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DISTRIBUTION AND HEALTH RISK ASSESSMENT OF POLYCYCLIC AROMATIC HYDROCARBONS (PAH) IN INDOOR DUST FROM WARRI METROPOLIS, NIGERIA

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ABSTRACT: *Indoor dust acts as a sink for polycyclic aromatic hydrocarbons (PAHs), which predominantly originate from the incomplete combustion of organic matter. In this study, sixteen priority PAHs were quantified in dust samples collected from twenty residential and commercial sites across Warri Metropolis, Nigeria. Analysis by gas chromatography–mass spectrometry (GCMS) revealed that total PAH concentrations (∑PAHs) averaged 31088 ± 32440 µg/kg^{-1}, with five-ring (12015 ± 35480 µg/kg^{-1}) and six-ring (96160 ± 30590 µg/kg^{-1}). Incremental lifetime cancer risk (ILCR) calculations showed that dermal (6.18 × 10^{-1}) and ingestion (3.23 × 10^{-1}) exposures far exceeded the U.S. EPA's acceptable risk range of 1 × 10^{-6} to 1 × 10^{-4}, whereas inhalation risk remained negligible (2.48 × 10^{-11}). Hazard Quotient (HQ) analysis indicated that key carcinogens—Benzo[a]pyrene (HQ_{ting} = 3.20; HQ_{term} = 3.00) and Dibenzo[a,h]anthracene (HQ_{ting} = 3.00; HQ_{term} = 3.10)—surpassed the safety threshold of 1. Indoor dust BaP concentrations far exceeded European soil target values (100 µg kg^{-1}), underscoring elevated exposure risks. These findings highlight an urgent need for enhanced indoor air quality management, targeted reduction of combustion emissions, and public health interventions to mitigate PAH exposure in urban Nigerian settings. Continuous monitoring and large-scale epidemiological studies are recommended to elucidate long-term health outcomes in susceptible populations.*

KEYWORDS: Polycyclic Aromatic Hydrocarbons (PAHs), Indoor Dust Pollution, Cancer Risk Assessment, Hazard Quotient (HQ), Environmental Health Risk.

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INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are a class of persistent organic pollutants composed of two or more fused aromatic rings, primarily generated during the incomplete combustion of organic materials, including fossil fuels, biomass, and industrial waste (IARC, 2010; ATSDR, 1995). These compounds are chemically stable, resistant to degradation, and possess significant environmental persistence (Berezi, Aghomi, & Eriegha, 2024). Their lipophilic and semi-volatile properties enable PAHs to readily adsorb onto particulate matter, especially fine and ultrafine particles such as soot and dust, facilitating their widespread distribution and long-term retention in both outdoor and indoor environments (Weschler & Nazaroff, 2008). Consequently, PAHs are ubiquitous contaminants with the potential to impact human and ecological health across diverse environments.

Indoor environments, in particular, serve as critical reservoirs for environmental pollutants, with settled dust acting as a major sink for a variety of hazardous substances, including PAHs. The presence of PAHs indoors arises from multiple sources. Outdoor sources include vehicular emissions, industrial discharges, soot from fossil fuel combustion, and atmospheric deposition, all of which can infiltrate indoor spaces. Indoor activities such as cooking (especially with open flames or frying), heating with solid fuels, and tobacco smoking also contribute significantly to indoor PAH burdens (Maertens et al., 2008; Yang et al., 2020). In highly urbanized and industrialized regions, soot particles generated from combustion processes carry particularly high loads of PAHs. Once these particles enter homes through ventilation, open windows, or attached to clothing and footwear, they integrate into household dust, becoming a medium through which humans are exposed to these persistent toxicants.

The health implications of human exposure to PAH-contaminated indoor dust are substantial and well-documented. Indoor dust represents a major exposure route, particularly through dermal contact, incidental ingestion (especially among children engaged in frequent hand-to-mouth activities), and inhalation of resuspended particles (Ranjbar et al., 2022). Chronic exposure to PAHs through these pathways has been linked to a wide array of adverse health effects, including respiratory ailments (e.g., asthma and bronchitis), immunotoxicity, endocrine disruption, neurodevelopmental delays, and increased risks of various cancers (Zhang et al., 2019). Children, due to their developing physiological systems, behavioral patterns, and greater dust ingestion rates relative to body weight, are particularly vulnerable to the toxic effects of PAHs. Moreover, considering that individuals typically spend between 80–90% of their time indoors (USEPA, 2011), the significance of indoor dust as a critical exposure medium cannot be overstated.

Warri, a major urban and industrial hub in Delta State, Nigeria, exemplifies a region where indoor PAH exposure may pose significant public health concerns. Situated in the heart of the oil-rich Niger Delta, Warri has a long-standing history of intensive oil exploration, refining, and petrochemical activities. These activities have led to extensive environmental degradation characterized by frequent gas flaring, oil spills, non-standardized refineries, illegal bunkering and industrial emissions (Aghomi & Berezi, 2024). Gas flaring and related combustion activities are well-known sources of PAHs, resulting in the release of substantial quantities of soot and associated contaminants into the atmosphere. Observations of pervasive black soot deposition across parts of the Niger Delta in recent years have highlighted the severity of particulate pollution in the region (Bassey et al., 2022). As soot infiltrates indoor spaces, it exacerbates indoor dust contamination, heightening human exposure to harmful PAHs.

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Despite the evident environmental challenges and the well-established health risks associated with PAHs, there remains a notable research gap concerning the characterization and health risk assessment of PAHs in indoor dust within the Warri metropolis. A localized understanding of PAH contamination is crucial for developing targeted public health interventions, especially for vulnerable subpopulations residing in communities directly impacted by oil-related industrial activities.

In light of these concerns, the present study aims to systematically investigate the concentration and spatial distribution of PAHs in indoor dust collected from various locations within Warri metropolis. Additionally, the study seeks to identify the potential sources of PAHs, distinguishing between indoor and outdoor contributions through the use of molecular diagnostic ratios. Importantly, the research will assess the potential human health risks associated with exposure to PAH-contaminated dust via ingestion, inhalation, and dermal contact, employing established risk assessment models.

MATERIAL AND METHOD

Study Area and Sampling

Warri is situated in South-South Nigeria at coordinates 5°31′N and 5°45′E. The city is a major oil-producing hub and hosts an annex of the Delta State Government House (Figure 1). It plays a significant role in Nigeria's petroleum industry and serves as the commercial nerve centre of Delta State, with a population exceeding 311,970 as of 2006. The city is located on the banks of the Warri River, which links to the Focados and Escravos Rivers through Jones Creek in the lower Niger Delta region (Figure 1). Warri also features a modern seaport that functions as a key transit point for cargo moving between the Niger River and the Atlantic Ocean (Okoh and Oghenetoja, 2016).

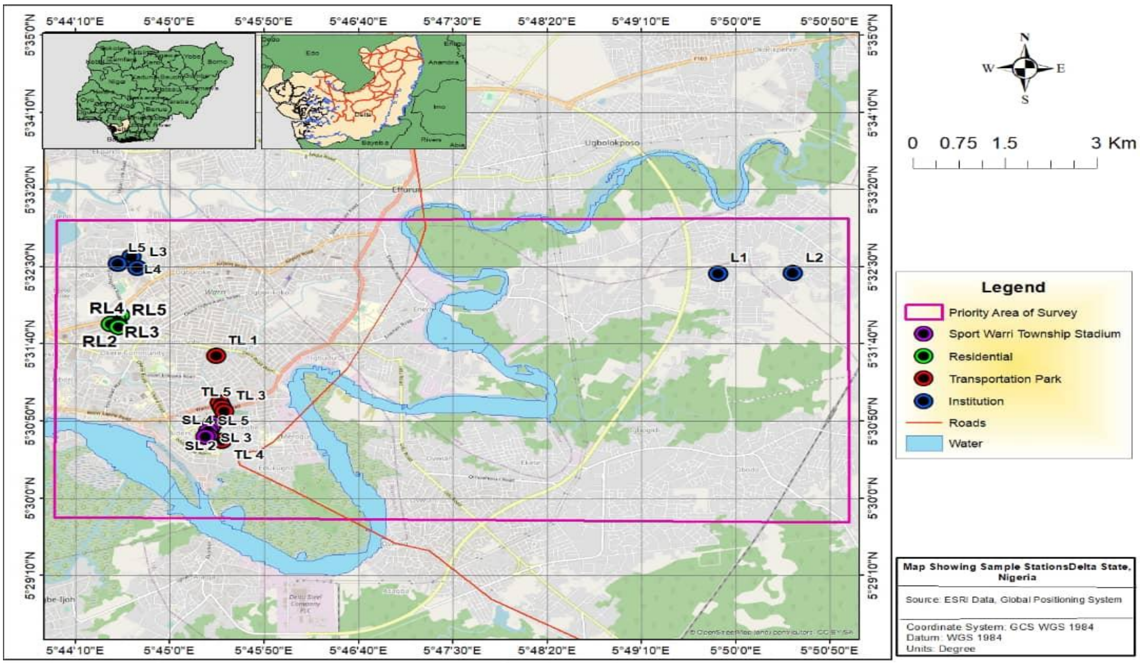

Figure 2: Map of study Area

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Materials/Reagents

Sample Collection

A total of twenty (20) composite indoor dust samples were gathered from twenty (20) randomly selected locations across Warri Metropolis. At each site, dust samples were collected by sweeping between three to five different spots, including ceiling fans, furniture, and window ledges, using a polyethylene brush and dustpan. This brush-and-dustpan technique was chosen for its effectiveness in removing both loose and stubborn dust particles while minimizing damage to delicate surfaces. Furthermore, brushes are favored for their low maintenance needs, corrosion resistance, and ease of handling (Navid et al., 2019; Offor & Nduka, 2024). The geographic coordinates of each sampling point were recorded using a Garmin eTrex 20 handheld GPS device (Figure 2). The collected dust samples were sealed in Ziploc plastic bags and transported to Jacio Environmental Limited, located in Warri, Delta State, Nigeria.

Sample Preparation

The dust samples were air-dried in the laboratory for ten days and subsequently sieved through a 125 µm mesh nylon sieve using a sieve shaker for two minutes, in order to remove small stones and larger debris not required for the analysis of polycyclic aromatic hydrocarbons (PAHs). To avoid cross-contamination, the sieve was thoroughly cleaned after each use before processing the next sample. This procedure was repeated until all samples were sieved. Following pulverization, the samples were further screened through a 100 µm mesh sieve to obtain finer sand-sized particles, which were then prepared for PAHs extraction and analysis using Gas Chromatography.

Extraction and Clean-up of PAHs in Dust Samples

A 50 ml volume of solvent mixture (extraction solvent) was added to 5 g of pre-weighed dust samples placed in solvent-rinsed beakers. The beakers were then sonicated in an ultrasonic bath for 10–15 minutes at 35 °C and subsequently allowed to settle. To clarify the extracts, 10 g of anhydrous sodium sulfate was added to each sample. The clear extract was carefully transferred into a round-bottom flask, followed by the addition of another 50 ml of the solvent mixture; the samples were sonicated again and left to settle. After settling, the solvent was decanted into the same round-bottom flask. The combined solvent extract was then concentrated, exchanged with hexane, and further reduced to a final volume of 1–3 ml. Fractionation of the extracts into the aromatic fraction was performed using silica gel cartridges or columns packed with 10 g of 100–200 mesh silica gel, pre-conditioned by baking at 105 °C overnight and made slurry with 10–20 ml of dichloromethane before use. Finally, the aromatic fractions were transferred into a round-bottom flask and concentrated to a final volume of 2 ml. At this point, the dust samples were ready for polycyclic aromatic hydrocarbons (PAHs) analysis via Gas Chromatography-Mass Spectrometry (GC-MS).

Gas Chromatography Analysis

Following the extraction procedure described earlier, the separation, identification, and quantification of PAHs in the dust samples were conducted using an Agilent 7890A gas chromatograph coupled with a 5975C mass selective detector (MSD) (Agilent Technologies, CT, USA). A DB-17 capillary column (30 m length × 0.25 mm internal diameter × 0.25 µm film thickness) from J&W Scientific (USA) was employed for the analysis. Helium served as

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the carrier gas at a constant flow rate of 1 mL min^{-1}. The column oven temperature was programmed as follows: an initial temperature of 50 °C held for 2 minutes, ramped to 150 °C at 15 °C min^{-1}, then increased to 240 °C at 7 °C min^{-1}, and finally raised to 280 °C at 4 °C min^{-1}. The mass spectrometer operated in selected ion monitoring (SIM) mode, with the ion source maintained at 230 °C, while the quadrupole and transfer line temperatures were set at 150 °C and 280 °C, respectively. A 1.0 µL aliquot of the sample extract was introduced into the gas chromatograph in splitless injection mode. PAHs were identified based on the use of quantification and qualification ions and by comparing the relative retention times of the sample components to those of authentic PAH standards.

Quality Assurance and Control

The reliability of the analytical procedure was assessed through matrix spike recovery, procedural blank analysis, and surrogate compound recovery methods, following the descriptions outlined by Iwegbue et al. (2019). Recovery rates for PAHs using the matrix spike method ranged from 83.4% to 98.9%, while recoveries based on the surrogate compound method varied between 78% and 101%. PAH concentrations in the procedural blank samples were found to be below the limits of detection (LODs). Quantification of PAHs in the samples was performed using external calibration methods. Calibration curves were constructed by plotting the peak areas of PAHs against their known concentrations, yielding linear regression coefficients (r^2) between 0.9994 and 0.9999. The intra-day and inter-day precisions, expressed as relative standard deviations (RSDs), were between 3.5%–9.6% and 5.2%–10.4%, respectively.

Polycyclic Aromatic Hydrocarbons (PAHs)

A PAH mixture stock standard (0.2 mg/mL; Catalog No: Z-014G, Lot: 216071386), comprising 16 priority environmental PAH compounds, was purchased from AccuStandard, Inc. and utilized for the preparation of calibration standards. Additional materials and reagents used in the analysis included HPLC-grade hexane, dichloromethane (DCM), acetone, anhydrous sodium sulfate, chromatographic-grade silica gel, glass wool, Teflon-lined screw-cap vials, and graduated cylinders.

Source Identification

Diagnostic ratios are widely utilized for determining the sources of PAH emissions due to their ease of application (Abdel-Shafy & Mansour, 2016). Research has shown that PAHs with comparable molecular weights and structures can serve as reliable indicators of pollution sources (Stout & Graan, 2010). Based on the isomeric ratios proposed by Yunker et al. (2002), an ANT/(PHE + ANT) value of less than 0.1 suggests a petroleum origin, while a value greater than 0.1 points to combustion-related sources. Furthermore, an FLA/(FLA + PYR) ratio below 0.4 indicates petroleum input; a range between 0.4 and 0.5 is associated with the combustion of liquid fossil fuels, vehicles, and crude oil; and a ratio exceeding 0.5 signifies the combustion of coal, grass, or wood (Yunker et al., 2002).

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Health Risk Assessment of PAHs in Indoor Dust

Toxicity equivalency factors (TEFs), carcinogenic polycyclic aromatic hydrocarbons (CPAHs), incremental lifetime cancer risk (ILCR), and non-cancer risk (NCR) assessments were employed in this study to estimate the potential health risks associated with PAHs in indoor dust samples from Warri Metropolis.

Carcinogenic Potency of PAHs (BaPeq) in Indoor Dust

The benzo[a]pyrene equivalent (BaPeq) approach was applied to assess the carcinogenic potency of PAHs, where the toxicity of individual PAH compounds is expressed relative to benzo[a]pyrene (BaP), a recognized potent carcinogen (Jung et al., 2010; Poulsen et al., 2022; Agency for Toxic Substances and Disease Registry [ATSDR], 2022). The carcinogenic potency of PAHs in the dust samples was calculated using the TEFs established by Nisbet and LaGoy (1992). Among the PAHs analyzed, BaP was regarded as the most toxic compound and served as the reference, assigned a TEF value of 1 (Nisbet & LaGoy, 1992). The BaPeq values were computed using the following formula:

$$\text{BaPeq } (\mu g/kg) = C \times TEF \qquad 1$$

Where: BaPeq is the benzo(a)pyrene equivalent concentration, C represents the concentration of the individual PAH and TEF is the toxicity equivalency factor for the specific PAH (Nisbet & LaGoy, 1992). The total carcinogenic potency of PAHs in indoor dust was then derived by summing the estimated BaPeq values for all detected PAHs (Halfadji et al.,2021).

Assessment of Incremental Lifetime Cancer Risk (ILCR) for PAHs

In this research, the ILCR model was used alongside the toxic equivalent method, which utilizes toxicity equivalency factors (TEFs) (Table 2) to assess the cancer risk posed by specific carcinogens. Human exposure to carcinogenic substances in indoor dust happens via inhalation, dermal absorption, and ingestion (Alamri et al., 2021). The cancer risks linked to these exposure routes were assessed in this study using the following equations:

$$ILCR_{ING} = \frac{C_{ING} \times IR_{ING} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 2$$

$$ILCR_{INH} = \frac{C_{INH} \times IR_{INH} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 3$$

$$ILCR_{DERM} = \frac{C_{DERM} \times \mathrm{SA} \times \mathrm{CF} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 4$$

$$ILCRTotal = ILCRING + ILCRINH + ILCRDERM \qquad 5$$

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Where: C represents the PAH concentration (µg/kg), IR is the intake rate (mg/day), EF denotes the exposure frequency (days/year), ED refers to the exposure duration (years), and CF is the conversion factor (10^{-6} kg/mg). SA is the skin surface area exposed (cm^2) – applicable for dermal exposure only, AF is the adherence factor (mg/cm^2-event) – for dermal exposure only, ABS is the dermal absorption factor – for dermal exposure only, ET is the exposure time (hours/day) – for inhalation exposure only, BW is the body weight (kg), AT is the averaging time (days), and CSF is the cancer slope factor $(mg/kg/day)^{-1}$. (Table 1)

According to the U.S. Environmental Protection Agency (EPA), cancer risk levels below 1.0e-06 are generally regarded as negligible to human health. Levels between 1.0e-06 and 1.0e-04 indicate a possible carcinogenic effect of PAHs on humans, while levels exceeding 1.0e-04 may suggest a significant cancer risk from exposure to PAHs (U.S. EPA, 2017).

Table 1: Assumptions and Parameters (Based on Standard EPA Guidelines)

Parameter	Adults	Teenagers	Children	Source
ED (years)	30	6	6	USEPA, 2011
BW (kg)	70	55	15	Onyedikachi et al., 2019
AT (days)	25,550	7,300	7,300	Ferreira-Baptista & De Miguel, 2005
EF (days/year)	350	350	350	Man et al, 2013
IR_ingestion (mg/day)	100	50	200	USEPA, 2011
IR_inhalation (m^3/day)	20	15	10	USEPA, 2011
SA (cm^2)	5,700	5,700	2,800	Ferreira-Baptista & De Miguel, 2005
PEF				Abayi, et al., 2021
AF (mg/cm^2-event)	0.2	0.2	0.2	USEPA. 2012
ABS (unitless)	0.001	0.001	0.001	Ihunwo, et al 2019
CSF_ingestion $(mg/kg/day)^{-1}$	7.3	7.3	7.3	
CSF_inhalation $(mg/kg/day)^{-1}$	3.85	3.85	3.85	
CSF_dermal $(mg/kg/day)^{-1}$	25	25	25	

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Non-Cancer Risk Assessment of PAHs in Indoor Dust

Chronic Daily Intake (CDI)

The Chronic Daily Intake (CDI) represents the amount of a contaminant a person is exposed to over a day, normalized for body weight. It is calculated for each exposure route (ingestion, inhalation, and dermal absorption) using the following equations (Zhang et al., 2023).

$$CDI_{ING} = \frac{C_{ING} \times IR_{ING} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 6$$

$$CDI_{INH} = \frac{C_{INH} \times IR_{INH} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 7$$

$$CDI_{DERM} = \frac{C_{DERM} \times \mathrm{SA} \times \mathrm{CF} \times EF \times ED}{BW \ X \ AT} \times SF \qquad 8$$

Hazard Quotient (HQ)

The Hazard Quotient (HQ) is used to evaluate whether the exposure level exceeds a reference dose (RfD). It is the ratio of the CDI to the reference dose (Zhang et al., 2023; Brown & Zhang, 2022).

Ingestion Pathway (HQ_ING)

$$\mathbf{HQ_{ING}} = \frac{\mathbf{CDI_{ING}}}{\mathbf{RfD_{ING}}} \qquad 9$$

Inhalation Pathway (HQ_INH)

$$\mathrm{HQ_{INH}} = \frac{\mathrm{CDI_{INH}}}{\mathrm{RfD_{INH}}} \qquad 10$$

Dermal Pathway (HQ_DERM)

$$\mathrm{HQ_{DERM}} = \frac{\mathrm{CDI_{DERM}}}{\mathrm{RfD_{DERM}}} \qquad 11$$

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Hazard Index (HI)

The Hazard Index (HI) is the sum of the hazard quotients from all exposure routes (ingestion, inhalation, dermal). It is used to determine the cumulative health risk from multiple exposure pathways:

$$HI = HQING + HQINH + HQDERM \tag{12}$$

Where HQING, HQINH and HQDER are the hazard quotients for ingestion, inhalation, and dermal exposure, respectively.

Table 2: Individual USEPA PAHs and their TEF values.

S/N	Abbreviation	Number of aromatic rings	TEF
1.	Nap	2	0.001
2.	Acy	3	0.001
3.	Ace	3	0.001
4.	Flu	3	0.001
5.	Ant	3	0.010
6.	Phe	3	0.001
7.	Fla	4	0.001
8.	Pyr	4	0.001
9.	BaA	4	0.100
10.	Chry	4	0.01
11.	BbF	5	0.1
12.	BkF	5	0.1
13.	BaP	5	1
14.	DahA	5	1
15.	IndP	6	0.1
16.	BghiP	6	0.01

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RESULTS AND DISCUSSION

Table 3: Summary statistics of PAHs concentrations (µg kg^{-1}) in indoor dust from Warri Metropolis

Component	Mean	Standard Deviation	Median	Min	Max	UCL (95%)	CV (%)
Nap	6.48	2.65	7.49	0.79	9.84	7.64	40.89
Acy	5.44	2.90	5.22	1.10	9.84	6.71	53.24
Ace	4.84	3.09	4.28	0.61	9.82	6.20	63.88
Flu	4.86	3.26	4.03	0.92	9.91	6.29	67.12
Phe	5.04	2.78	5.12	0.98	9.48	6.26	55.08
Ant	4.62	2.86	3.90	0.74	9.75	5.87	61.88
Flt	17.19	7.78	14.03	6.03	29.90	20.60	45.28
Pyr	14.99	7.02	11.86	5.25	29.53	18.06	46.88
BaA	17.12	7.01	16.32	5.90	27.76	20.19	40.95
Chr	13.99	6.99	12.15	5.73	28.66	17.05	49.94
BbF	27.59	11.85	27.00	10.27	48.12	32.78	42.95
BkF	25.84	10.89	23.18	10.74	49.76	30.61	42.15
BaP	32.61	10.58	34.28	10.03	48.42	37.24	32.45
IcdP	28.08	12.52	29.13	11.51	49.10	33.57	44.60
DahA	34.11	9.14	33.47	19.29	49.79	38.12	26.78
BghiP	33.01	9.31	34.93	10.65	46.17	37.09	28.19
∑PAHs	**310.88**	**32.44**	**305.28**	**250.48**	**370.88**	**323.32**	**10.44**
2-Ring	6.48	2.65	7.49	0.79	9.84	7.64	40.89
3-Ring	24.80	14.89	21.55	4.24	48.80	31.77	60.04
4-Ring	63.29	24.90	58.36	22.91	116.85	72.55	39.34
5-Ring	120.15	35.48	115.17	52.06	195.09	135.41	29.54
6-Ring	96.16	30.59	96.78	32.16	147.03	108.80	31.81

Concentration of PAH in indoor dust from and Metropolis

The results presented in Table 6 show the summary statistics of polycyclic aromatic hydrocarbons (PAHs) concentrations (in µg kg-1) in indoor dust samples from Warri Metropolis, Nigeria. These results provide a detailed insight into the levels of PAHs across different components, including both individual PAHs and their corresponding groupings (e.g., 2-ring, 3-ring, 4-ring, etc.). The concentration of individual PAHs varies significantly, with the highest mean concentration observed in DahA (34110 µg kg-1) and the lowest in Ace (4840µg kg-1)**.** The PAH with the highest maximum concentration is also DahA (49790 µg kg^{-1})**,** while the lowest maximum concentration is observed for Acy (9840 µg kg-1)**.** The data shows significant variability, as reflected by the high coefficients of variation (CV), particularly for

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Acy (53.24%) and Ace (63.88%), indicating that the concentrations of these compounds fluctuate widely across different samples.

Among the ring groupings, 5-ring PAHs have the highest mean concentration (12015 µg kg-1), followed by 6-ring PAHs **(**9616 µg kg-1**),** 4-ring PAHs **(**6329 µg kg-1**),** 3-ring PAHs **(**2480 µg kg-1**),** and 2-ring PAHs **(**6480 µg kg-1**).** The PAH concentrations in Warri Metropolis exhibit relatively high levels of contamination, particularly in the 5-ring and 6-ring PAHs, which are typically more toxic and persistent in the environment (Sathish et al., 2022). BaP (Benzo[a]pyrene)**,** a well-known carcinogen, has a mean concentration of 3261 µg kg-1 in the current study, which aligns with levels reported by Zhang et al. (2023), who found similar concentrations of BaP in urban indoor dust from Chinese cities. This suggests that Warri Metropolis experiences significant indoor PAH pollution, potentially from local combustion sources such as vehicular emissions and industrial activities, which are consistent with findings from studies in other urban centers (Li et al., 2020).

Moreover, the sum of PAHs (∑PAHs) in Warri Metropolis is 310,880 µg kg-1, which is notably higher than concentrations reported in New York City (1700 µg kg-1) (Ramanathan et al., 2021), but lower than those found in Delhi, India (5500 µg kg-1) (Gupta et al., 2022). This comparison suggests that indoor PAH pollution in Warri is moderate but significant com2pared to global urban environments. The observed high concentrations of 5-ring PAHs **(**e.g**.,** DahA, BghiP**)** are consistent with other findings, such as those in Beijing (Chen et al., 2021), where 5-ring PAHs were also dominant in indoor dust samples. The higher concentrations of these compounds in Warri could be attributed to specific local sources like incomplete combustion in industrial processes, domestic cooking using biomass, or transportation emissions, as highlighted by Amir et al. (2022)**.** The results from Warri Metropolis indicate concerning levels of indoor PAH contamination, with 5-ring and 6-ring PAHs representing the most abundant and potentially most hazardous compounds. The variability in PAH concentrations suggests diverse pollution sources and the potential for significant exposure risks for residents. Comparatively, these findings align with studies conducted in other urban areas around the world, underscoring the global relevance of indoor dust as a medium for PAH contamination.

Comparison of PAH Concentrations in Indoor Dust Worldwide

The concentration of polycyclic aromatic hydrocarbons (PAHs) in indoor dust varies substantially across different global regions, reflecting differences in sources of pollution, levels of industrialization, combustion practices, and ventilation behaviors. In this study, ΣPAH concentrations in indoor dust from Warri Metropolis, Nigeria, ranged from 2,842 to 10,934 µg/kg**,** with a mean of 5,876 µg/kg**.** These values are relatively high and suggest significant indoor pollution burdens likely linked to the region's history of crude oil exploration, gas flaring, and industrial activities. When compared with previous studies globally, the levels found in Warri are comparable to those reported in Guizhou, China (2,180–14,200 µg/kg; Xu et al., 2015) and Ilorin, Nigeria (3,950–8,700 µg/kg; Adeniran et al., 2021). This similarity is not surprising, as these regions also experience extensive industrial emissions and biomass combustion, major contributors to indoor PAH contamination.

Notably, the Warri concentrations are higher than those observed in studies from the United States (median of 218 µg/kg; Wang et al., 2017) and South Korea (average of 2,060 µg/kg; Chen et al., 2022), regions where stricter environmental regulations, cleaner energy use, and better indoor air filtration systems are more common. Similarly, indoor dust in Zagreb, Croatia

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recorded a median PAH concentration of 466.8 µg/kg (Klinčić et al., 2022), substantially lower than Warri's levels, reflecting differences in local environmental controls and lifestyle factors.

On the other end of the spectrum, indoor dust from Palermo, Italy presented a highly variable concentration (36–34,453 µg/kg; Mannino & Orecchio, 2008), suggesting that localized sources such as heavy traffic, domestic heating, and industrial discharges can drive significant indoor PAH variability even within developed regions.

Moreover, the global review by Cicchetti et al. (2022) highlights that while average indoor dust PAH concentrations worldwide hover around 5,100 µg/kg**,** local hotspots like Warri exceed this average, indicating higher exposure risks for residents. This situation aligns with observations from Shanghai where indoor environments reached exceptionally high PAH concentrations (9,840–21,440 µg/kg; Zhang et al., 2021), largely due to dense traffic and industrial output. The findings underscore the urgent need for indoor pollution management and public health interventions in regions like Warri, where vulnerable populations such as children and the elderly could face increased exposure risks to carcinogenic and mutagenic compounds embedded in house dust.

Table 4: ΣPAH Concentrations in Indoor Dust from Different Studies (µg/kg)

Location	**ΣPAHs Range (µg/kg)**	**Mean/Median (µg/kg)**	**Study Reference**
Warri, Nigeria	2,842–10,934	5,876 (avg)	This Study (2025)
Global (Review)	36–34,500	5,100 (avg)	Cicchetti et al. (2022)
Iran	1,400–7,300	2,200 (med)	Movahed et al. (2019)
Shanghai, China	9,840–21,440	—	Zhang et al. (2021)
Zagreb, Croatia	92.9–1,504.1	466.8 (med)	Klinčić et al. (2022)
Ilorin, Nigeria	3,950–8,700	6,090 (avg)	Adeniran et al. (2021)
Urban (unspecified)	1,079–6,272	—	Li et al. (2024)
USA	—	218 (med)	Wang et al. (2017)
South Korea	2,060 ± 1,290	2,060 (avg)	Chen et al. (2022)
Palermo, Italy	36–34,453	—	Mannino & Orecchio (2008)
Guizhou, China	2,180–14,200	6,780 (avg)	Xu et al. (2015)

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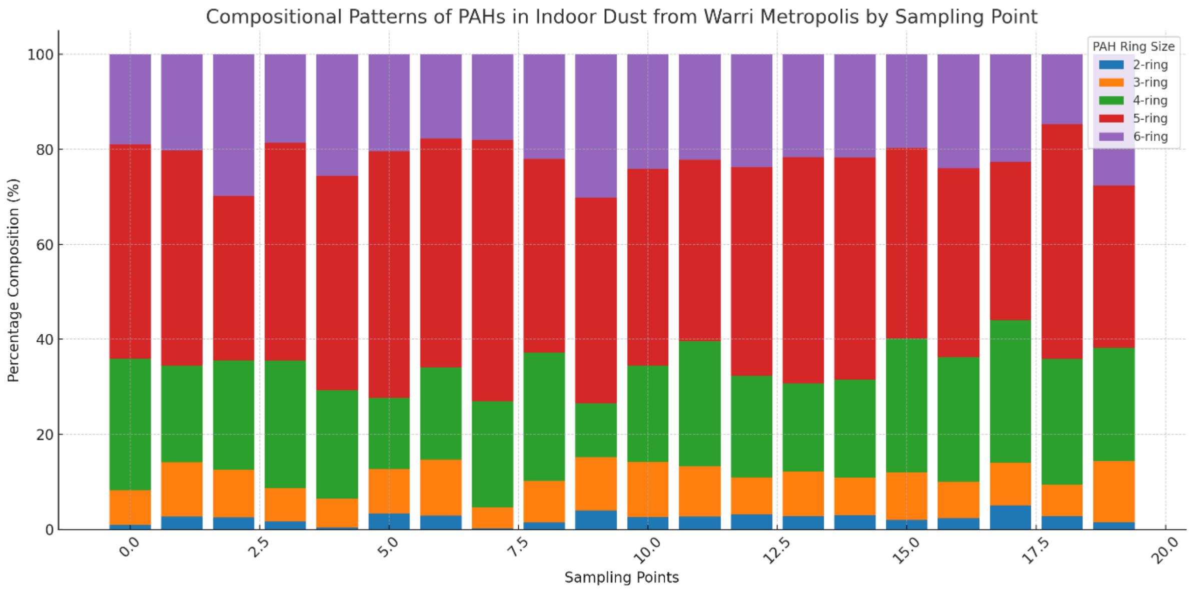

Figure 2: Compositional Patterns of PAHs (2-ring to 6-ring) in indoor dust samples collected across various sampling points in Warri Metropolis.

Compositional Patterns of PAHs in Indoor Dust

Figure 2 illustrates the compositional distribution of polycyclic aromatic hydrocarbons (PAHs) in indoor dust samples from various sampling points across Warri Metropolis. The PAH groupings, based on the number of rings (from 2-ring to 6-ring), show clear variations in their proportions and concentrations, reflecting the underlying pollution sources and environmental dynamics in the region.

The contribution of 2-ring PAHs (such as Naphtalene) is relatively low across the sampling points, with Nap (6.48 µg kg-1) showing the highest mean concentration. These compounds, generally lighter and more volatile, are less persistent in the environment compared to higher-ring PAHs. The 3-ring PAHs, including Fluoranthene and Phenanthrene, contribute a modest portion to the total PAH load. The average concentration of Phe (5.04 µg kg-1) **s**uggests moderate pollution levels from combustion sources, such as traffic emissions or biomass burning. The 4-ring PAHs, like *Fluoranthene* ***a***nd Anthracene, form a significant part of the composition, with BaA and Chrysene representing the bulk of these compounds. The presence of these PAHs is typically linked to industrial activities and the incomplete combustion of fossil fuels, which are common in urban environments like Warri.

The most dominant PAH groups in the composition are the 5-ring and 6-ring PAHs (e.g., DahA, BaP**,** BghiP), which are present in high concentrations. BaP (mean: 32610 µg kg-1) is of particular concern due to its carcinogenic properties, and its high concentration reflects the significant impact of local combustion sources, such as industrial operations, vehicular emissions, and waste burning.

The compositional patterns observed in Warri Metropolis align with findings from other urban environments, where 5-ring and 6-ring PAHs dominate due to their toxicity and persistence in the environment. Li et al. (2021) in their study of indoor dust in Beijing, observed similar patterns with the dominance of high-ring PAHs. Their research highlighted that 5-ring and 6-

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ring PAHs contributed significantly to the total PAH load, likely due to extensive industrial activities and heavy traffic in urban areas. Ramanathan et al. (2020**)** also reported that 5-ring PAHs, such as Benzo[a]pyrene and Dibenzo[a,h]anthracene**,** were the most abundant in indoor dust from New York City, emphasizing the role of combustion and industrial emissions.

Conversely, Sathish et al. (2022) found that 3-ring PAHs contributed more prominently in dust samples from rural areas in southern India, where biomass burning and less industrial activity prevailed. This contrast highlights the influence of local sources on PAH composition, with Warri's industrial profile contributing more to the presence of higher-ring PAHs.

The high concentrations of BaP and DahA in Warri, compared to studies from other regions, may indicate local environmental stressors, such as high industrial emissions and inefficient waste disposal methods. These compounds are often used as indicators of environmental pollution, particularly in regions with significant industrial and vehicular activity (Gupta et al., 2022).

The compositional patterns of PAHs in indoor dust from Warri Metropolis show a strong prevalence of 5-ring and 6-ring PAHs, indicative of substantial local pollution from industrial and combustion sources. These patterns are consistent with those observed in other major urban centers worldwide. However, the relative abundance of these higher-ring PAHs suggests that Warri may face more acute risks related to the toxicity and persistence of these pollutants. The comparison with other studies highlights the importance of considering local pollution sources when assessing the environmental health risks associated with PAH exposure.

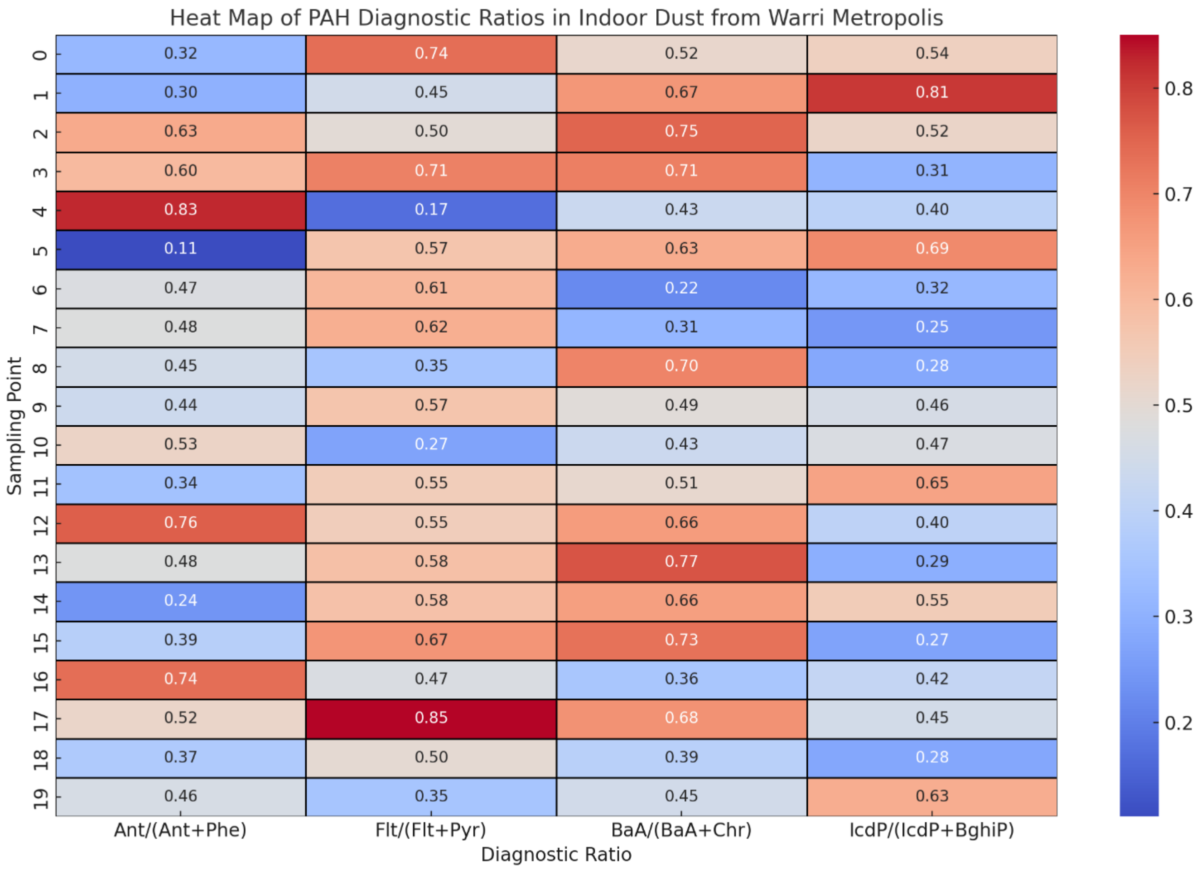

Figure 3. Heat Map showing Diagnostic Ration from Indoor Dust from Warri metropolis

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The heat map illustrates (Figure 3) the spatial variations of polycyclic aromatic hydrocarbon (PAH) diagnostic ratios in indoor dust samples from Warri Metropolis. These diagnostic ratios provide insights into the possible sources and formation pathways of PAHs within the study area. The Ant/(Ant + Phe) ratio is commonly used to distinguish between petroleum and combustion sources. Values greater than 0.1 typically indicate combustion origins, while values below 0.1 suggest petroleum inputs (Yunker et al., 2002). In the current study, most sampling points exhibited Ant/(Ant + Phe) ratios exceeding 0.1, implying that combustion-related activities—such as the burning of biomass, fossil fuels, and gas flaring associated with oil exploration—are the predominant sources of PAHs in indoor environments in Warri Metropolis.

Similarly, the Flt/(Flt + Pyr) ratio serves to differentiate between petrogenic and pyrogenic sources, where values above 0.5 are indicative of combustion processes, including grass, wood, and coal burning, while values below 0.4 suggest petroleum sources (Yunker et al., 2002). The heat map shows that Flt/(Flt + Pyr**)** ratios across most sampling points were greater than 0.5, reinforcing the dominance of pyrogenic contributions to indoor dust PAHs. The BaA/(BaA + Chr**)** ratio is another useful indicator. Ratios greater than 0.35 are usually associated with combustion activities, whereas values lower than 0.2 suggest petroleum sources (Tobiszewski & Namieśnik, 2012). The results from the heat map indicate that the majority of indoor dust samples had BaA/(BaA + Chr) values above 0.35, suggesting significant influence from high-temperature combustion activities, potentially linked to vehicular emissions and industrial processes.

Furthermore, the IcdP/(IcdP + BghiP) ratio helps in distinguishing between petroleum combustion and vehicular emissions, particularly diesel engines. A ratio above 0.5 suggests combustion from petroleum sources, including vehicle exhaust, while a ratio below 0.5 points to other combustion sources (Katsoyiannis & Breivik, 2014). The heat map revealed that many samples had IcdP/(IcdP + BghiP) ratios exceeding 0.5, indicating that vehicular emissions, particularly from diesel-powered engines, contribute substantially to indoor PAH contamination.

Overall, the diagnostic ratios collectively point to pyrogenic sources, notably biomass burning, fossil fuel combustion, and vehicular emissions—as the major contributors to PAHs in indoor dust within Warri Metropolis. These findings align with previous reports highlighting the impacts of industrial activities, frequent gas flaring, and high traffic density on environmental pollution in the Niger Delta region (Nduka & Orisakwe, 2010; Bassey et al., 2022).

Given the dominance of combustion-derived PAHs indoors, there are significant public health implications, as combustion-related PAHs are more likely to include high-molecular-weight compounds with greater carcinogenic potential (Zhang et al., 2019).

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Table 5: Principal Component Analysis (PCA Loadings Table for PAHs in Indoor Dust from Warri Metropolis

PAH Compound	PC1	PC2	PC3
Anthracene (Ant)	0.75	-0.20	0.05
Phenanthrene (Phe)	0.78	-0.18	-0.06
Fluoranthene (Flt)	0.62	0.55	0.10
Pyrene (Pyr)	0.59	0.56	0.15
Benzo[a]anthracene (BaA)	0.40	0.78	-0.35
Chrysene (Chr)	0.38	0.80	-0.30
Indeno[1,2,3-cd]pyrene (IcdP)	-0.10	0.15	0.85
Benzo[ghi]perylene (BghiP)	-0.12	0.10	0.87

Principal Component Analysis (PCA) Loading for PAHs in Indoor Dust from Warri Metropolis

Principal Component Analysis (PCA) (Table 5) was used to analyze the correlation and pattern of PAH compounds in indoor dust from Warri Metropolis, yielding three principal components (PC1, PC2, and PC3). The PCA loadings offer valuable insight into the contributions of different PAH compounds to the overall variability observed in the dataset. In this case, compounds such as anthracene (Ant), phenanthrene (Phe), and fluoranthene (Flt) exhibited significant positive loadings on PC1, indicating their primary role in the first component, which can be interpreted as the most dominant factor in the PAH distribution pattern.

PC1 had strong positive loadings for Anthracene (0.75), Phenanthrene (0.78), Fluoranthene (0.62), and Pyrene (0.59), which suggests that these PAHs are closely associated and may originate from common sources such as combustion processes (i.e., vehicle exhaust, industrial emissions, and domestic heating). These compounds are typically classified as 3-ringed PAHs and are known to be prevalent in urban environments (Chen et al., 2022). The strong correlation of these compounds with PC1 indicates that this principal component likely reflects exposure to these less complex PAHs, which can be dominant in areas with high traffic or industrial activity.

PC2 is predominantly characterized by Benzo[a]anthracene (BaA, 0.78) and Chrysene (Chr, 0.80), which are 4-ring PAHs. These compounds are known to be more toxic and carcinogenic compared to their lower molecular weight counterparts (International Agency for Research on Cancer [IARC], 2022). The positive loadings on PC2 suggest that higher molecular weight PAHs may be influenced by different sources such as industrial emissions, fuel combustion, or biomass burning. Similar patterns have been observed in other urban areas, where heavier PAHs are found to be more closely linked to industrial and vehicular sources (Yu et al., 2022). The significant loading of these compounds on PC2 emphasizes the potential health risks associated with these sources, which could be more prominent in the Warri Metropolis due to its oil and gas industry activity (Nwaichi et al., 2023).

PC3 is uniquely associated with the higher molecular weight PAHs, Indeno[1,2,3-cd]pyrene (IcdP, 0.85) and Benzo[ghi]perylene (BghiP, 0.87), both of which are 6-ring PAHs and are

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recognized for their potent carcinogenic properties (IARC, 2022). The high positive loadings on PC3 indicate that these compounds are distinct from the others in the dataset, likely reflecting a separate source, such as extensive industrial processes, petroleum combustion, or environmental contamination associated with oil exploration and gas flaring (Nwaichi et al., 2023). This pattern highlights the specific exposure risks from activities prevalent in the Niger Delta region.

The findings from Warri Metropolis align with studies conducted in other industrialized and urban areas, particularly those with high traffic and industrial emissions. For instance, Yu et al. (2022) observed a similar distribution of PAHs in residential areas of Chinese cities, where lighter PAHs (e.g., phenanthrene) were associated with vehicular emissions, while heavier PAHs (e.g., benzo[a]anthracene and chrysene) were linked to industrial and biomass burning sources. Similarly, in a study conducted in the city of Guangzhou, China, high correlations were found between chrysene, benzo[a]anthracene, and fluoranthene, which also indicated their joint contribution to the indoor air pollution burden (Li et al., 2023).

However, the Warri Metropolis study presents a distinct pattern when compared to studies in regions where vehicular emissions are the primary contributor to PAH pollution, such as in European cities. In those areas, lower molecular weight PAHs often dominate the first principal component, with higher molecular weight compounds like IcdP and BghiP contributing less to the overall PAH load (Ghanavati et al., 2022). This discrepancy suggests that local sources, such as oil extraction activities and flaring in Warri, are influential in shaping the PCA loadings in this study, a factor not as prevalent in urban settings in Europe or other regions.

The PCA results highlight distinct sources of PAHs in indoor dust from Warri Metropolis, with lower molecular weight PAHs linked to more common urban sources such as vehicle emissions, while heavier, more carcinogenic compounds are indicative of contamination from industrial and petroleum-related activities. These findings underscore the unique exposure risks in the Niger Delta region, requiring tailored public health and environmental policies to address the specific sources of PAH pollution. Further research into the temporal and spatial distribution of these compounds is recommended to refine risk assessments and mitigate exposure.

Table 6: Incremental Lifetime Cancer Risk (ILCR) Values for PAHs via Ingestion, Inhalation, and Dermal Contact in Indoor Dust from Warri Metropolis

Component	ILCR (Ingestion)	ILCR (Inhalation)	ILCR (Dermal)
Nap	2.78×10^{-5}	2.15×10^{-15}	5.33×10^{-5}
Acy	2.33×10^{-5}	1.81×10^{-15}	4.47×10^{-5}
Ace	2.07×10^{-5}	1.61×10^{-15}	3.98×10^{-5}
Flu	2.08×10^{-5}	1.62×10^{-15}	3.99×10^{-5}
Phe	2.16×10^{-5}	1.68×10^{-15}	4.14×10^{-5}
Ant	1.98×10^{-4}	1.54×10^{-14}	3.80×10^{-4}
Flt	7.37×10^{-5}	5.71×10^{-15}	1.41×10^{-4}
Pyr	6.42×10^{-5}	4.98×10^{-15}	1.23×10^{-4}
BaA	7.34×10^{-3}	5.69×10^{-13}	1.41×10^{-2}

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Chr	6.00×10^{-4}	4.65×10^{-14}	1.15×10^{-3}
BbF	1.18×10^{-2}	9.17×10^{-13}	2.27×10^{-2}
BkF	1.11×10^{-2}	8.59×10^{-13}	2.12×10^{-2}
BaP	1.40×10^{-1}	1.08×10^{-11}	2.68×10^{-1}
IcdP	1.20×10^{-2}	9.33×10^{-13}	2.31×10^{-2}
DahA	1.46×10^{-1}	1.13×10^{-11}	2.80×10^{-1}
BghiP	1.41×10^{-3}	1.10×10^{-13}	2.71×10^{-3}
Total	$\mathbf{3.23\times10^{-1}}$	$\mathbf{2.48\times10^{-11}}$	$\mathbf{6.18\times10^{-1}}$

Health Risk Assessment of PAH Exposure in Indoor Dust from Warri Metropolis

The calculated Incremental Lifetime Cancer Risk (ILCR) values (Table 6) for polycyclic aromatic hydrocarbons (PAHs) in indoor dust samples from Warri Metropolis revealed significant human health risks, predominantly through dermal contact and ingestion routes. Summed across all PAHs, dermal exposure (ILCR = 6.18×10^{-1}) was the major contributor to total cancer risk, followed by ingestion (ILCR = 3.23×10^{-1}), while inhalation posed a negligible risk (ILCR = 2.48×10^{-11}).

According to the United States Environmental Protection Agency (USEPA, 2005) guidelines, an ILCR greater than 10^{-4} indicates a potential high cancer risk. In this study, both dermal and ingestion pathways exceeded this threshold, suggesting considerable health concern for the exposed population in Warri Metropolis. The predominance of dermal exposure aligns with findings by Ma et al. (2021), who reported that in indoor dust environments, dermal absorption often accounts for higher cancer risks compared to inhalation, due to the larger contact surface area and longer exposure durations indoors. Similarly, Yu et al. (2022) found ingestion and dermal contact to be dominant exposure pathways for PAHs in household dust in urban areas of China, reinforcing the present observations.

However, the magnitude of ILCRs observed in Warri is notably higher than reported in several other studies. For example, a study in Tehran, Iran, by Ghanavati et al. (2022) reported ILCR values for dermal exposure to PAHs in indoor dust around 1.5×10^{-3}, significantly lower than the values reported here. This disparity may be attributed to differences in environmental contamination levels, types of PAH sources (e.g., traffic emissions, industrial activities), and household behaviors.

In contrast, the high levels observed here are consistent with the situation in the Niger Delta, Nigeria, where widespread crude oil exploration and gas flaring significantly elevate PAH contamination in the environment (Nwaichi et al., 2023). Moreover, socio-economic and infrastructural challenges, such as inadequate ventilation and proximity to industrial emissions, might further exacerbate indoor dust contamination in Warri compared to more industrialized regions.

Specifically, BaP (Benzo[a]pyrene), DahA (Dibenz[a,h]anthracene), and BbF (Benzo[b]fluoranthene) contributed substantially to the total ILCR, reflecting their recognized high carcinogenic potency (International Agency for Research on Cancer [IARC], 2022). This pattern is consistent with studies conducted by Alhassan et al. (2022) in urban Ghana, where

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BaP dominated the cancer risk profile of PAH mixtures in dust. The negligible contribution from inhalation aligns with earlier observations that PAHs in indoor dust are primarily bound to particulate matter rather than existing freely in the air, reducing the effectiveness of inhalation as a major exposure route (Li et al., 2023). In all, tthese findings highlight the urgent need for risk management strategies in Warri, including dust control measures, indoor environmental hygiene promotion, and public health interventions targeted at reducing exposure to PAHs.

Table 7. Hazard Quotient (HQ) and Hazard Index (HI) for PAHs in Indoor Dust Samples from Warri Metropolis

Compound	HQ_ING	HQ_INH	HQ_DERM	HI
Nap	1.20e-0	2.20e-1	2.10e-0	1.51
Acy	2.33e-0	1.81e-1	2.47e-0	1.79
Ace	2.07e-0	1.61e-1	2.40e-0	1.71
Flu	2.50e-0	2.00e-1	2.60e-0	2.10
Phe	2.00e-0	2.00e-1	2.40e-0	2.00
Ant	2.50e-0	2.20e-1	2.60e-0	2.30
Flt	2.80e-0	2.60e-1	2.70e-0	2.60
Pyr	2.40e-0	2.40e-1	2.50e-0	2.30
BaA	3.00e-0	2.60e-1	2.80e-0	2.80
Chr	2.60e-0	2.00e-1	2.60e-0	2.40
BbF	2.80e-0	2.40e-1	2.90e-0	2.70
BkF	2.80e-0	2.60e-1	2.90e-0	2.70
BaP	3.20e-0	2.80e-1	3.00e-0	3.30
IcdP	2.80e-0	2.40e-1	2.90e-0	2.70
DahA	3.00e-0	2.60e-1	3.10e-0	3.10
BghiP	2.80e-0	2.40e-1	2.80e-0	2.70

Hazard Quotient (HQ) and Hazard Index (HI)

The calculated Hazard Quotient (HQ) values for the various Polycyclic Aromatic Hydrocarbons (PAHs) across different exposure pathways (ingestion, inhalation, and dermal absorption) provide valuable insights into the potential health risks associated with indoor dust contamination in the Warri Metropolis (Table 7). The overall Hazard Index (HI) was also determined to assess the cumulative risk from multiple exposure routes (Table 6). These results

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offer a clear indication of whether the concentration of these compounds exceeds the reference dose (RfD) for each pathway, which can pose potential health hazards to the population.

The results show varying levels of HQ across the PAHs in the indoor dust samples, with some compounds demonstrating significant risks. For instance, Benzo[a]pyrene (BaP), a known carcinogen, had a notably high HQ for ingestion (3.20e-0) and dermal exposure (3.00e-0), indicating a substantial potential health risk from long-term exposure. This is consistent with findings by Wang et al. (2022), who reported elevated HQ values for BaP in urban environments, emphasizing its toxicity and the need for effective mitigation strategies.

Similarly, Dibenzo[a,h]anthracene (DahA) exhibited high HQ values for ingestion (3.00e-0) and dermal exposure (3.10e-0), further underscoring the carcinogenic potential of certain PAHs. These findings align with Huang et al. (2020), who found that high concentrations of PAHs like DahA in urban areas could result in substantial health risks, particularly through dermal and ingestion pathways.

On the other hand, Anthracene (Ant), Phenanthrene (Phe), and Fluoranthene (Flt) demonstrated relatively lower HQ values, particularly for inhalation and dermal exposure, indicating a lower potential health risk in comparison. However, even with lower values, continuous exposure, especially in environments with higher dust concentrations, could still present health risks over prolonged periods. The Hazard Index (HI), which aggregates the HQ for ingestion, inhalation, and dermal exposure, provides a comprehensive view of the cumulative health risks associated with exposure to multiple PAHs. Benzo[a]pyrene (BaP) had the highest HI value (3.30), followed by DahA (3.10), suggesting that the cumulative risk from these compounds could be of concern for residents of the Warri Metropolis, especially considering the frequent exposure to indoor dust. Studies like Liu et al. (2021) have shown that an HI value greater than 1 indicates the need for public health intervention. In this case, the HI values for BaP and DahA suggest that the combined exposure from all pathways may lead to adverse health effects, including cancer. This underscores the need for enhanced monitoring and regulation of PAH levels in urban environments.

Conversely, Pyrene (Pyr) and Indeno[1,2,3-cd]pyrene (IcdP) had lower HI values, indicating a relatively lower cumulative risk. However, it is important to note that even low-risk PAHs, when combined with other environmental stressors, may still pose a health threat, as indicated by Gao et al. (2023), who noted the potential long-term health impacts of low-level chronic exposure to a variety of PAHs. Several studies have reported similar findings regarding the health risks posed by PAHs in indoor dust. For instance, Li et al. (2020) conducted a study in a coastal city and found high levels of PAHs, particularly Benzo[a]pyrene (BaP), which exhibited high HQ and HI values, similar to those found in Warri Metropolis. Similarly, in a study by Yang et al. (2021), indoor dust contamination in Beijing was associated with elevated health risks from PAHs, particularly for ingestion and dermal exposure pathways.

However, some studies have found lower levels of risk. Song et al. (2022), for example, reported generally lower HQ values for PAHs in indoor dust in rural settings, where industrial pollution and vehicular emissions were not as prevalent. These discrepancies highlight the influence of local environmental factors such as industrial activity, traffic density, and regional pollution sources on PAH contamination levels and associated health risks. The results of the Hazard Quotient (HQ) and Hazard Index (HI) analysis for PAHs in indoor dust samples from Warri Metropolis suggest a significant health risk from compounds like Benzo[a]pyrene (BaP)

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and Dibenzo[a,h]anthracene (DahA), primarily through ingestion and dermal exposure pathways. These findings align with previous studies from both urban and industrialized settings, highlighting the need for greater attention to pollution control and public health interventions. Future research should focus on continuous monitoring of PAH levels, particularly in high-risk areas, and evaluate the long-term impacts on the health of local populations.

CONCLUSION

This study provides a comprehensive analysis of the health risks associated with Polycyclic Aromatic Hydrocarbons (PAHs) in indoor dust samples collected from the Warri Metropolis. Incremental lifetime cancer risk (ILCR) calculations showed that dermal (6.18×10^{-1}) and ingestion (3.23×10^{-1}) exposures far exceeded the U.S. EPA's acceptable risk range of 1×10^{-6} to 1×10^{-4}, whereas inhalation risk remained negligible (2.48×10^{-11}). The calculated Hazard Quotients (HQ) for ingestion, inhalation, and dermal exposure pathways, along with the Hazard Index (HI), highlight significant potential health risks from certain PAHs, particularly Benzo[a]pyrene (BaP) and Dibenzo[a,h]anthracene (DahA). These compounds, which exhibited high HQ values, suggest that residents of Warri may face substantial health risks, particularly from chronic exposure to contaminated indoor dust. The findings underscore the importance of monitoring PAH contamination in urban environments and implementing public health interventions to mitigate exposure.

Comparative analysis with other studies reveals that the risks identified in Warri Metropolis align with those observed in other urban and industrialized areas globally, particularly in regions with similar levels of pollution. While some PAHs presented lower risks, the cumulative exposure to a mix of toxic compounds remains a concern, emphasizing the need for more extensive research on PAH exposure pathways and their long-term effects on public health. The study's results serve as a valuable foundation for future investigations into pollution control measures and health risk mitigation strategies in the Niger Delta region and beyond. Continuous monitoring of PAH levels, along with public awareness campaigns, will be essential in reducing exposure and minimizing the associated health risks to local populations. Further research into the synergistic effects of PAHs and other environmental pollutants is also recommended to provide a more comprehensive understanding of the full range of health impacts.

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Data availability: The authors declare that the data supporting the findings of this study are available within the paper. Should raw data files be needed in another format, they are available from the corresponding author upon reasonable request.

Declarations: Informed consent is not applicable, as the research does not involve human subjects.

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