elements, and phthalates) that can threaten aquatic and terrestrial life in river basins impacted by e-waste. There is a need for comprehensive studies on the distribution, transport, fate, and trophic transfer of e-waste associated contaminants, as well as water and atmosphere processes to better understand the impact of e-waste recycling on environmental and human health.

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CRediT authorship contribution statement

Jingchun Shi: Conceptualization, Methodology, Investigation, Formal analysis. Visualization, Writing – review & editing. **Linlin Huang:** Methodology, Formal analysis. **Edmond Sanganyado:** Conceptualization, Formal analysis, Writing – review & editing. **Jiezhang Mo:** Conceptualization, Review. **Hongzhi Zhao**: Methodology, Investigation. **Li Xiang**: Methodology, Investigation. **Ming Hung Wong:** Supervision, Project administration. **Wenhua Liu:** Resources, Funding acquisition, Writing – review & editing.

Availability of data and material

All data pertinent to the study is available in the Supplementary Information. Additional raw data will be made available upon request.

Ethics approval

Not applicable.

Code availability

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request. All data pertinent to the study is available in the Supplementary Information. Additional raw data will be made available upon request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2022.114010.

References

Aganbi, E., Iwegbue, C.M., Martincigh, B.S., 2019. Concentrations and risks of polychlorinated biphenyls (PCBs) in transformer oils and the environment of a power plant in the Niger Delta, Nigeria. Toxicol. Rep. 6, 933–939.

Alava, J.J., Ross, P.S., Lachmuth, C., Ford, J.K., Hickie, B.E., Gobas, F.A., 2012. Habitat-based PCB environmental quality criteria for the protection of endangered killer whales (Orcinus orca). Environ. Sci. Technol. 46 (22), 12655–12663.

Anim, A.K., Drage, D.S., Goonetilleke, A., Mueller, J.F., Ayoko, G.A., 2017. Distribution of PBDEs, HBCDs and PCBs in the Brisbane River estuary sediment. Mar. Pollut. Bull. 120 (1–2), 165–173.

Bagnati, R., Terzaghi, E., Passoni, A., Davoli, E., Fattore, E., Maspero, A., Palmisano, G., Zanardini, E., Borin, S., Di Guardo, A., 2019. Identification of sulfonated and hydroxy-sulfonated polychlorinated biphenyl (PCB) metabolites in soil: new classes of intermediate products of PCB degradation? Environ. Sci. Technol. 53 (18), 10601–10611.

Baqar, M., Sadef, Y., Ahmad, S.R., Mahmood, A., Qadir, A., Aslam, I., Li, J., Zhang, G., 2017. Occurrence, ecological risk assessment, and spatio-temporal variation of polychlorinated biphenyls (PCBs) in water and sediments along River Ravi and its northern tributaries, Pakistan. Environ. Sci. Pollut. Res. 24 (36), 27913–27930.

Bersuder, P., Smith, A., Hynes, C., Warford, L., Barber, J., Losada, S., Limpenny, C., Khamis, A., Abdulla, K., Le Quesne, W., 2020. Baseline survey of marine sediments collected from the Kingdom of Bahrain: PAHs, PCBs, organochlorine pesticides, perfluoroalkyl substances, dioxins, brominated flame retardants and metal contamination. Mar. Pollut. Bull. 161, 111734.

Birch, G., 2018. A review of chemical-based sediment quality assessment methodologies for the marine environment. Mar. Pollut. Bull. 133, 218–232.

Bobovnikova, T., Dibtseva, A., Mitroshkov, A., Pleskachevskaya, G., 1993. Ecological assessment of a region with PCB emissions using samples of soil, vegetation and breast milk: a case study. Sci. Total Environ. 139, 357–364.

Brázová, T., Miklisová, D., Barčák, D., Uhrovič, D., Šalamún, P., Orosová, M., Oros, M., 2021. Hazardous pollutants in the environment: fish host-parasite interactions and bioaccumulation of polychlorinated biphenyls. Environ. Pollut. 291, 118175.

Brito, E.M., De la Cruz Barrón, M., Caretta, C.A., Goñi-Urriza, M., Andrade, L.H., Cuevas-Rodríguez, G., Malm, O., Torres, J.P., Simon, M., Guyoneaud, R., 2015. Impact of hydrocarbons, PCBs and heavy metals on bacterial communities in Lerma River, Salamanca, Mexico: investigation of hydrocarbon degradation potential. Sci. Total Environ. 521, 1–10.

Butcher, J.B., Garvey, E.A., 2004. PCB loading from sediment in the Hudson River: congener signature analysis of pathways. Environ. Sci. Technol. 38 (12), 3232–3238.

Castro-Jiménez, J., Banaru, D., Chen, C.-T., Jiménez, B., Muñoz-Arnanz, J., Deviller, G., Sempere, R., 2021. Persistent organic pollutants burden, trophic magnification and risk in a pelagic food web from coastal NW Mediterranean Sea. Environ. Sci. Technol. 55 (14), 9557–9568.

Chakraborty, P., Gadhavi, H., Prithiviraj, B., Mukhopadhyay, M., Khuman, S.N., Nakamura, M., Spak, S.N., 2021. Passive air sampling of PCDD/Fs, PCBs, PAEs, DEHA, and PAHs from informal electronic waste recycling and allied sectors in Indian megacities. Environ. Sci. Technol. 55 (14), 9469–9478.

Chitsaz, M., Fennell, D.E., Rodenburg, L.A., 2020. Sources of polychlorinated biphenyls to Upper Hudson River sediment post-dredging. Chemosphere 259, 127438.

Combi, T., Pintado-Herrera, M.G., Lara-Martín, P.A., Lopes-Rocha, M., Miserocchi, S., Langone, L., Guerra, R., 2020. Historical sedimentary deposition and flux of PAHs, PCBs and DDTs in sediment cores from the western Adriatic Sea. Chemosphere 241, 125029.

Cui, S., Fu, Q., Guo, L., Li, Y.-F., Li, T.-x, Ma, W.-l, Wang, M., Li, W.-l, 2016. Spatial–temporal variation, possible source and ecological risk of PCBs in sediments from Songhua River, China: Effects of PCB elimination policy and reverse management framework. Mar. Pollut. Bull. 106 (1–2), 109–118.

Deng, Z., Han, X., Chen, C., Wang, H., Ma, B., Zhang, D., Zhang, Z., Zhang, C., 2020. The distribution characteristics of polychlorinated biphenyls (PCBs) in the surface sediments of Ross Sea and Drake Passage, Antarctica: a 192 congeners analysis. Mar. Pollut. Bull. 154, 111043.

Dinc, B., Çelebi, A., Avaz, G., Canlı, O., Güzel, B., Eren, B., Yetis, U., 2021. Spatial distribution and source identification of persistent organic pollutants in the sediments of the Yeşilırmak River and coastal area in the Black Sea. Mar. Pollut. Bull. 172, 112884.

Dumanoglu, Y., Gaga, E.O., Gungormus, E., Sofuoglu, S.C., Odabasi, M., 2017. Spatial and seasonal variations, sources, air-soil exchange, and carcinogenic risk assessment for PAHs and PCBs in air and soil of Kutahya, Turkey, the province of thermal power plants. Sci. Total Environ. 580, 920–935.

Faroon, O., Olson, J.N. 2000. Toxicological profile for polychlorinated biphenyls (PCBs).

Fu, J., Zhang, H., Zhang, A., Jiang, G., 2018. E-waste recycling in China: a challenging field. Environ. Sci. Technol. 52 (12), 6727–6728.

Gómez-Gutiérrez, A., Garnacho, E., Bayona, J.M., Albaigés, J., 2007. Screening ecological risk assessment of persistent organic pollutants in Mediterranean sea sediments. Environ. Int. 33 (7), 867–876.

Habibullah-Al-Mamun, M., Ahmed, M.K., Islam, M.S., Tokumura, M., Masunaga, S., 2019. Seasonal-spatial distributions, congener profile, and risk assessment of polychlorinated biphenyls (PCBS) in the surficial sediments from the coastal area of Bangladesh. Soil Sediment Contam. 28 (1), 28–50.

Hakanson, L., 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. Water Res. 14 (8), 975–1001.

Helou, K., Harmouche-Karaki, M., Karake, S., Narbonne, J.-F., 2019. A review of organochlorine pesticides and polychlorinated biphenyls in Lebanon: environmental and human contaminants. Chemosphere 231, 357–368.

Hidayati, N.V., Asia, L., Khabouchi, I., Torre, F., Widowati, I., Sabdono, A., Doumenq, P., Syakti, A.D., 2021. Ecological risk assessment of persistent organic pollutants (POPs) in surface sediments from aquaculture system. Chemosphere 263, 128372.

Hong, W.-J., Jia, H., Ding, Y., Li, W.-L., Li, Y.-F., 2018. Polychlorinated biphenyls (PCBs) and halogenated flame retardants (HFRs) in multi-matrices from an electronic waste (e-waste) recycling site in Northern China. J. Mater. Cycles Waste Manag. 20 (1), 80–90.

Irerhievwie, G.O., Iwegbue, C.M., Lari, B., Tesi, G.O., Nwajei, G.E., Martincigh, B.S., 2020. Spatial characteristics, sources, and ecological and human health risks of

polychlorinated biphenyls in sediments from some river systems in the Niger Delta, Nigeria. Mar. Pollut. Bull. 160, 111605.
Iwegbue, C.M., Bebenimibo, E., Tesi, G.O., Egobueze, F.E., Martincigh, B.S., 2020. Spatial characteristics and risk assessment of polychlorinated biphenyls in surficial sediments around crude oil production facilities in the Escravos River Basin, Niger Delta, Nigeria. Mar. Pollut. Bull. 159, 111462.
Jafarabadi, A.R., Bakhtiari, A.R., Mitra, S., Maisano, M., Cappello, T., Jadot, C., 2019. First polychlorinated biphenyls (PCBs) monitoring in seawater, surface sediments and marine fish communities of the Persian Gulf: distribution, levels, congener profile and health risk assessment. Environ. Pollut. 253, 78–88.
Jin, R., Fu, J., Zheng, M., Yang, L., Habib, A., Li, C., Liu, G., 2020. Polychlorinated naphthalene congener profiles in common vegetation on the tibetan plateau as biomonitors of their sources and transportation. Environ. Sci. Technol. 54 (4), 2314–2322.
Johansen, S., Poste, A., Allan, I., Evenset, A., Carlsson, P., 2021. Terrestrial inputs govern spatial distribution of polychlorinated biphenyls (PCBs) and hexachlorobenzene (HCB) in an Arctic fjord system (Isfjorden, Svalbard). Environ. Pollut. 281, 116963.
Kim, A., Vane, C., Moss-Hayes, V., Engelhart, S., Kemp, A., 2018. PAH, PCB, TPH and mercury in surface sediments of the Delaware River Estuary and Delmarva Peninsula, USA. Mar. Pollut. Bull. 129 (2), 835–845.
Li, A., Rockne, K.J., Sturchio, N., Song, W., Ford, J.C., Wei, H., 2009. PCBs in sediments of the Great Lakes–Distribution and trends, homolog and chlorine patterns, and in situ degradation. Environ. Pollut. 157 (1), 141–147.
Li, C., Li, J., Lyu, B., Wu, Y., Yang, L., Zheng, M., Min, Y., Zhang, L., Liu, G., 2021. Burden and risk of polychlorinated naphthalenes in Chinese human milk and a global comparison of human exposure. Environ. Sci. Technol. 55 (10), 6804–6813.
Li, W., Achal, V., 2020. Environmental and health impacts due to e-waste disposal in China–a review. Sci. Total Environ. 737, 139745.
Li, Y.-n, Li, J., Shao, Z., Duan, Z., Xie, Y., Cui, Z., Li, J., Zhou, H., Chen, M., Li, S., 2020. Quantitative analysis of 209 polychlorinated biphenyl (PCB) congeners in sediments of the Raritan River estuary, USA. Water Supply 20 (6), 2400–2414.
Liu, G., Zheng, M., Cai, M., Nie, Z., Zhang, B., Liu, W., Du, B., Dong, S., Hu, J., Xiao, K., 2013b. Atmospheric emission of polychlorinated biphenyls from multiple industrial thermal processes. Chemosphere 90 (9), 2453–2460.
Liu, G., Zheng, M., Liu, W., Wang, C., Zhang, B., Gao, L., Su, G., Xiao, K., Lv, P., 2009. Atmospheric emission of PCDD/Fs, PCBs, hexachlorobenzene, and pentachlorobenzene from the coking industry. Environ. Sci. Technol. 43 (24), 9196–9201.
Liu, G., Liu, W., Cai, Z., Zheng, M., 2013a. Concentrations, profiles, and emission factors of unintentionally produced persistent organic pollutants in fly ash from coking processes. J. Hazard. Mater. 261, 421–426.
Lu, Q., Liang, Y., Fang, W., Guan, K.-L., Huang, C., Qi, X., Liang, Z., Zeng, Y., Luo, X., He, Z., 2021. Spatial distribution, bioconversion and ecological risk of PCBs and PBDEs in the surface sediment of contaminated urban rivers: a nationwide study in China. Environ. Sci. Technol. 55 (14), 9579–9590.
Luo, C., Hu, B., Wang, S., Wang, Y., Zhao, Z., Wang, Y., Li, J., Zhang, G., 2020. Distribution and chiral signatures of polychlorinated biphenyls (PCBs) in soils and vegetables around an e-waste recycling site. J. Agric. Food Chem. 68 (39), 10542–10549.
MacDonald, D.D., Ingersoll, C.G., Berger, T., 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Arch. Environ. Contam. Toxicol. 39 (1), 20–31.
McCauley, D.J., DeGraeve, G., Linton, T.K., 2000. Sediment quality guidelines and assessment: overview and research needs. Environ. Sci. Policy 3, 133–144.
Mehdinia, A., Bateni, F., Vaighan, D.J., Fumani, N.S., 2021. Occurrence of polychlorinated biphenyl congeners in marine sediment of Makran region, Chabahr bay, Iran. Mar. Pollut. Bull. 164, 112038.
Net, S., El-Osmani, R., Prygiel, E., Rabodonirina, S., Dumoulin, D., Ouddane, B., 2015. Overview of persistent organic pollution (PAHs, Me-PAHs and PCBs) in freshwater sediments from Northern France. J. Geochem. Explor. 148, 181–188.
Olisah, C., Adams, J.B., Rubidge, G., 2021. The state of persistent organic pollutants in South African estuaries: a review of environmental exposure and sources. Ecotoxicol. Environ. Saf. 219, 112316.
Purchase, D., Abbasi, G., Bisschop, L., Chatterjee, D., Ekberg, C., Ermolin, M., Fedotov, P., Garelick, H., Isimekhai, K., Kandile, N.G., 2020. Global occurrence, chemical properties, and ecological impacts of e-wastes (IUPAC Technical Report). Pure Appl. Chem. 92 (11), 1733–1767.
Qadeer, A., Liu, S., Liu, M., Liu, X., Ajmal, Z., Huang, Y., Jing, Y., Khalil, S.K., Zhao, D., Weining, D., 2019. Historically Linked Residues Profile of OCPs and PCBs in Surface Sediments of Typical Urban River Networks. In: J. Clean. Prod, 231. Ecotoxicological State and Sources, Shanghai, pp. 1070–1078.
Remili, A., Letcher, R.J., Samarra, F.I., Dietz, R., Sonne, C., Desforges, J.-P., Víkingsson, G., Blair, D., McKinney, M.A., 2021. Individual prey specialization drives PCBs in Icelandic killer whales. Environ. Sci. Technol. 55 (8), 4923–4931.
Ren, J., Wang, X., Gong, P., Wang, C., 2019. Characterization of Tibetan soil as a source or sink of atmospheric persistent organic pollutants: seasonal shift and impact of global warming. Environ. Sci. Technol. 53 (7), 3589–3598.
Rodenburg, L.A., Ralston, D.K., 2017. Historical sources of polychlorinated biphenyls to the sediment of the New York/New Jersey Harbor. Chemosphere 169, 450–459.
Sanganyado, E., Bi, R., Teta, C., Buruaem Moreira, L., Yu, X., Yajing, S., Dalu, T., Rajput, I.R., Liu, W., 2021. Toward an integrated framework for assessing micropollutants in marine mammals: challenges, progress, and opportunities. Crit. Rev. Environ. Sci. Technol. 51 (23), 2824–2871.
Shi, J., Li, P., Li, Y., Liu, W., Zheng, G.J.-S., Xiang, L., Huang, Z., 2016a. Polychlorinated biphenyls and organochlorine pesticides in surface sediments from Shantou Bay, China: sources, seasonal variations and inventories. Mar. Pollut. Bull. 113 (1–2), 585–591.
Shi, J., Li, Y., Liang, H., Zheng, G.J., Wu, Y., Liu, W., 2013. OCPs and PCBs in marine edible fish and human health risk assessment in the eastern Guangdong, China. Arch. Environ. Contam. Toxicol. 64 (4), 632–642.
Shi, J., Xiang, L., Luan, H., Wei, Y., Ren, H., Chen, P., 2019. The health concern of polychlorinated biphenyls (PCBs) in a notorious e-waste recycling site. Ecotoxicol. Environ. Saf. 186, 109817.
Shi, J., Xiang, L., Wang, X., Ren, H., Wei, L., Chen, P., 2020a. Residual effects of organochlorine pesticides (OCPs) in an e-waste recycling area compared with heavy metal pollution. Ecotoxicol. Environ. Saf. 198, 110651.
de Souza, A.C., Taniguchi, S., Figueira, R.C.L., Montone, R.C., Bicego, M.C., Martins, C. C., 2018. Historical records and spatial distribution of high hazard PCBs levels in sediments around a large South American industrial coastal area (Santos Estuary, Brazil). J. Hazard. Mater. 360, 428–435.
Shi, J., Xu, C., Xiang, L., Chen, J., Cai, Z., 2020b. Tris (2, 4-di-tert-butylphenyl) phosphate: an unexpected abundant toxic pollutant found in PM2. 5. Environ. Sci. Technol. 54 (17), 10570–10576.
Shi, J., Zheng, G.J.-S., Wong, M.-H., Liang, H., Li, Y., Wu, Y., Li, P., Liu, W., 2016b. Health risks of polycyclic aromatic hydrocarbons via fish consumption in Haimen bay (China), downstream of an e-waste recycling site (Guiyu). Environ. Res. 147, 233–240.
Taylor, A.R., Wang, J., Liao, C., Schlenk, D., Gan, J., 2019. Effect of aging on bioaccessibility of DDTs and PCBs in marine sediment. Environ. Pollut. 245, 582–589.
Teunen, L., Jonge, De, Malarvannan, M., Covaci, G., Belpaire, A., Focant, C., Blust, R, J.-F., Bervoets, L., 2021. Effect of abiotic factors and environmental concentrations on the bioaccumulation of persistent organic and inorganic compounds to freshwater fish and mussels. Sci. Total Environ. 799, 149448.
Ullah, R., Asghar, R., Baqar, M., Mahmood, A., Alamdar, A., Qadir, A., Sohail, M., Schäfer, R.B., Eqani, S.A.M.A.S., 2020. Assessment of polychlorinated biphenyls (PCBs) in the Himalayan riverine network of Azad Jammu and Kashmir. Chemosphere 240, 124762.
Valizadeh, S., Lee, S.S., Baek, K., Choi, Y.J., Jeon, B.-H., Rhee, G.H., Lin, K.-Y.A., Park, Y.-K., 2021. Bioremediation strategies with biochar for polychlorinated biphenyls (PCBs)-contaminated soils: a review. Environ. Res. 200, 111757.
Vane, C.H., dos Santos, R.A.L., Kim, A.W., Moss-Hayes, V., Fordyce, F.M., Bearcock, J.M., 2017. Persistent organic pollutants (PAH, PCB, TPH) in freshwater, urban tributary and estuarine surface sediments of the River Clyde, Scotland, UK. Earth Environ. Sci. Trans. R. Soc. Edinb. 108 (2–3), 299–313.
Wang, H., Adamcakova-Dodd, A., Flor, S., Gosse, L., Klenov, V.E., Stolwijk, J.M., Lehmler, H.-J., Hornbuckle, K.C., Ludewig, G., Robertson, L.W., 2020. Comprehensive subchronic inhalation toxicity assessment of an indoor school air mixture of PCBs. Environ. Sci. Technol. 54 (24), 15976–15985.
Wang, W., Bai, J., Zhang, G., Jia, J., Wang, X., Liu, X., Cui, B., 2019. Occurrence, sources and ecotoxicological risks of polychlorinated biphenyls (PCBs) in sediment cores from urban, rural and reclamation-affected rivers of the Pearl River Delta, China. Chemosphere 218, 359–367.
Weitekamp, C.A., Phillips, L.J., Carlson, L.M., DeLuca, N.M., Hubal, E.A.C., Lehmann, G. M., 2021. A state-of-the-science review of polychlorinated biphenyl exposures at background levels: relative contributions of exposure routes. Sci. Total Environ. 776, 145912.
Wu, Y., Wang, X., Ya, M., Li, Y., Hong, H., 2016. Distributions of organochlorine compounds in sediments from Jiulong River Estuary and adjacent Western Taiwan Strait: implications of transport, sources and inventories. Environ. Pollut. 219, 519–527.
Xing, G.H., Chan, J.K.Y., Leung, A.O.W., Wu, S.C., Wong, M.H., 2009. Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ. Int. 35 (1), 76–82.
Xu, C., Hu, J., Wu, J., Wei, B., Zhu, Z., Yang, L., Zhou, T., Jin, J., 2020. Polychlorinated naphthalenes, polychlorinated dibenzo-p-dioxins and dibenzofurans, and polychlorinated biphenyls in soils in an industrial park in Northwestern China: levels, source apportionment, and potential human health risks. Ecotoxicol. Environ. Saf. 188, 109895.
Yang, H., Zhuo, S., Xue, B., Zhang, C., Liu, W., 2012. Distribution, historical trends and inventories of polychlorinated biphenyls in sediments from Yangtze River Estuary and adjacent East China Sea. Environ. Pollut. 169, 20–26.
Yang, J., Qadeer, A., Liu, M., Zhu, J.-M., Huang, Y.-P., Du, W.-N., Wei, X.-Y., 2019. Occurrence, source, and partition of PAHs, PCBs, and OCPs in the multiphase system of an urban lake, Shanghai. Appl. Geochem. 106, 17–25.
Yang, L., Jin, F., Liu, G., Xu, Y., Zheng, M., Li, C., Yang, Y., 2020. Levels and characteristics of polychlorinated biphenyls in surface sediments of the Chaobai river, a source of drinking water for Beijing, China. Ecotoxicol. Environ. Saf. 189, 109922.
Zhang, K., Schnoor, J.L., Zeng, E.Y., 2012. E-waste recycling: where does it go from here? Environ. Sci. Technol. 46 (20), 10861–10867.
Zhang, Z., Pei, N., Sun, Y., Li, J., Li, X., Yu, S., Xu, X., Hu, Y., Mai, B., 2019. Halogenated organic pollutants in sediments and organisms from mangrove wetlands of the Jiulong River Estuary, South China. Environ. Res. 171, 145–152.
Zhao, T., Guo, Z., Yao, P., Hu, L., Wu, Z., Lin, T., 2019. Deposition flux and mass inventory of polychlorinated biphenyls in sediments of the Yangtze River Estuary and inner shelf, East China Sea: implications for contributions of large-river input and e-waste dismantling. Sci. Total Environ. 647, 1222–1229.