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Distribution and human health risk of polychlorinated biphenyls in soil and plants in Koko Town, Delta State, Nigeria

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Polychlorinated biphenyls (PCBs) remain a global concern due to their environmental persistence and toxicity. However, their distribution in industrial and residential areas in Nigeria is insufficiently documented. This study investigated PCB concentrations in soils and commonly consumed plants from five sites around industrial areas in Koko Town, Delta State. Soil and plant samples were extracted using a Soxhlet extraction method and analyzed via GC-MS following the USEPA method 3540 C. Mean PCB concentrations were significantly higher in plants (20.75 mg kg^{-1}) than in soils (10.32 mg kg^{-1}), with both matrices exceeding the WHO recommended limits. PCB accumulation was highest in *Pueraria phaseoloides*, followed by *Ceiba pentandra*, *Chromolaena odorata*, *Vermonia amygdalina*, and *Musa sapientum*. The estimated daily intake (EDI) for adults and children exceeded the USEPA reference dose (0.000007 mg kg^{-1}) with a hazard ratio > 1, indicating a notable health risk, particularly for children. The findings underscore the need for regular monitoring and mitigative strategies for communities vulnerable to PCB pollution.

Keywords Polychlorinated biphenyls, Bioaccumulation, Niger delta, Human exposure, Risk assessment

Polychlorinated biphenyls (PCBs) are organic pollutants of global concern due to their environmental persistence, bioaccumulation, and toxicity to humans and wildlife[1]. They originate primarily from anthropogenic activities such as petrochemical production, industrial discharge and municipal waste streams[2]. PCB presence in soils is largely influenced by chemical properties, soil composition, and climatic conditions[3]. Plants readily take up PCBs through foliar absorption and root uptake, and are further ingested by animals, thereby facilitating biomagnification across food webs[4]. Human exposure to PCBs has been linked to carcinogenic and non-carcinogenic effects, including chronic lymphocytic leukaemia, soft-tissue sarcoma, Hodgkin and non-Hodgkin lymphoma, lung, prostate, bronchus, and laryngeal cancer, endocrine disruption and reproductive abnormalities[5].

Previous studies indicate that lower chlorinated congeners (2–5 Cl) are more prevalent in soils and bioaccumulate readily in plants than highly chlorinated congeners (6–10 Cl)[2,6,7]. The release of PCBs from industrial activities, their accumulation in soil and leafy vegetables, should necessitate their regular monitoring within industrial and residential areas. Koko is a historic site for PCB dumping[8], and the growing industrial activities in the town could intensify concerns over plant and soil contamination. Although previous research has examined PCB contamination in parts of the Niger Delta, comprehensive soil–plant transfer assessment and associated human health risk estimates for Koko Town remain limited. This study, therefore, aims to (1) quantify PCB concentrations in soils and edible plants in Koko town, (2) evaluate plant bioaccumulation factors, and (3) assess human health risks associated with consumption.

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Materials and methods

Study location

The study was carried out in Koko (5°44′0″, 6°08′0″N and 5°4′0″, 5°36′0″E), Delta State, Nigeria (Fig. 1). The region falls within the tropical rainforest zone, characterized by annual rainfall of 2000 mm to 3000 mm, mean temperature of 21–35 °C, and relative humidity of 60–90%[9]. Koko is bordered by the Benin River, a brackish water system that drains into the Gulf of Guinea section of the Atlantic Ocean. The river supports small-scale fishing, coastal transportation, and maritime logistics operations, while the town hosts petroleum-related industries, small and medium-scale manufacturing, and subsistence agriculture as the main economic activities. Koko gained international attention following the illegal dumping of hazardous waste in 1987, prompting major regulatory frameworks for environmental management in Nigeria[8].

Sample collection

Soil and plant samples were collected using a stratified random approach in five industrial sites: (1) Koko Seaport, (2) lubricant factory, (3) waste treatment facility, (4) oil shipping yards, and (5) bitumen plant. Composite soil samples from a sampling frame of 10 by 10 m from topsoil (0–15 cm) and subsoil (15–30 cm) were collected in triplicate using a soil auger and wrapped in aluminium foil, labelled with markers, and placed in an ice chest. Leaves (numbering 20–30 per plant) from five edible plant species commonly used for food and medicine, such as *Ceiba pentandra* (silk-cotton), *Pueraria phaseoloides* (kudzu), *Vermonia amygdalina* (bitter leaf), *Musa sapientum* (banana) and *Chromolaena odorata* (awolowo leaf), were collected, wrapped in aluminium foil, labelled properly, and kept in ice. Plants were selected following Plank's[10] method for the determination of plant growth and maturity. Both soil and plant samples were transported to the EISL Laboratory in Port Harcourt for analysis. Voucher specimens of plant species (UBH-C531 *C. pentandra*, UBH-P565 *P. phaseoloides*, UBH-V342 *V. amygdalina*, UBH-M416 *M. sapientum*, and UBH-C496 *C. odorata*) were deposited at the University of Benin Herbarium.

Laboratory analysis

Soil samples were air-dried and sieved to remove debris, and 10 g of the soil sample was extracted using a Soxhlet extractor (Method 3540) to extract the non-volatile and semi-volatile organic PCB compounds from the soil. The extracts for PCB analysis were subjected to a sequential hexane cleanup (Method 8082) according to USEPA[11]. After cleanup, the extract was analyzed by injecting a measured aliquot into a GC-MS (Agilent 7890 A) equipped with a wide-bore fused silica capillary column. Plant leaves were air-dried for seven days and then ground into powder. About 2 g of the plant material was placed in a cellulose thimble and extracted by heating the flask until the hexane solvent vaporizes, condenses, and drips into the collecting chamber. This continued for 6 h on the Soxhlet extractor until the solvent completely dissolved the soluble compounds from the solid sample. Impurities were removed using column chromatography, and the extract was analyzed for PCBs using GC-MS.

Quality control and quality assurance

All equipment used for analysis was calibrated to the standard. The detected concentrations of targeted compounds were compared with certified reference materials following the Acq Method 3540 and multi-level calibration standards. The limits of detection (LOD) and quantification were 0.1ppb and 0.3ppb, respectively. For quantification, calibration curves were constructed for PCB compounds using a series of quantification values (Q-values) for both low and high-chlorinated congeners. The quantitation ion (QIon) was a constant of 57 for higher congeners and precisely 149 for the PCB-167 in plant samples.

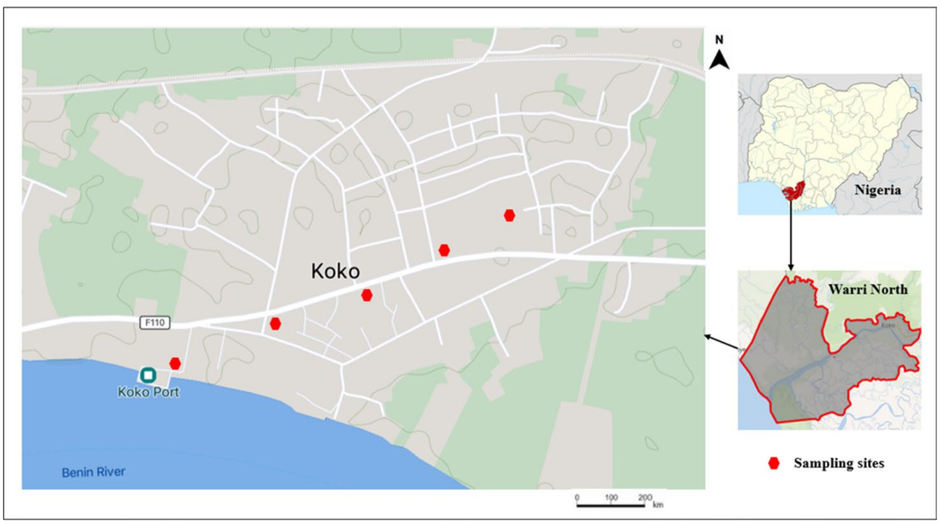

Fig. 1. Map of the study area with sample collection points in Koko town.

Data analysis

Data was analysed using SPSS version 25. The outputs were summarised into mean and standard deviation. Comparative analysis of the mean values was done using a one-way analysis of variance (ANOVA) at a probability level of 0.05 (95% confidence level).

Bioaccumulation factor

The bioaccumulation factor was calculated by dividing the concentration of PCBs in plants by the concentration in soil, as indicated in Eq. (1).

$$\mathrm{BAF} = \frac{\mathrm{PCB\ \ concentration\ \ in\ \ plant}}{\mathrm{PCB\ \ concentration\ \ in\ \ soil}} \tag{1}$$

Human health risk assessment

To evaluate the human health risk associated with the consumption of edible plants contaminated with PCBs, the risk assessment was calculated using the estimated daily intake (EDI) and hazard ratio (HR). The EDI was calculated by using Eq. (2).

$$\mathrm{EDI} = \frac{C \times CR}{BW} \tag{2}$$

where EDI = the estimated daily intake for edible plants (mg kg^{-1} day^{-1}), C = PCB concentration in plant in mg kg^{-1}, CR = plant ingestion rate using FAO Food Balance Sheets for Nigeria[12], and BW = average body weight for Nigerians, which is 60.7 kg for adults[13] and 30 kg for children[14]. The hazard ratio (HR) was calculated following Eq. (3).

$$\mathrm{HR} = \mathrm{EDI/RfD} \tag{3}$$

where RfD = reference dose factors (0.000007 mg kg^{-1}) according to the United States Environmental Protection Agency[15]. An HR value less than 1.0 indicates a low risk, while a value above or equal to 1.0 means a high risk.

Results and discussion

Concentration and distribution of PCB congeners

A total of twenty-eight PCB congeners, comprising thirteen dioxin-like (DL-PCBs) and fifteen non-dioxin-like (NDL-PCBs), were detected in soil and plant samples (Table 1). The mean concentration of PCB congeners in soil (except PCB-167, which was below detection) and plants exceeded permissible limits[16]. PCB-66 had the highest concentration in both matrices, indicating high mobility and uptake potential, consistent with its greater potency and industrial applications, while PCB-156 was the lowest. Higher chlorinated compounds were found at moderate levels in both matrices. Congeners such as PCB-114 and PCB-118 were dominant in soil, whereas PCB-126, 153, 169, 170, 180, 187, 195, 206, and 209 had elevated levels in plants. These patterns align with global findings linking PCB uptake to climatic variation and atmospheric deposition rather than solely soil composition[1,3,7,17–19]. Industrial activities in the area, such as oil and gas activities, bitumen, paints and lubricants production and wastes from industrial activities, could be the chief contributing factors to the increased levels of PCBs in soil and plants in Koko.

Comparison of dioxin-like and non-dioxin-like PCBs

Total DL-PCBs were lower than NDL-PCBs in both soil and plants (Table 2). However, DL-PCBs with similar toxicity equivalence to 2,3,7,8-TCDD were higher in plants compared to soil, suggesting elevated human dietary risk if consumed from contaminated plants, given their potential carcinogenicity[18]. These concentrations are harmful to the ecosystem and human health[7,9,20–22].

Bioaccumulation factor (BAF)

The bioaccumulation factor reflects the accumulation of contaminants in a biota compared to the concentration in the surroundings. In this study, all species of plants except *M. sapientum* had BAF values > 1 (Fig. 2). The BAF values for the plant species were in the decreasing order of *P. phaseoloides* > *C. pentandra* > *C. odorata* > *V. amygdalina* > *M. sapientum*. This is supported by studies of significant concentrations of PCBs in hyperaccumulating plants from the region[21,23,24]. The significantly elevated BAF in *P. phaseoloides* may be due to its extensive root system, perennial growth, and high lipid content[9,19]. The use of species like *V. amygdalina* and *C. odorata* for herbal medicine may increase exposure risks through dietary and therapeutic use. Furthermore, the tendency of persistent pollutants like PCBs to translocate in biota, due to their lipophilic nature, leads to accumulation in plant lipids through air absorption via leaf surfaces[3].

Health risk assessment to humans

The most notable pathway of exposure to PCBs is through dietary intake. The EDI values, which represent the average daily intake of PCBs through edible plant consumption compared to the reference dose, reflect the risk exposure to adults and children. The calculated EDI and HR values were higher than the USEPA reference dose[15] and the HR thresholds (HR > 1) for all plant species except for *C. pentandra*, which depicts a potential health risk for adults and children.

Across the plant species, EDIs and HR values for PCBs were highest in *C. odorata*, followed by *P. phaseoloides*, *V. amygdalina*, and *M. sapientum* (Table 3). Children exhibited significantly higher risk values due to their

Type	Congener	Soil	Plant	*P*-value
Non-ortho dl-PCB	PCB-77	3.55 ± 4.32	20.75 ± 28.37	$P > 0.05$
	PCB-81	6.93 ± 8.09	16.06 ± 6.21	$P > 0.05$
	PCB-126	9.85 ± 14.23	12.49 ± 3.62	$P > 0.05$
	PCB-169	4.47 ± 5.03	33.72 ± 65.45	$P > 0.05$
Mono-ortho dl-PCB	PCB-105	10.32 ± 15.25	11.36 ± 5.15	$P > 0.05$
	PCB-114	12.49 ± 20.95	28.84 ± 16	$P > 0.05$
	PCB-118	16.79 ± 16.96	13.04 ± 3.68	$P > 0.05$
	PCB-123	5.68 ± 8.97	7.07 ± 6.92	$P > 0.05$
	PCB-156	0.98 ± 1.3	0.95 ± 0.42	$P > 0.05$
	PCB-157	1.57 ± 1.91	2.42 ± 8.17	$P > 0.05$
	PCB-167	0 ± 0	4.57 ± 6.55	$P > 0.05$
	PCB-189	11.85 ± 16.42	1.76 ± 2.32	$P > 0.05$
Mono-ortho ndl-PCB	PCB-128	1.85 ± 2.23	1.3 ± 0.81	$P > 0.05$
	PCB-170	2.91 ± 2.57	12.32 ± 10.04	$P > 0.05$
Indicator ndl-PCB	PCB-28	1.27 ± 1.82	1.76 ± 0.71	$P > 0.05$
	PCB-52	9.4 ± 12.2	32.25 ± 51.67	$P > 0.05$
	PCB-101	6.27 ± 0.25	4.1 ± 1.16	$P > 0.05$
	PCB-138	2.05 ± 2.08	2.71 ± 2.23	$P > 0.05$
	PCB-153	4.32 ± 4.03	13.17 ± 15.03	$P > 0.05$
	PCB-180	2.96 ± 4.02	38.34 ± 37.37	$P > 0.05$
Ndl-PCB	PCB-8	8.52 ± 12.91	26.68 ± 12.29	$P > 0.05$
	PCB-18	6.27 ± 8.74	9.01 ± 2.86	$P > 0.05$
	PCB-44	9.37 ± 11.99	11.9 ± 3.27	$P > 0.05$
	PCB-66	37.82 ± 46.27	116.72 ± 84.4	$P > 0.05$
	PCB-187	3.63 ± 5.1	13.78 ± 17.43	$P > 0.05$
	PCB-195	6.86 ± 7.95	22.02 ± 22.73	$P > 0.05$
Higher chlorinated PCB				
Ndl- PCB	PCB-206	10.91 ± 19.23	19.41 ± 20.32	$P > 0.05$
Dl-PCB	PCB-209	3.48 ± 1.83	46.68 ± 83.46	$P > 0.05$

Table 1. Summary (mean + standard deviation in Mg kg^{-1}) of PCB in soil and plants collected around industrial areas in Koko, Delta State, Nigeria.

PCBs	Soil	Plant
Total DL-PCBs	87.96 ± 115.26	199.71 ± 229.4
Total NDL-PCBs	112.24 ± 145.62	330.78 ± 287.1

Table 2. Comparison between total DL-PCBs and NDL-PCBs in soil and plants from Koko, Delta State, Nigeria.

lower body weight. The higher values for *C. odorata* and *P. phaseoloides* underscore their strong potential as hyperaccumulators, yet al.so raise concerns about heightened exposure for consumers. Given the widespread use of these plants in traditional medicine and diet, the implications for chronic exposure are significant. These results from both the estimated daily intake and the hazard ratio are consistent with similar studies from environmental conduits by Aziza et al.[1], Bantum et al.[25], and Irerhievwie et al.[22], whose work covers PCBs from the region as well as the impacts associated with industrial activities. Our findings align with studies in Colombia and Spain[17], but contradict the estimated daily intake reported in studies by Eghgbaljoo et al., Kumar et al., and Li & Su[26–28], whose values were below the WHO/FAO reference dose[29]. Edible hyper-accumulating plants, such as *C. odorata* and *V. amygdalina*, possess antibacterial and antioxidant properties that are beneficial to human health[30,31]. However, the capacity of the studied plants to accumulate organic pollutants raises concern.

Conclusion

The study demonstrates elevated levels of PCB contamination in soil and edible plants in Koko, Delta State, Nigeria. The high bioaccumulation, particularly in *P. phaseoloides* and *C. odorata*, presents a notable health risk, especially for children. This raises significant concern about fruit/vegetable consumption in this region, as this study provides baseline concentrations of PCBs in edible plants in Koko, Delta State, Nigeria. Lower congeners of PCBs are highly adsorbed in soils along the Niger Delta coasts, which raises concern over industrial operations. These findings underscore the urgent need for routine environmental monitoring of industrial

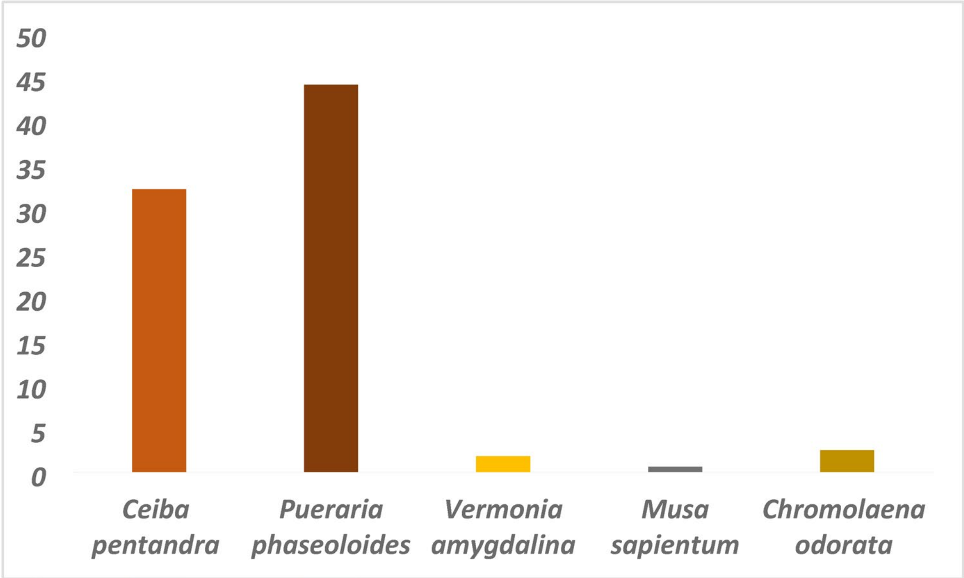

Fig. 2. Bioaccumulation factor for PCB congeners in plants collected from Koko, Delta State, Nigeria.

Risk indicator	Categories	*C. pentandra*	*P. phaseoloides*	*V. amygdalina*	*M. sapientum*	*C. odorata*
EDI	Adult	0.000003	0.001562	0.000812	0.000152	0.002553
	Children	0.000005	0.003161	0.001643	0.000307	0.005166
HR	Adult	0.38	223.19	116.01	21.64	364.77
	Children	0.76	451.60	234.73	43.82	738.05

Table 3. Human health risk associated with the consumption of edible plants in Koko, Delta State, Nigeria.

zones and phytoremediation programmes using available nature-based solutions such as hyperaccumulating plant species to mitigate long-term exposure in oil-impacted communities. Furthermore, risk communication on dietary exposure to communities affected and stricter regulatory enforcement of environmental regulations related to waste management are suggested. Persistent PCB exposure threatens food safety and ecosystem health in the Niger Delta region and requires immediate intervention.

Data availability
Data are available upon request from the corresponding author.

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Author contributions
Amaka Michael, prepared the manuscript, interpreted the results and wrote the paper, Abraham O. Ekperusi revised the work, Ndu P. Okeke initiated the study, and Anthonia E. Gbuvboro wrote the summary. All authors read and approve the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information

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