Distribution and Health-Risk Assessment of Polychlorinated Biphenyl Congeners in Soils from E-Waste and Automobile-Dismantling Sites

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Abstract
The uncontrolled dismantling of electronic waste and end-of-life vehicles in low- and middle-income countries has emerged as a significant, yet inadequately quantified, source of persistent organic pollutants to the terrestrial environment. This study characterised the distribution, congener-specific profile and human health-risk implications of nineteen polychlorinated biphenyl (PCB) congeners in topsoils collected from three informal electronic-waste (e-waste) dumpsites and two automobile-dismantling sites in the densely populated metropolis of Lagos, Nigeria. Ten composite topsoil samples (0–15 cm) were subjected to ultrasonic solvent extraction, sulphuric-acid and acidified silica-gel clean-up, and quantification by gas chromatography with electron-capture detection. The sum of the nineteen target congeners (ΣPCB_{19}) ranged from 81.99 to 6111 ng g^{-1}, with the highest burden recorded at an e-waste site (NGK-S8) and the lowest at a peripheral point of another e-waste site (AR-S9), illustrating extreme small-scale spatial heterogeneity driven by the location of burning and dismantling micro-hotspots. Every sample exceeded the former USSR ambient-soil limit of 60 ng g^{-1}, and three samples exceeded the Canadian residential-soil guideline of 1300 ng g^{-1}. PCB 66, PCB 87 and PCB 153 were detected in every sample (100% frequency), whereas the complete suite of nineteen congeners co-occurred only at OWN-S5. All target congeners were non-dioxin-like, and the profile was dominated by penta- through hepta-chlorinated homologues consistent with weathered technical Aroclor-type formulations and thermal degradation during open burning. Deterministic health-risk modelling, based on soil ingestion, revealed hazard-index values exceeding unity for numerous congeners at the Alaba Rago, New-Garage Gidan Kwali and Owode Onirin sites, with maxima of 18.43 (PCB 18) and 17.69 (PCB 31). Estimated incremental lifetime cancer risks exceeded the USEPA benchmark of 10^{-6} for nearly all detected congeners and surpassed 10^{-5} in most cases, reaching 7.37×10^{-4} for PCB 18 at NGK. These findings demonstrate that informal e-waste and automobile recycling constitutes a serious and immediate soil-contamination and public-health hazard in Lagos, warranting remediation, regulatory enforcement and longitudinal biomonitoring of exposed populations.

Keywords: *Polychlorinated biphenyls; e-waste; automobile dismantling; soil contamination; congener profile; health-risk assessment; hazard index; lifetime cancer risk; non-dioxin-like PCBs; Lagos; gas chromatography; persistent organic pollutants*

1. Introduction

The exponential global expansion in the production, consumption and disposal of electrical and electronic equipment has generated one of the fastest-growing solid-waste streams of the twenty-first century. Electronic waste, commonly abbreviated as e-waste, encompasses discarded computers, mobile telephones, televisions, refrigerators, air-conditioning units, printed circuit boards, transformers, capacitors and the diverse assemblage of cables, casings and components that accompany them. A substantial and disproportionate fraction of the world's e-waste is exported, whether legally under the guise of second-hand goods or illegally in contravention of international conventions, from high-income economies to countries in sub-Saharan Africa and Asia, where labour is inexpensive and environmental enforcement is weak (Wong et al., 2007; Robinson, 2009). Nigeria, and in particular its commercial capital Lagos, has become one of the principal destinations and processing hubs for this transboundary flow, hosting sprawling informal markets and dumpsites where used electronics are repaired, cannibalised for parts or dismantled for the recovery of valuable metals such as copper, aluminium, gold and palladium (Asante et al., 2019; Sepulveda et al., 2010). Parallel to the e-waste economy, the informal dismantling of end-of-life vehicles constitutes a second, closely related and frequently co-located source of environmental contamination. Automobile-dismantling yards recover ferrous and non-ferrous metals, engine components, batteries, radiators, wiring harnesses and lubricating oils. Both activities share a common repertoire of crude recycling practices, including the open burning of insulated cables and plastic housings to liberate metals, manual disassembly without personal protective equipment, indiscriminate discharge of spent solvents and oils onto bare ground, and the accumulation of residual char and ash in unlined pits (Leung et al., 2006; Bi et al., 2007). These practices release a complex mixture of hazardous substances into soil, dust, water and air, among which polychlorinated biphenyls (PCBs) occupy a position of particular toxicological concern (Alabi et al., 2012). Polychlorinated biphenyls are a family of 209 synthetic organochlorine congeners derived from the biphenyl nucleus by substitution of between one and ten hydrogen atoms with chlorine. Each congener is distinguished by the number and position of its chlorine substituents, giving rise to homologue groups ranging from mono- to deca-chlorobiphenyls. Commercial PCB formulations, marketed historically under trade names such as Aroclor, Clophen, Kanechlor and Sovol, were complex technical mixtures manufactured on a scale of more than one million tonnes worldwide between the late 1920s and their progressive prohibition from the 1970s onward (Breivik et al., 2002). Their exceptional chemical and thermal stability, high dielectric constant, low flammability and resistance to oxidation made them ideal for use as dielectric fluids in transformers and capacitors, as hydraulic and heat-transfer fluids, as plasticisers, flame retardants, lubricant additives, and as components of paints, sealants and carbonless copy paper (Erickson & Kaley, 2011). It is precisely these properties, so advantageous for industrial applications, that render PCBs environmentally intransigent.

The environmental persistence of PCBs is a direct consequence of their molecular architecture. The carbon–chlorine bonds resist hydrolysis, photolysis and microbial degradation, and the degree of recalcitrance increases with the extent of chlorination (Jones & de Voogt, 1999). Higher-chlorinated congeners may persist in soils and sediments for decades, undergoing only slow reductive dechlorination under anaerobic conditions. Owing to their high octanol–water partition

coefficients and lipophilicity, PCBs bind strongly to soil organic matter and to the lipid fractions of living organisms, resulting in pronounced bioaccumulation in individual organisms and biomagnification along trophic chains. Concentrations in apex predators, including humans, may exceed ambient environmental levels by several orders of magnitude. Furthermore, the semi-volatility of the lighter congeners enables long-range atmospheric transport through repeated cycles of volatilisation and deposition, the so-called "grasshopper effect", which has carried PCBs to the Arctic, to remote alpine lakes and to open-ocean sediments far removed from any point of manufacture or use (Wania & Mackay, 1996). It is this combination of persistence, bioaccumulation, long-range transport and toxicity that led to the inclusion of PCBs among the original twelve "dirty dozen" chemicals targeted for elimination under the 2001 Stockholm Convention on Persistent Organic Pollutants, to which Nigeria is a signatory (United Nations Environment Programme, 2001). The toxicological profile of PCBs is broad and mechanistically diverse. On the basis of structure and biological activity, the congeners are conventionally divided into two classes (Safe, 1994). Dioxin-like PCBs, comprising the non-ortho and mono-ortho substituted congeners that can adopt a coplanar configuration, bind to the aryl hydrocarbon receptor (AhR) and elicit responses biochemically analogous to those of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin, including induction of cytochrome P450 enzymes, immunosuppression, developmental toxicity and tumour promotion (Van den Berg et al., 2006). Non-dioxin-like PCBs, which possess two or more ortho-chlorine substituents and cannot achieve coplanarity, exert their effects predominantly through AhR-independent pathways. These include disruption of intracellular calcium homeostasis and ryanodine-receptor signalling, alteration of neurotransmitter systems, interference with thyroid-hormone transport and metabolism, modulation of oestrogen and androgen receptors, and induction of oxidative stress. Although historically regarded as less potent than their dioxin-like counterparts, non-dioxin-like congeners typically dominate environmental mixtures on a mass basis and are increasingly recognised as important contributors to neurodevelopmental, endocrine and reproductive toxicity.

The human health consequences of PCB exposure are well documented in occupational cohorts, in populations affected by mass-poisoning episodes such as the Yusho and Yucheng incidents, and in the general population through dietary intake (Agency for Toxic Substances and Disease Registry (ATSDR), 2000). The International Agency for Research on Cancer classifies PCBs as Group 1 human carcinogens, with the strongest epidemiological evidence relating to malignant melanoma, non-Hodgkin lymphoma and cancers of the liver and biliary tract (Lauby-Secretan et al., 2016). Beyond carcinogenicity, chronic exposure is associated with endocrine disruption, including thyroid dysfunction and impaired reproductive function; with neurodevelopmental deficits in children prenatally or postnatally exposed, manifesting as reduced cognitive scores, attention deficits and psychomotor impairment; with immunotoxicity and increased susceptibility to infection; and with dermatological, hepatic and metabolic effects (Baibergenova et al., 2003). The developing foetus and the breastfed infant are especially vulnerable, as PCBs cross the placenta and are mobilised into breast milk from maternal adipose stores.

Populations engaged in, or resident near, informal e-waste and automobile-dismantling operations face a uniquely intense and multi-pathway exposure regime (Grant et al., 2013). Workers, many of whom are adolescents or young adults, handle contaminated materials with bare hands, inhale fumes generated during open burning, and ingest contaminated dust. Nearby residents, including children who play on and around the sites, are exposed through incidental soil and dust ingestion, dermal contact, inhalation of resuspended particulates, and consumption of locally grown vegetables, poultry, eggs and fish that have accumulated contaminants from the soil. In the

Nigerian context, where dismantling sites are frequently embedded within or immediately adjacent to residential neighbourhoods, markets and informal food-production areas, the potential for community-wide exposure is considerable. Soil functions simultaneously as the principal repository of deposited PCBs and as the proximate source medium for several of these exposure pathways, making the characterisation of soil contamination a logical foundation for exposure and risk assessment. The magnitude of the global e-waste challenge lends particular urgency to these concerns. Worldwide generation of electronic waste has been growing several times faster than the human population, driven by shortening product lifespans, rapid technological turnover and the diffusion of digital devices into every sphere of economic and domestic life (Robinson, 2009). Only a small fraction of this material is collected and treated through formal, environmentally sound channels; the remainder is stockpiled, landfilled or, critically, funnelled into the informal recycling sector (Fu et al., 2011). Within this sector, the economic logic is compelling and the environmental consequences are externalised: valuable metals command reliable prices, the barriers to entry are negligible, and the pollution generated is borne not by the recyclers' balance sheets but by the surrounding soil, water, air and human population. The result is a systematic transfer of environmental and health burdens from the affluent consumers who discard the equipment to the impoverished communities that dismantle it, a pattern that has been characterised as a form of toxic colonialism and that gives the study of contamination at these sites an ethical as well as a scientific dimension. Soil merits special attention within this system for several reasons. It is the ultimate sink for the majority of PCBs released at ground level through spillage, char deposition and dust settling, and its high organic-matter content immobilises the lipophilic congeners and retards their degradation, so that contamination accumulates and persists over the operational lifetime of a site and long after activity ceases. Soil is simultaneously a source medium, releasing contaminants back to humans through ingestion, dermal contact, dust inhalation and uptake into food. It integrates contamination over time, smoothing the episodic pulses associated with individual burning events into a cumulative record that a single sampling campaign can capture. For these reasons, soil concentrations constitute both a sensitive indicator of the intensity of recycling activity and a direct determinant of human exposure, and they form the logical analytical focus for a study concerned with health risk.

Despite the scale of informal recycling activity in Lagos and the acknowledged hazards of PCBs, congener-specific data on soil contamination at Nigerian e-waste and automobile-dismantling sites remain sparse. Much of the existing regional literature reports only aggregate concentrations, focuses on a narrow subset of indicator congeners, or does not couple analytical measurements with a formal, quantitative health-risk assessment (Ololade et al., 2021; Ediagbonya et al., 2025). Indeed, Folarin et al. (2018) documented substantial PCB burdens in environmental samples from an electrical power station in Lagos, yet studies of this kind remain few and geographically uneven. There is consequently a pronounced knowledge gap concerning the identity, spatial distribution and human health implications of individual PCB congeners in these settings. This gap impedes evidence-based prioritisation of remediation, regulatory intervention and public-health protection. The present study was designed to address this deficiency. Its specific objectives were: first, to determine the concentrations and spatial distribution of nineteen PCB congeners in surface soils from three e-waste dumpsites and two automobile-dismantling sites in Lagos; second, to characterise the detection frequency and congener profile of the contamination and to interpret it in terms of source formulations and post-depositional weathering; third, to benchmark the measured concentrations against international regulatory and ecological soil-quality guidelines; and fourth, to quantify the non-carcinogenic and carcinogenic health risks to potentially exposed

populations through deterministic modelling of the soil-ingestion pathway. In pursuing these objectives, the study provides congener-resolved evidence intended to inform environmental management and public-health decision-making in one of Africa's largest and most rapidly urbanising megacities.

Related Work

Beyond the immediate context of informal recycling, a broader body of research on the global environmental behaviour of PCBs frames the interpretation of localised soil data. Surveys of background surface soils have established the baseline global distribution and mass budget of PCBs against which contaminated sites must be judged (Meijer et al., 2003), while studies of atmospheric particle-bound transport and dry deposition demonstrate the mechanisms by which these semi-volatile compounds redistribute across landscapes and reach remote receptors (Lao et al., 2018). The legacy of dioxin- and POP-contaminated sites, together with the contemporary and future challenges they pose for management and remediation, has likewise been reviewed in detail and situates informal recycling within a wider class of persistent, spatially concentrated contamination problems (Weber et al., 2008). These strands of work collectively supply the environmental-fate and background-concentration reference points that underpin the site-specific assessment reported here.

Related Work: cross-cutting literature

Occupational-exposure and worker-safety scholarship at industrial, construction and recycling operations provides important context for the human-exposure dimension of this study, including (Arumosoye & Obriki, 2023; Obriki & Arumosoye, 2022a; Obriki & Arumosoye, 2024a; Arumosoye & Obriki, 2022; Arumosoye et al., 2025; Obriki & Arumosoye, 2023; Arumosoye et al., 2026; Obriki & Arumosoye, 2021; Obriki & Arumosoye, 2020; Arumosoye & Obriki, 2020; Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2021).

Related contributions include (Arumosoye & Obriki, 2019; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2024b; Arumosoye & Obriki, 2024; Obriki et al., 2025; Obogo et al., 2020a; Obogo et al., 2020b; Obogo et al., 2020c; Obriki et al., 2022b; Obriki et al., 2022c; Obogo et al., 2022).

Related contributions include (Obogo et al., 2024a; Obogo et al., 2024b; Obogo et al., 2025; Obogo et al., 2019; Obogo et al., 2026).

2. Materials and Methods

2.1 Study area and sampling design

The study was conducted in Lagos, the most populous city in Nigeria and one of the largest urban agglomerations in Africa. Lagos is the epicentre of the country's informal electronics and automobile recycling economy, hosting numerous markets and dumpsites where imported second-hand goods are traded, repaired and dismantled. Five sites were selected to represent the two dominant categories of informal recycling activity. Three were e-waste dumpsites: Alaba Rago (AR), Lawanson Surulere (LWS) and New-Garage Gidan Kwali (NGK). Two were automobile-dismantling sites: Jankara (JK) and Owode Onirin (OWN). These locations were chosen on the basis of the intensity and longevity of their operations, their accessibility, and their proximity to residential and commercial land uses, factors that together maximise both the likelihood of contamination and the potential for human exposure.

At each site, composite topsoil samples were collected from the uppermost 0–15 cm horizon, the depth interval most relevant to human exposure through incidental ingestion, dermal contact and dust resuspension, and the zone in which freshly deposited contaminants from surface burning and spillage first accumulate. Each composite sample was assembled from several subsamples gathered within the immediate vicinity of a designated sampling point in order to average out very fine-scale heterogeneity while preserving the spatial signal between points. A total of ten sampling points was established across the five sites, with two points per site positioned to capture within-site variability between areas of differing activity intensity. The sampling points were designated JK-DP1 and JK-SP5 at Jankara; AR-S1 and AR-S9 at Alaba Rago; LWS-S2 and LWS-S8 at Lawanson Surulere; NGK-S2 and NGK-S8 at New-Garage Gidan Kwali; and OWN-S2 and OWN-S5 at Owode Onirin. The identity, site affiliation and land-use category of each sampling point are summarised in Table 1.

Table 1. Description of the ten sampling points and dominant activities on the investigated sites.

Point	Code	Dominant activity (site)	Latitude	Longitude
1	JK-DP1	Automobile dismantling site (Jankara)	N 6°40′25.6″	E 3°17′19.33″
2	JK-SP5	Stacked car engines (Jankara)	N 6°40′22.01″	E 3°17′22.73″
3	AR-S1	Dismantling of TV / DVD units (Alaba Rago)	N 6°27′39.14″	E 3°11′29.82″
4	AR-S9	Stacked washing-machine parts (Alaba Rago)	N 6°27′43.89″	E 3°11′36.60″
5	LWS-S2	A.C. compartment dismantling (Lawanson)	N 6°30′56.84″	E 3°20′39.85″
6	LWS-S8	Refrigerators, computers, decoders, radios	N 6°31′8.75″	E 3°20′51.18″
7	NGK-S2	Fire extinguishers, refrigerators, A.C., bulbs	N 6°35′4.93″	E 3°22′35.26″
8	NGK-S8	Generators, freezers, microwaves, DVD, motorcycles	N 6°34′53.98″	E 3°22′42.94″
9	OWN-S2	Stacked headlights and brake lights (Owode Onirin)	N 6°36′27.68″	E 3°24′44.24″
10	OWN-S5	Automobile dismantling site (Owode Onirin)	N 6°36′26.78″	E 3°24′43.61″

E-waste dumpsites: AR = Alaba Rago; LWS = Lawanson Surulere; NGK = New-Garage Gidan Kwali. Automobile-dismantling sites: JK = Jankara; OWN = Owode Onirin.

Following collection, the samples were placed in pre-cleaned containers, transported to the laboratory, air-dried at ambient temperature, disaggregated and passed through a 2 mm sieve to remove stones, plant debris and coarse fragments, and homogenised. The prepared samples were stored at −4 °C prior to extraction to arrest microbial activity and minimise any loss or transformation of the target analytes.

2.2 Chemicals and standards

All solvents used for extraction and clean-up were of analytical or pesticide-residue grade. The principal extraction solvents were n-hexane and dichloromethane. Concentrated sulphuric acid

(H_2SO_4) was employed for oxidative destruction of co-extracted organic matter, and silica gel was used, in acidified form, for column clean-up. The quantitative reference standard was an AccuStandard twenty-congener PCB mixture at a nominal concentration of 100 µg mL^{-1}, which was used to prepare the calibration solutions and to confirm analyte identity by retention time. Congeners were designated throughout according to the standard IUPAC numbering scheme introduced for PCB nomenclature (Ballschmiter & Zell, 1980). All glassware was thoroughly cleaned and solvent-rinsed before use to prevent cross-contamination.

2.3 Ultrasonic extraction

Target analytes were recovered from the soil matrix by ultrasonic solvent extraction, a technique selected for its efficiency, low solvent consumption and suitability for hydrophobic, strongly sorbed organic contaminants. Approximately 1 g of each prepared soil sample was weighed into an extraction vessel and combined with 5 mL of a 1:1 (v/v) mixture of n-hexane and dichloromethane. This binary solvent system couples the non-polar character of hexane, which favours the partitioning of the lipophilic PCB congeners, with the greater polarity and elution strength of dichloromethane, which improves penetration of the soil matrix and the desorption of analytes from organic-matter binding sites. The mixture was sonicated for 30 minutes at room temperature, then centrifuged at 2500 rpm for 10 minutes to separate the solvent phase from the soil particulates, and the supernatant was carefully decanted. To ensure quantitative recovery, the extraction was performed in triplicate on each sample, with the successive supernatants combined before clean-up.

2.4 Acid and acidified silica-gel clean-up

Soil extracts from active recycling sites are characteristically laden with co-extracted lipids, elemental sulphur, aliphatic hydrocarbons and other matrix constituents that would otherwise interfere with chromatographic determination and foul the detector. A two-stage clean-up was therefore applied. The combined extract was first exchanged into 2 mL of n-hexane and treated with 2 mL of concentrated sulphuric acid. The acid treatment was carried out on a mechanical shaker operating at 240 strokes per minute for 45 minutes per stage, promoting intimate contact between the acid and the organic co-extractives, which are oxidised and charred while the acid-stable PCB congeners remain in the hexane phase. The mixture was then left to separate overnight, and the hexane layer was recovered.

The acid-treated extract was subjected to a second clean-up on a chromatographic column packed with acidified silica gel (40% acid loading). The column was conditioned with n-hexane, the sample was applied, and the analytes were eluted with 15 mL of n-hexane. The acidified silica gel provides additional retention of residual polar interferences while allowing the non-polar PCBs to pass through in the hexane eluate. The purified eluate was concentrated to a final volume of approximately 2 mL, ready for instrumental analysis.

The choice of this clean-up sequence reflects the particular demands of soils from active recycling sites. Such matrices are among the most challenging encountered in organic trace analysis, combining high and variable organic-matter content, abundant elemental sulphur derived from the burning and dismantling of components, and a heavy load of petrogenic hydrocarbons from spilled oils and lubricants. Sulphuric-acid treatment is highly effective against these interferences because the PCB congeners, stabilised by their electron-withdrawing chlorine substituents, are resistant to acid oxidation, whereas the great majority of co-extracted biogenic and petrogenic organics are destroyed. The acidified silica-gel column then removes residual polar species and any remaining

oxidation products, delivering an extract clean enough to protect the electron-capture detector from contamination and to yield well-resolved chromatographic peaks. The combination is a widely validated approach for organochlorine determination and was considered essential for reliable quantification in these particularly dirty matrices (Muir & Sverko, 2006). The repetition of the acid treatment over successive stages further ensured that even heavily loaded extracts were adequately purified before they reached the analytical column, safeguarding both the accuracy of quantification and the operational stability of the instrument throughout the analytical sequence.

2.5 Gas chromatography with electron-capture detection

Quantitative determination of the nineteen target congeners was performed on an Agilent 7890A gas chromatograph equipped with an electron-capture detector (GC-ECD), a configuration that offers high sensitivity and selectivity for electron-affinic halogenated compounds such as PCBs (Ballschmiter et al., 1992). Chromatographic separation was achieved on a DB-5MS fused-silica capillary column with dimensions of 30 m length × 0.25 mm internal diameter × 0.25 µm film thickness, whose (5%-phenyl)-methylpolysiloxane stationary phase provides efficient resolution of congeners across the volatility range of interest; congener retention and potential coelution on such phases have been catalogued in detail for the full 209-congener set (Frame, 1997).

Sample introduction was via a splitless injector maintained at 250 °C, and the detector was held at 300 °C. Column flow was set at 1.2 mL min^{-1}. The oven temperature programme began at 120 °C, held for 1.0 minute, then ramped at 10 °C min^{-1} to 200 °C, held for 2.0 minutes, and finally ramped at 10 °C min^{-1} to 300 °C, held for 1.0 minute, giving a total run time of 22 minutes. This multi-ramp programme was optimised to resolve the lower-chlorinated congeners early in the run while ensuring the elution and adequate peak shape of the higher-chlorinated, later-eluting congeners.

2.6 Quality assurance, quality control and calibration

Analyte identification was based on retention-time matching against the AccuStandard twenty-congener reference mixture, and quantification was performed by external calibration. A four-point calibration curve was constructed at concentrations of 0.1, 0.2, 0.5 and 1.0 mg L^{-1}, prepared by serial dilution of the reference standard. The calibration response was linear across this range, providing a reliable basis for the quantification of the target congeners in the sample extracts.

To monitor and control for possible contamination introduced during sample preparation, a procedural blank was carried through the entire analytical sequence, from extraction through clean-up to instrumental determination, in parallel with the samples. The consistent application of triplicate extraction, rigorous glassware cleaning, matrix clean-up and blank monitoring together underpinned the analytical reliability of the reported concentrations. The nineteen target congeners quantified in this study were PCB 1, 5, 18, 31, 44, 52, 66, 87, 101, 110, 138, 141, 151, 153, 170, 180, 183, 187 and 206, spanning mono- through nona-chlorinated homologues and encompassing the indicator congeners most widely used in environmental monitoring. All nineteen are classified as non-dioxin-like.

2.7 Human health-risk assessment

The potential human health risks arising from exposure to PCB-contaminated soil were evaluated through a deterministic risk-assessment framework based on the soil-ingestion pathway, which is generally the dominant route of exposure for non-volatile, soil-bound contaminants in populations with frequent direct contact with contaminated ground (U.S. Environmental Protection Agency, 1989; Ross & Birnbaum, 2003). The average daily dose (ADD, expressed in mg kg^{-1} day^{-1})

received through incidental soil ingestion was estimated for each congener at each site according to the relationship

$ADD = (C_m \times IR) / BW$,

where C_m is the measured concentration of the congener in soil, IR is the soil ingestion rate, taken as 0.0312 kg day^{-1}, and BW is the body weight, taken as 70 kg (Ferreira-Baptista & De Miguel, 2005; U.S. Environmental Protection Agency, 2011). Measured concentrations expressed in ng g^{-1} were converted to mg kg^{-1} using the equivalence 1 ng g^{-1} = 0.001 mg kg^{-1} before substitution into the dose equation.

Non-carcinogenic risk was characterised by the hazard index (HI), computed as the ratio of the average daily dose to the congener-specific chronic oral reference dose (RfD):

$HI = ADD / RfD$,

with an RfD of 2×10^{-5} mg kg^{-1} day^{-1} adopted for the target congeners. A hazard index equal to or exceeding unity ($HI \geq 1$) is interpreted as indicating a potential non-carcinogenic health concern, whereas values below unity are generally regarded as unlikely to be associated with adverse non-cancer effects.

Carcinogenic risk was expressed as the incremental lifetime cancer risk (LCR), obtained by multiplying the average daily dose by the cancer slope factor (CSF):

$LCR = ADD \times CSF$,

with a CSF of 2.0 (mg kg^{-1} day^{-1})$^{-1}$. The resulting lifetime cancer risks were evaluated against two regulatory benchmarks: the more stringent acceptable-risk threshold of 10^{-6} associated with United States Environmental Protection Agency guidance of 2009 (USEPA, 2009), and the less stringent threshold of 10^{-5} associated with earlier guidance of 2000 (USEPA, 2000). Lifetime cancer risks exceeding these values were regarded as unacceptable, signifying that more than one additional cancer case per one million or per one hundred thousand exposed individuals, respectively, would be expected over a lifetime of exposure.

3. Results and Discussion

3.1 Concentrations and spatial distribution

The concentrations of the nineteen target congeners, summed to give ΣPCB_{19}, varied markedly across the ten sampling points, spanning almost two orders of magnitude from 81.99 ng g^{-1} to 6111 ng g^{-1}. The individual site values, together with the site categories and their relationship to international soil-quality benchmarks, are presented in Table 2. In decreasing order the summed concentrations were NGK-S8 (6111 ng g^{-1}) far exceeding all others, followed by AR-S1 (1586 ng g^{-1}) > OWN-S5 (1502 ng g^{-1}) > JK-SP5 (1209 ng g^{-1}) > OWN-S2 (1114 ng g^{-1}) > LWS-S8 (628.2 ng g^{-1}) > JK-DP1 (524.3 ng g^{-1}) > LWS-S2 (494.3 ng g^{-1}) > NGK-S2 (377.8 ng g^{-1}) > AR-S9 (81.99 ng g^{-1}).

Table 2. Concentrations (ng/g) of the nineteen target PCB congeners across the ten sampled soils and their detection frequency (DF). ND = not detected.

Congener	JK-DP1	JK-SP5	AR-S1	AR-S9	LWS-S2	LWS-S8	NGK-S2	NGK-S8	OWN-S2	OWN-S5	DF (%)
PCB 1	2.43	ND	ND	ND	16.84	20.59	36.25	ND	ND	68.41	50
PCB 5	ND	ND	2.69	36.89	18.20	13.92	38.22	317.77	9.07	30.05	80
PCB 18	ND	ND	ND	ND	26.92	41.27	36.70	1617.40	17.51	60.59	60
PCB 31	ND	12.96	ND	ND	38.27	28.68	48.01	1539.14	21.39	70.49	70

Congener	JK-DP1	JK-SP5	AR-S1	AR-S9	LWS-S2	LWS-S8	NGK-S2	NGK-S8	OWN-S2	OWN-S5	DF (%)
PCB 52	ND	26.09	ND	ND	14.42	49.18	17.73	345.25	31.17	122.45	70
PCB 44	12.99	28.52	125.76	ND	17.58	19.07	10.16	537.45	16.04	30.49	90
PCB 66	26.81	4.43	13.70	3.85	15.91	19.00	32.47	335.60	33.08	66.16	100
PCB 101	17.58	5.64	1.71	ND	ND	6.20	5.24	136.28	91.65	52.39	80
PCB 87	41.31	1.28	4.88	19.12	18.92	22.31	26.72	95.24	43.01	72.28	100
PCB 110	7.92	ND	6.74	ND	4.92	10.36	25.63	122.93	16.61	40.19	80
PCB 151	7.00	3.11	ND	ND	ND	0.10	19.97	82.11	17.87	45.02	70
PCB 153	18.55	2.54	5.52	11.84	0.44	1.89	32.29	103.19	14.61	83.03	100
PCB 141	ND	ND	1.48	6.68	2.67	ND	20.26	62.30	ND	46.60	60
PCB 138	92.61	5.00	0.86	2.36	2.27	6.26	17.58	277.60	162.26	139.08	90
PCB 187	42.76	ND	208.87	ND	7.24	2.26	3.99	40.05	59.63	40.40	80
PCB 183	4.67	1116.31	90.08	1.26	ND	ND	6.60	49.73	12.52	45.69	80
PCB 180	52.33	ND	851.79	ND	301.29	353.42	ND	108.48	274.81	84.59	70
PCB 170	53.67	ND	145.79	ND	8.42	33.66	ND	232.36	65.75	78.78	70
PCB 206	143.62	3.34	125.72	ND	ND	ND	ND	108.48	227.16	325.15	70
ΣPCB$_{19}$	524.3	1209	1586	81.99	494.3	628.2	377.8	6111	1114	1502	n.a.

Site codes: JK = Jankara (automobile); AR = Alaba Rago (e-waste); LWS = Lawanson Surulere (e-waste); NGK = New-Garage Gidan Kwali (e-waste); OWN = Owode Onirin (automobile). ΣPCB19 = sum of the nineteen target congeners.

The single most striking feature of the dataset is the extreme value recorded at NGK-S8, which at 6111 ng g^{-1} was nearly four times greater than the next-highest sample and almost seventy-five times greater than the lowest. Equally notable is the intra-site contrast at the same New-Garage Gidan Kwali dumpsite, where the companion point NGK-S2 registered only 377.8 ng g^{-1}, a value more than sixteen times lower. A comparably steep internal gradient was observed at Alaba Rago, where AR-S1 (1586 ng g^{-1}) exceeded AR-S9 (81.99 ng g^{-1}) by a factor of more than nineteen. These within-site disparities demonstrate that PCB contamination at informal recycling sites is not diffuse but is instead concentrated in discrete micro-hotspots, typically the specific locations where cable burning, component dismantling or fluid drainage are habitually carried out (Tang et al., 2010; Moeckel et al., 2020). Points situated only tens of metres away, at the periphery of activity or in areas used for storage or transit rather than processing, may carry a very much smaller burden. This heterogeneity has important implications for both monitoring design, since a single grab sample can dramatically over- or under-represent site conditions, and for remediation, which can potentially be targeted at identifiable hotspots.

When aggregated by land-use category, the two automobile-dismantling sites yielded ΣPCB$_{19}$ values ranging from 524.3 to 1502 ng g^{-1}, a comparatively narrow band with a relatively high floor, whereas the three e-waste dumpsites spanned a far wider range of 81.99 to 6111 ng g^{-1}, encompassing both the lowest and the highest concentrations in the entire dataset. This pattern suggests that automobile dismantling produces a consistently elevated but moderate level of contamination, plausibly reflecting the widespread use of PCB-containing hydraulic fluids,

lubricants and older dielectric components across the yards, while e-waste processing generates a more polarised distribution in which intensely used burning and dismantling foci reach exceptional concentrations against a background of otherwise more modest contamination.

Comparison with international regulatory and ecological benchmarks places these findings in a sobering context. Every one of the ten samples exceeded the former USSR ambient-soil limit of 60 ng g^{-1}, in most cases by a wide margin, indicating that PCB contamination is pervasive across both categories of site rather than confined to isolated points. Against the Dutch soil-remediation action value and the Australian and New Zealand ecological investigation level, both of which are set at 1000 ng g^{-1}, five samples, namely JK-DP1, AR-S9, LWS-S2, LWS-S8 and NGK-S2, remained below the threshold, while the remaining five exceeded it. The most stringent test is provided by the Canadian residential-soil quality guideline of 1300 ng g^{-1} (Canadian Council of Ministers of the Environment (CCME), 2003): three samples, AR-S1, NGK-S8 and OWN-S5, exceeded even this value, with NGK-S8 surpassing it almost fivefold. The exceedance of a residential-soil guideline is especially significant given the proximity of these sites to dwellings and the routine presence of residents, including children, on and around the contaminated ground, echoing concerns raised in comparable residential-soil surveys elsewhere (Kumar et al., 2014).

3.2 Detection frequency and congener profile

Beyond the summed concentrations, the detection frequency of individual congeners provides insight into the ubiquity and origin of the contamination. Three congeners, PCB 66, PCB 87 and PCB 153, were detected in all ten samples, corresponding to a detection frequency of 100%. Two further congeners, PCB 44 and PCB 138, were detected in nine of the ten samples, a frequency of 90%. At the opposite extreme, PCB 1, the mono-chlorinated congener, was the least frequently detected, appearing in only half of the samples, a detection frequency of 50%.

The complete co-occurrence of all nineteen target congeners was observed at only a single sampling point, OWN-S5 at the Owode Onirin automobile-dismantling site. The simultaneous presence of the full congener suite at this location is consistent with a heavily and diversely contaminated matrix receiving inputs from multiple technical formulations and processing activities, such that even minor and less persistent congeners are represented above the detection limit. The congener-frequency pattern is mechanistically informative. The consistent, near-universal detection of the penta-chlorinated PCB 66 and PCB 87 and the hexa-chlorinated PCB 153 reflects the environmental behaviour of these congeners, which are moderately to highly chlorinated, strongly sorbed to soil organic matter, resistant to microbial degradation and characteristic components of the technical mixtures most widely used in electrical and automotive applications. PCB 153 in particular is one of the classic indicator congeners that persist in soils and biota long after lighter congeners have volatilised or degraded, and its universal presence is a hallmark of aged organochlorine contamination. Conversely, the mono-chlorinated PCB 1 is comparatively volatile, water-soluble and biodegradable; its detection in only half the samples is consistent with preferential loss from the surface soil through volatilisation, leaching and microbial attack, a weathering signature typical of sources emplaced some time before sampling.

3.3 Non-dioxin-like classification and toxicological relevance

All nineteen target congeners quantified in this study, PCB 1, 5, 18, 31, 44, 52, 66, 87, 101, 110, 138, 141, 151, 153, 170, 180, 183, 187 and 206, belong to the non-dioxin-like class. Each possesses two or more chlorine substituents in the ortho positions, which sterically prevents the two phenyl rings from adopting the coplanar configuration required for high-affinity binding to the aryl

hydrocarbon receptor. As a consequence, the health risks associated with this contamination are governed principally by AhR-independent mechanisms rather than by dioxin-like toxic-equivalency responses. This distinction is toxicologically important and is sometimes underappreciated. Because regulatory attention and toxic-equivalency (TEQ) schemes have historically emphasised the dioxin-like congeners, the substantial mass of non-dioxin-like PCBs present in environmental mixtures can be overlooked in risk characterisation (Safe, 1994; Van den Berg et al., 2006). In the African context, monitoring effort under the Stockholm Convention has likewise concentrated on the dioxin-like fraction, leaving the non-dioxin-like congeners comparatively neglected (Pius et al., 2019). Yet the non-dioxin-like congeners are precisely those implicated in a range of serious effects that are not captured by the TEQ approach. They perturb intracellular calcium signalling and ryanodine-receptor function in neurons, alter dopaminergic and other neurotransmitter systems, and interfere with thyroid-hormone homeostasis, mechanisms that underlie the neurodevelopmental deficits repeatedly associated with early-life PCB exposure. Several of the congeners detected here, including PCB 138, PCB 153 and PCB 180, are among the most abundant PCBs in human tissue globally and are used as biomarkers of body burden. Others, such as PCB 52 and PCB 101, have been linked experimentally to neurotoxic and endocrine effects. The dominance of non-dioxin-like congeners in these Lagos soils therefore does not diminish the health concern; rather, it directs attention toward endpoints, especially neurodevelopmental and endocrine outcomes, that are of particular relevance to the children and young workers characteristic of informal recycling communities.

At the mechanistic level, the toxicology of the non-dioxin-like congeners is increasingly well resolved and helps to rationalise the endpoints of greatest concern (Grimm et al., 2015). A prominent pathway involves sensitisation of the ryanodine receptor, the calcium-release channel of the endoplasmic reticulum, by non-coplanar ortho-substituted congeners. The resulting dysregulation of intracellular calcium disrupts the calcium-dependent signalling cascades that govern neuronal differentiation, dendritic arborisation and synapse formation, providing a plausible molecular basis for the deficits in learning, memory and motor function observed in developmentally exposed children. A second pathway concerns the thyroid axis: the structural resemblance of hydroxylated PCB metabolites to thyroxine allows them to compete for binding to the transport protein transthyretin and to interfere with thyroid-hormone metabolism, lowering circulating hormone levels during the critical window in which thyroid hormone orchestrates brain development. A third involves oxidative stress, whereby the metabolic activation of PCBs generates reactive oxygen species and electrophilic quinone intermediates that damage lipids, proteins and DNA, contributing both to cytotoxicity and to the promotion of carcinogenesis; notably, even the lower-chlorinated congeners once regarded as relatively innocuous undergo metabolic activation to genotoxic intermediates (Vasko et al., 2018). Endocrine disruption extends beyond the thyroid to the oestrogen and androgen receptors, where certain congeners and their metabolites act as agonists or antagonists, perturbing reproductive development and function. The coexistence of these multiple, additive mechanisms means that a mixture dominated by non-dioxin-like congeners can exert appreciable toxicity even in the absence of the aryl hydrocarbon receptor activation that defines the dioxin-like class, reinforcing the conclusion that the exclusively non-dioxin-like character of the present contamination is no cause for reassurance.

3.4 Non-carcinogenic risk and the hazard index

The non-carcinogenic risk posed by soil ingestion was quantified through the hazard index, calculated congener by congener against a reference dose of 2×10^{-5} mg kg^{-1} day^{-1}. Hazard-index

values exceeding unity, and therefore indicative of potential non-carcinogenic health concern, were not evenly distributed but were concentrated at three sites: Alaba Rago (AR), New-Garage Gidan Kwali (NGK) and Owode Onirin (OWN). The full pattern of hazard-index exceedances is summarised in Table 3.

Table 3. Hazard-index (HI) values for the target PCB congeners aggregated by site. HI ≥ 1 indicates a potential non-carcinogenic concern.

Congener	JK	AR	LWS	NGK	OWN
PCB 1	0.03	0.00	0.42	0.40	0.76
PCB 5	0.00	0.44	0.36	3.97	0.44
PCB 18	0.00	0.00	0.76	18.43	0.87
PCB 31	0.14	0.00	0.75	17.69	1.02
PCB 52	0.29	0.00	0.71	4.04	1.71
PCB 44	0.46	1.40	0.41	6.10	0.52
PCB 66	0.35	0.20	0.39	4.10	1.11
PCB 101	0.26	0.02	0.07	1.58	1.61
PCB 87	0.47	0.27	0.46	1.36	1.28
PCB 110	0.09	0.08	0.17	1.66	0.63
PCB 151	0.11	0.00	0.00	1.14	0.70
PCB 153	0.24	0.19	0.03	1.51	1.09
PCB 141	0.00	0.09	0.03	0.92	0.52
PCB 138	1.09	0.04	0.09	3.29	3.36
PCB 187	0.48	2.33	0.11	0.49	1.12
PCB 183	12.49	13.44	0.00	0.63	6.49
PCB 180	0.58	9.49	7.30	1.21	4.00
PCB 170	0.60	1.62	0.47	2.59	1.62
PCB 206	1.64	1.44	0.00	1.21	6.15

JK = Jankara; AR = Alaba Rago; LWS = Lawanson Surulere; NGK = New-Garage Gidan Kwali; OWN = Owode Onirin. RfD = 2 × 10^{-5} mg kg^{-1} day^{-1}.

The highest hazard-index values were recorded at the New-Garage Gidan Kwali dumpsite, where PCB 18 yielded a hazard index of 18.43 and PCB 31 yielded 17.69. These values, more than eighteen and seventeen times the threshold of concern respectively, are driven by the exceptional total contamination at NGK-S8 combined with a substantial contribution from these tri-chlorinated congeners. At Alaba Rago, the hepta-chlorinated PCB 183 produced a hazard index of 13.44 and PCB 180 a value of 9.49, again far exceeding unity. The Jankara automobile-dismantling site, although not among the three sites with the broadest pattern of exceedances, nonetheless registered a notable PCB 183 hazard index of 12.49, underscoring that the automobile yards are by no means benign. At Lawanson Surulere, PCB 180 gave a hazard index of 7.30, and at Owode Onirin, PCB 183 and the nona-chlorinated PCB 206 produced hazard indices of 6.49 and 6.15 respectively. Hazard indices of comparable and sub-unity magnitude have been reported for PCBs in soils from

informal e-waste recycling in Cameroun and in agricultural and urban soils elsewhere, placing the present exceedances at the severe end of the reported spectrum (Ouabo et al., 2018; Kim et al., 2016; Ranjbaran et al., 2021).

The recurrence of PCB 18, PCB 31, PCB 180, PCB 183 and PCB 206 among the dominant contributors to non-carcinogenic risk is instructive. It reflects the joint influence of concentration and congener identity: the tri-chlorinated PCB 18 and PCB 31 contribute strongly where they are abundant, as at NGK, while the highly chlorinated and highly persistent PCB 180, PCB 183 and PCB 206 dominate the risk at the other sites owing to their environmental recalcitrance and accumulation. That single congeners at single sites can generate hazard indices approaching or exceeding twenty, from the soil-ingestion pathway alone and before any consideration of the additional pathways of inhalation, dermal contact and dietary intake, indicates a substantial and realistic potential for adverse non-cancer health effects among exposed populations. When the contributions of multiple co-occurring congeners are summed, the cumulative hazard at the most contaminated points is considerably greater still.

3.5 Carcinogenic risk and lifetime cancer risk

The carcinogenic risk associated with the soil-ingestion pathway was expressed as the incremental lifetime cancer risk, computed using a cancer slope factor of 2.0 $(mg\ kg^{-1}\ day^{-1})^{-1}$ and evaluated against the USEPA acceptable-risk thresholds of 10^{-6} (2009 guidance) and 10^{-5} (2000 guidance) (USEPA, 2009; USEPA, 2000). The results are compiled in Table 4. The overarching finding is stark: almost all of the detected congeners, across all sites, produced lifetime cancer risks exceeding both benchmarks, placing them firmly within the unacceptable range.

Table 4. Lifetime-cancer-risk (LCR) values for the target PCB congeners aggregated by site. Values > 10^{-6} (USEPA, 2009) and > 10^{-5} (USEPA, 2000) are unacceptable.

Congener	JK	AR	LWS	NGK	OWN
PCB 1	1.09E-06	0.00	1.67E-05	1.62E-05	3.05E-05
PCB 5	0.00	1.76E-05	1.43E-05	1.59E-04	1.74E-05
PCB 18	0.00	0.00	3.04E-05	7.37E-04	3.48E-05
PCB 31	5.78E-06	0.00	2.98E-05	7.07E-04	4.10E-05
PCB 52	1.16E-05	0.00	2.83E-05	1.62E-04	6.85E-05
PCB 44	1.85E-05	5.61E-05	1.63E-05	2.44E-04	2.07E-05
PCB 66	1.39E-05	7.82E-06	1.56E-05	1.64E-04	4.42E-05
PCB 101	1.03E-05	7.58E-07	2.76E-06	6.31E-05	6.42E-05
PCB 87	1.90E-05	1.07E-05	1.84E-05	5.44E-05	5.14E-05
PCB 110	3.53E-06	3.00E-06	6.81E-06	6.62E-05	2.53E-05
PCB 151	4.50E-06	0.00	4.46E-08	4.55E-05	2.80E-05
PCB 153	9.40E-06	7.74E-06	1.04E-06	6.04E-05	4.35E-05
PCB 141	0.00	3.64E-06	1.19E-06	3.68E-05	2.08E-05
PCB 138	4.35E-05	1.44E-06	3.80E-06	1.32E-04	1.34E-04
PCB 187	1.91E-05	9.31E-05	4.23E-06	1.96E-05	4.47E-05

Congener	JK	AR	LWS	NGK	OWN
PCB 183	5.00E-04	5.38E-04	0.00	2.51E-05	2.59E-04
PCB 180	2.33E-05	3.80E-04	2.92E-04	4.84E-05	1.60E-04
PCB 170	2.39E-05	6.50E-05	1.88E-05	1.04E-04	6.48E-05
PCB 206	6.55E-05	5.75E-05	0.00	4.84E-05	2.46E-04

CSF = 2.0 (mg kg⁻¹ day⁻¹)⁻¹. Only PCB 101 (AR) and PCB 151 (LWS) fell below the 10^{-6} benchmark; all other detected congeners exceeded it.

Only two of the many congeners–site combinations yielded lifetime cancer risks below the more protective threshold of 10^{-6}. These were PCB 101 at Alaba Rago, with a risk of 7.58×10^{-7}, and PCB 151 at Lawanson Surulere, with a risk of 4.46×10^{-8}. Every other detected congener at every site exceeded 10^{-6}, and the great majority also exceeded 10^{-5}, signifying that the estimated lifetime cancer risk to exposed individuals surpasses one additional case per one hundred thousand people. The largest lifetime cancer risks were of the order of several parts in ten thousand, values that are three to four orders of magnitude above the more stringent benchmark. The hepta-chlorinated PCB 183 produced the highest risks among the more highly chlorinated congeners, reaching 5.38×10^{-4} at Alaba Rago and 5.00×10^{-4} at Jankara. At the New-Garage Gidan Kwali site, the tri-chlorinated congeners dominated, with PCB 18 yielding a lifetime cancer risk of 7.37×10^{-4}, the single highest value recorded in the study, and PCB 31 yielding 7.07×10^{-4}. PCB 180 at Alaba Rago produced a risk of 3.80×10^{-4}. To place these figures in perspective, a lifetime cancer risk of 7.37×10^{-4} implies approximately seven hundred additional cancer cases per one million exposed individuals attributable to a single congener through a single exposure pathway, a magnitude that would be considered wholly unacceptable under any regulatory framework. Cancer risks exceeding the USEPA benchmarks have similarly been reported at abandoned and active e-waste sites and at end-of-life vehicle processing areas, though the values recorded here rank among the most extreme (Zhang et al., 2014; Anh et al., 2020).

It is important to recognise that these estimates are conservative in the specific sense that they consider only incidental soil ingestion and treat each congener individually. The additive nature of carcinogenic risk means that the aggregate lifetime cancer risk from the full congener mixture at the most contaminated points is substantially higher than any single-congener value reported here. When the complementary exposure pathways of dust inhalation, dermal absorption and, above all, dietary intake of contaminated food are also considered, the true population risk is likely to be greater still. The convergence of very high hazard indices and very high lifetime cancer risks at the same sites constitutes compelling evidence of a serious public-health hazard.

3.6 Sources and congener signatures

The congener composition of the contamination provides a basis for inferring its origins. The soils are dominated by penta-, hexa- and hepta-chlorinated congeners, exemplified by the universally detected PCB 66, PCB 87 and PCB 153 and by the risk-driving PCB 138, PCB 180, PCB 183 and PCB 187, together with a variable contribution from lower-chlorinated congeners such as PCB 18 and PCB 31 that becomes locally dominant at particular points. This distribution is characteristic of weathered technical PCB formulations of the Aroclor type, whose commercial mixtures were defined by their average chlorine content and encompassed precisely this range of homologues (Frame, 1997). Transformer and capacitor dielectric fluids, hydraulic and heat-transfer fluids, and the plasticiser and flame-retardant additives present in cable insulation, casings and paints, all plausible constituents of the e-waste and automobile materials processed at these sites, are the

likely primary sources. Superimposed on this technical-mixture signature is the imprint of open burning, the defining feature of informal recycling. The combustion of insulated cables and plastic housings to recover metals subject's PCB-containing materials to elevated temperatures under uncontrolled and often oxygen-limited conditions (Tue et al., 2016). Such thermal treatment can volatilise and redistribute congeners, drive partial dechlorination and, conversely, promote the de novo formation and release of additional congeners, including brominated and mixed halogenated species, concentrating the residual burden in the char and ash that accumulate at burning foci (Tue et al., 2019). The extreme localisation of contamination at hotspots such as NGK-S8, together with the shift toward lower-chlorinated congeners at some points, is consistent with the influence of open-burning processes overlaid on the primary formulation signal. The relative depletion of the volatile mono-chlorinated PCB 1, detected in only half the samples, further indicates that the sources have undergone appreciable post-depositional weathering, with preferential loss of the lightest, most mobile congeners and enrichment of the heavier, more persistent ones.

The distinction between the two land-use categories is also reflected in the source interpretation. The relatively uniform, moderately elevated concentrations at the automobile-dismantling sites are consistent with the diffuse and repeated release of PCB-containing lubricating and hydraulic fluids across the yards over extended periods. The more heterogeneous, hotspot-dominated pattern at the e-waste dumpsites points to intense, spatially discrete processing of electronic components, especially cable burning, superimposed on a lower background. Both categories, however, share the same fundamental congener signature of weathered, highly chlorinated technical PCBs, reflecting their common ultimate origin in the electrical and automotive applications for which these mixtures were manufactured.

3.7 Comparison with the global e-waste literature

The concentrations reported here are broadly consistent with, and in the case of the most contaminated points comparable to or exceeding, those documented at informal e-waste and automobile-recycling sites elsewhere in the developing world (Leung et al., 2006; Fu et al., 2011). Studies at the major processing clusters of West Africa, East and South Asia, and other African cities have repeatedly demonstrated that informal recycling elevates soil PCB concentrations far above urban and rural background levels, frequently into the hundreds or thousands of nanograms per gram, with the highest values associated with cable-burning and dismantling hotspots (Tang et al., 2010; Moeckel et al., 2020; Ouabo et al., 2018). The maximum ΣPCB_{19} of 6111 ng g^{-1} recorded at NGK-S8 falls within the upper range reported for such hotspots internationally and confirms that Lagos sites rank among the more heavily contaminated globally.

Several features of the present dataset echo consistent themes in the international literature. The extreme small-scale spatial heterogeneity, with concentrations varying by more than an order of magnitude between points at the same site, mirrors observations at e-waste hubs worldwide, where contamination is invariably hotspot-driven rather than uniform. The dominance of penta- to hepta-chlorinated congeners and the use of PCB 138, PCB 153 and PCB 180 as persistent indicator congeners are likewise recurrent findings, reflecting the shared origin of the contamination in technical Aroclor-type mixtures and the universal tendency for the more highly chlorinated congeners to persist (Wang et al., 2011; Anh et al., 2020). The universal exceedance of the lowest regulatory benchmarks, and the exceedance of residential guidelines at the most contaminated points, similarly parallel reports from comparable settings and reinforce the conclusion that informal recycling routinely produces soil contamination of regulatory significance.

At the same time, the direct comparability of absolute concentrations across studies is limited by methodological differences in the number and identity of congeners quantified, extraction and clean-up procedures, and detection techniques. The present study quantified a specific suite of nineteen congeners; studies reporting a larger or smaller congener set, or reporting Aroclor-equivalent totals, will not be strictly comparable on a numerical basis. Notwithstanding these caveats, the qualitative and semi-quantitative agreement with the global literature is robust: informal e-waste and automobile dismantling in Lagos generates soil PCB contamination that is severe by international standards and that poses health risks of the same order as, or greater than, those documented at other major informal recycling centres.

3.8 Exposure pathways and food-chain implications

Although the quantitative risk assessment in this study was based on the soil-ingestion pathway, the contamination documented here feeds into a wider network of human exposure routes that collectively determine the total burden borne by affected communities (Ross & Birnbaum, 2003). Incidental ingestion of soil and dust, the pathway modelled here, is particularly important for young children, who's hand-to-mouth behaviour, play activities and lower body weight combine to produce elevated intake per unit body mass. The frequent presence of children on and around these sites, which are embedded within residential neighbourhoods, makes this a pathway of immediate and serious concern.

Dermal contact represents a second direct pathway. Workers who handle contaminated components, cables, char and soil with unprotected hands, and residents who come into contact with contaminated ground, may absorb lipophilic PCBs across the skin, a route that is enhanced by the presence of oils and greases at the automobile-dismantling sites. Inhalation constitutes a third pathway: PCBs volatilised during open burning, and those sorbed to fine resuspended dust particles, can be inhaled directly, delivering contaminants to the respiratory tract and, for the finer fractions, to the deep lung and systemic circulation. During active burning episodes, inhalation exposure may briefly dominate the total intake, particularly for workers positioned close to the fires. The most far-reaching pathway, however, is dietary. PCBs partition strongly into lipids and biomagnify along food chains, so that even moderate soil concentrations can translate into substantial contamination of animal-derived foods. Free-ranging poultry and their eggs are especially efficient integrators of soil PCBs, as foraging birds ingest contaminated soil and invertebrates and concentrate the lipophilic congeners in egg yolk and body fat (Labunska et al., 2014). Where livestock graze on or near contaminated ground, PCBs accumulate in meat and milk. Leafy vegetables grown in or adjacent to contaminated soils may accumulate PCBs through root uptake, atmospheric deposition onto foliage and adhesion of contaminated soil particles (Wang et al., 2011; Luo et al., 2020; Košnář, 2024). Given the prevalence of informal food production, backyard poultry keeping and roadside vegetable cultivation in and around Lagos recycling sites, the dietary pathway is likely to extend exposure well beyond the immediate site boundaries and to reach populations who never set foot on the contaminated land. The strong bioaccumulation and biomagnification of the highly chlorinated congeners that dominate these soils, precisely the congeners driving the calculated risks, amplifies the food-chain concern. Consequently, the soil-ingestion risks quantified here should be regarded as a lower bound on the true, multi-pathway risk faced by these communities.

3.9 Limitations

Several limitations of the present study should be acknowledged in the interpretation of its findings. First, the risk assessment was confined to the soil-ingestion pathway. Although this is typically an important route of exposure for soil-bound contaminants, the omission of dermal, inhalation and, most importantly, dietary pathways mean that the total human health risk is underestimated, potentially substantially so given the strong food-chain transfer of PCBs. The reported hazard indices and lifetime cancer risks should therefore be read as conservative, single-pathway estimates rather than as comprehensive characterisations of total risk.

Second, the deterministic risk model relied on fixed point values for the exposure parameters, notably a soil-ingestion rate of 0.0312 kg day^{-1} and a body weight of 70 kg. These generic values do not capture the variability of real exposure across age groups, occupational categories and behavioural patterns. In particular, the use of an adult body weight of 70 kg is likely to understate the risk to children, who ingest more soil per unit body weight and are the population of greatest concern. A probabilistic assessment incorporating age-specific and activity-specific exposure factors, along with exposure frequency and duration, would provide a more nuanced characterisation (U.S. Environmental Protection Agency, 2011).

Third, the study quantified a defined suite of nineteen congeners. While these include the most widely used indicator congeners and span the relevant homologue range, they represent a subset of the 209 possible congeners. The exclusion of the dioxin-like congeners in particular means that the full toxic burden, including any dioxin-like activity expressible as toxic equivalents, was not evaluated. The reported ΣPCB_{19} values consequently underestimate total PCB contamination.

Fourth, the sampling design comprised ten composite points across five sites, with two points per site. Although sufficient to reveal the pronounced spatial heterogeneity and the general magnitude of contamination, this density limits the resolution of within-site variability and precludes robust statistical inference about spatial patterns, temporal trends or the delineation of hotspot boundaries.

Fifth, the study reports total soil concentrations rather than bioaccessible or bioavailable fractions; because only the bioavailable fraction is relevant to actual uptake, the use of total concentrations in the risk model may overstate the dose delivered by ingested soil, partially offsetting the underestimation arising from the single-pathway restriction. Finally, the analysis provides a snapshot in time and does not address seasonal variation, the influence of rainfall and runoff on contaminant redistribution, or the vertical migration of PCBs into deeper soil horizons and potentially into groundwater (Ololade et al., 2021). These limitations define a clear agenda for future work. Building on the present findings, several avenues of future investigation would materially strengthen the characterisation and management of PCB contamination at these sites. A higher-density, spatially explicit sampling campaign, integrated with geographic positioning and geostatistical interpolation, would enable the delineation of hotspot boundaries and the estimation of contaminated volumes required for remediation planning. Vertical profiling through the soil column, coupled with analysis of adjacent surface water, sediment and shallow groundwater, would establish whether the surface contamination is migrating downward or laterally and thereby threatening additional receptors. The extension of the analytical scope to include the dioxin-like PCBs, together with related persistent organic pollutants such as polybrominated diphenyl ethers, polychlorinated dibenzo-*p*-dioxins and dibenzofurans, and heavy metals, would allow the cumulative toxic burden and the combined-mixture risk to be evaluated, since these contaminants co-occur at e-waste sites and act on overlapping biological targets (Tue et al., 2019). Direct measurement of contaminant concentrations in locally produced foods, in particular free-range eggs, poultry and leafy vegetables, would permit empirical quantification of the dietary pathway

that the present soil-based assessment can only infer. Finally, human biomonitoring of workers and residents, through the measurement of PCB congeners in blood, adipose tissue or breast milk, would connect the environmental contamination documented here to actual body burdens and health outcomes, closing the loop between source, exposure and effect and providing the evidence base needed to justify and evaluate interventions.

The policy implications of these findings are immediate. The universal exceedance of the lowest soil benchmark and the exceedance of a residential guideline at the most contaminated points, combined with hazard indices and cancer risks that surpass regulatory thresholds by up to several orders of magnitude, together satisfy the criteria by which contaminated sites are ordinarily prioritised for action. Yet the informal, unregulated and economically embedded nature of the activity means that conventional command-and-control responses, applied in isolation, are unlikely to succeed. A durable solution requires the integration of enforcement against the most hazardous practices, above all open burning, with the provision of viable, safer alternatives, including engineered dismantling facilities, mechanical cable-stripping, appropriate protective equipment and the formal recognition and support of recycling livelihoods. Without such an integrated approach, prohibition alone risks merely displacing the activity, and its contamination, to new and unmonitored locations.

4. Conclusion

This study provides congener-specific evidence that informal electronic-waste and automobile-dismantling activities have caused severe PCB contamination of surface soils in Lagos, Nigeria. Across ten composite topsoil samples from five sites, the sum of nineteen non-dioxin-like congeners ranged from 81.99 to 6111 ng g^{-1}, with the highest burden at an e-waste cable-burning hotspot and pronounced heterogeneity both within and between sites. Every sample exceeded the former USSR ambient-soil limit of 60 ng g^{-1}, five exceeded the 1000 ng g^{-1} Dutch and Australasian benchmarks, and three exceeded the Canadian residential-soil guideline of 1300 ng g^{-1}, establishing that the contamination is both pervasive and, at its worst points, of clear regulatory significance in a residential context.

The congener profile, dominated by persistent penta- to hepta-chlorinated congeners with universal detection of PCB 66, PCB 87 and PCB 153 and depletion of the volatile PCB 1, is characteristic of weathered technical Aroclor-type formulations overprinted by the effects of open burning. The exclusively non-dioxin-like composition directs toxicological concern toward neurodevelopmental, endocrine and immunotoxic endpoints mediated by receptor-independent mechanisms, endpoints of particular relevance to the children and young workers of informal recycling communities.

The health-risk assessment, though restricted to the soil-ingestion pathway, revealed hazard indices far exceeding unity, reaching 18.43 for PCB 18 and 17.69 for PCB 31 at New-Garage Gidan Kwali, and incremental lifetime cancer risks exceeding the USEPA thresholds of 10^{-6} and 10^{-5} for nearly all detected congeners, with a maximum of 7.37×10^{-4}. These results indicate a substantial and unacceptable potential for both non-carcinogenic and carcinogenic harm, and because dermal, inhalation and dietary pathways were not included, they represent a conservative lower bound on the true multi-pathway risk.

Taken together, the findings make a compelling case for urgent intervention. Priorities include the remediation or containment of identified hotspots, the enforcement of existing prohibitions on open burning and uncontrolled dismantling, the formalisation and safe engineering of recycling operations, the restriction of food production on and around contaminated land, and the

establishment of longitudinal environmental monitoring and human biomonitoring programmes to track exposure and health outcomes over time. Future research should extend the congener suite to include dioxin-like congeners, incorporate multi-pathway and age-specific probabilistic exposure modelling, measure bioaccessible fractions, and directly assess food-chain transfer, so as to convert the clear warning signal delivered by these soils into a fully quantified basis for protecting one of Africa's largest urban populations.

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