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Contamination levels, health risks and source apportionment of in-vehicle and park dusts potentially toxic elements (PTEs) in Abuja, Nigeria

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ABSTRACT

Introduction: The rapid urbanization and heavy traffic in cities raise concerns about health and environmental risks from Potentially Toxic Elements (PTEs). This study analyses the levels of contamination, origins, and exposure hazards of 10 PTEs (Fe, As, Cd, Zn, Cu, Mn, Pb, Cr, Co, Ni) in dust from five public vehicles and five motor parks in Abuja, Nigeria.

Materials and methods: Digested samples of park dust were analysed for Fe, Pb, Zn, As, Co, Cr, Cu, Cd, Mn, Ni (ten PTEs) using Atomic Absorption Spectrophotometer (AAS). PTE sources were ascertained using Positive Matrix Factorization (PMF) alongside contamination indicators comprising of Enrichment Factor, Geo-accumulation Index, Contamination Factor and Ecological Risk Factor. A new pollution indicator, the Nemerov Integrated Risk Index (NIRI), was evaluated for consistency with existing methods. Exposure risks (cancer and non-cancer causing) were assessed for commuters.

Results: PMF revealed five PTE sources: brake/engine wear (50%), vehicular body wear (1%), tyre wear/lubrication leaks (12%), coal combustion (6%), and vehicular emissions (31%). Cd exhibited the highest contamination levels across all indices. NIRI results aligned with traditional indices, confirming severe Cd pollution. Health risk assessments showed insignificant non-carcinogenic and carcinogenic risks for adults and children, though children were more vulnerable.

Conclusion: Traffic-related activities were the dominant sources of PTEs in Abuja's vehicle and motor park dusts. Cadmium (Cd) exhibited the highest enrichment, exceeding background levels and posing high ecological risk particularly for children, while other PTEs presented low health risks. This study underlines the necessity for targeted mitigation and non-stop monitoring to reduce PTE exposure in urban transit environments.

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Introduction

Increasing vehicular emissions, accelerated urban expansion, and intensified industrial activities have contributed distinctly to the accretion of Potentially Toxic Elements (PTEs) in indoor vehicle dust and outdoor parking environments within major urban centres. In recent years, the presence of PTEs in city environments has become a focal point of global scientific attention, largely due to their pronounced toxicity and the substantial threats they pose to human health and ecological integrity [1-7].

The main contributors to PTEs enrichment in urban dusts are anthropogenic and lithogenic activities [8-10]. In urban environments, PTEs in vehicular cabin and parking area dust originate from various sources including atmospheric deposition, pavement surfaces, and emissions originating from domestic, transportation, and industrial processes (such as construction and mining activities) [11-14].

Dust particles consist of a heterogeneous mixture of surface soil components, anthropogenically derived metallic elements, and naturally occurring biogenic substance [15]. In 2018, the World Health Organization (WHO) reported that ambient (outdoor) air pollutants, which includes particles from vehicles and parks, caused about 4.2 million untimely mortalities globally [16]. Dust suspended or re-suspended by cars accounted for 33% of overall air pollution in cities [6, 17]. PTE-laden dust found inside vehicles and in surrounding parking areas could pose serious adverse effects on the health of pedestrians, street vendors, road workers, and the environment [3, 9, 18].

Over the past decades, numerous investigations conducted across various global regions have examined the spatial distribution of PTEs, their contamination intensity, associated human health implications, and source contributions [4, 9, 19]. A variety of pollution assessment tools, including the Enrichment Factor (EF), Geo-accumulation Index (Igeo), as well as Ecological Risk Index (ERI), are widely applied to investigate PTE pollution across diverse environmental matrices worldwide [1-3, 5, 9, 19-35]. More recently, the Nemerov Integrated Risk Index (NIRI) has been introduced as a comprehensive approach for assessing the cumulative ecological risk of PTEs in relatively few studies. NIRI integrates both the Potential Ecological Risk Index (ERI) in addition to the Nemerov Integrated Pollution Index (NIPI) [28, 36]. Unlike classical single-parameter indices (EF, Igeo, ERI) that assess contamination or risk independently, NIRI combines multiple indices into a unified framework, providing a more comprehensive and balanced evaluation of both pollution intensity and ecological risk. This integrated approach makes NIRI a novel and robust tool for assessing complex multi-element contamination in urban environments.

There have been several investigations on contamination of PTEs in park dust within Africa. However, only a few research has explored the health threats and origins of PTEs in vehicle and outdoor park dusts in African metropolises. Thus, this study looked into the pollution levels of PTEs (heavy metals) in dust samples collected from public vehicles and major vehicular parks in Nigeria's capital city, Abuja. Abuja is one of Africa's fastest developing cities, due to rapid urbanisation. Abuja is Nigeria's capital city, with strategic positioning along the national railway corridor, the presence of an international airport, and an extensive network of highways linking it to other major cities, Abuja serves as a key commercial and transportation nexus, as well as a vital transit route within inland regions in Nigeria. This present study (i) assessed and characterized the spatial distribution patterns of PTEs in dust samples collected from vehicles and outdoor parking environments within Abuja; (ii) quantitatively identified and apportioned the origins and relative impacts of PTE in vehicular and parking area dust; (iii) determined the degree of PTE contamination using both conventional and recently developed pollution indices; and (iv) assessed the potential human health risks associated with exposure to PTE-contaminated dust within vehicles and adjacent parking areas.

Materials and methods

Study area

Abuja, the federal capital of Nigeria, is situated in the country's central region (Fig. 1). Geopolitically, it shares boundaries with Kaduna State to the north, Niger State to the west, Nasarawa State to the east and southeast, and Kogi State to the southwest [37]. Designated as Nigeria's capital on 12 December 1991, Abuja functions as the country's primary administrative and political centre, covering a total land expanse of 7,315 km^2 (2,824 $mile^2$) with coordinates 9.50°N, 7.32°E. With a population exceeding 2.5 million and a growth rate of about 140%, Abuja ranks among the fastest-growing cities in Africa and the world [38]. Rapid urbanization, population expansion, and increasing vehicular traffic in Abuja have intensified energy use and transportation activities, resulting in elevated emissions and deposition of PTEs in road, vehicle, and park dust. Abuja municipality experiences two distinct climatic seasons which are the rainy season (March to October) and the dry season (October to March), with a brief harmattan period occurring between them. This harmattan period is typified by dusty haze, arid conditions with lower temperatures resulting from the northeast trade winds.

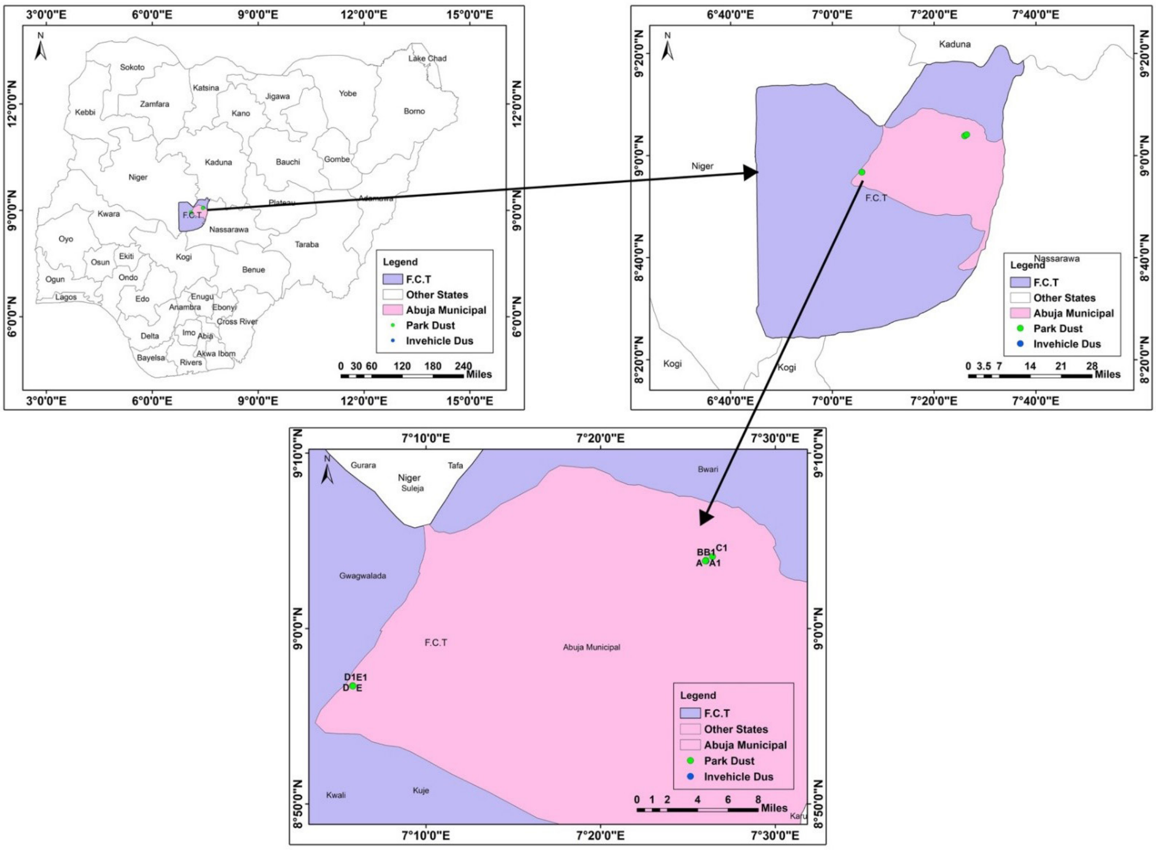


Fig. 1. Location of the study area

Sample collection and chemical analysis

The modified dust collection protocol described in previous studies [39, 40] was employed for collecting dust samples at five key motor parks (sampling sites) in Abuja during August 2023. Park dust samples were gathered by sweeping the roofs, bodies, interior, and exterior surfaces of designated park areas with pre-cleaned polyethylene brushes. In each park, four subsamples were obtained within a 25–30 m radius and subsequently homogenized to produce a composite sample weighing approximately 200–300 g. Dust samples from vehicle interiors (in-vehicle dusts) were collected separately from the park (outdoor) dust samples to allow for comparative analysis. To avoid cross-contamination of in-vehicle and outdoor park dusts samples at each sampling location, the brushes and collectors were consistently prewashed with Deionized Distilled Water (DDW) before taking samples. All collected dust samples were sealed in zipper-lock polyethylene bags, properly labelled, and conveyed to the test centre for digestion and elemental study. To eliminate coarse materials and debris, the air-dried in-vehicle and outdoor parking dust samples were separated through a mesh (2 mm) and subsequently ground into grit (fine particle) (< 100 µm) prior to analysis. 1 g of the homogenized dust of each sample, was digested in a 50 mL conical flask using 10 mL of aqua regia (a mixture of hydrochloric acid and nitric acid in a 3:1 volumetric ratio). Samples were digested on a hotplate maintained at 90 °C for 120 minutes. After digestion, the mixtures were allowed to cool in a fume hood until the evolution of brown nitrogen oxide fumes ceased. The solutions were then carefully concentrated to approximately 0.005 L, cooled to ambient temperature, and subsequently sieved into 50 mL volumetric flasks using filter paper (110 mm diameter, 11 µm pore size, whatman No. 5C).

Analyses were carried out on the digested park dust samples using Atomic Absorption Spectrophotometer (AAS) having double-beam with deuterium lamp background correction (model: BK-AA4530F; Manufactured by Biobase) to obtain the concentrations (mg/kg) of ten PTEs [iron, lead, zinc, arsenic, cobalt, chromium, copper, cadmium, manganese, and nickel] that were possibly harmful elements in urban settings [5, 28, 41-45]. Aqua regia solution was produced using analytical reagent grade hydrochloric acid and nitric acid, while all working and diluting mixtures were produced with deionized distilled water. 1 g/L standard stock solutions of all PTEs studied were made from their respective salt of metal (analytical reagent grade). Stock solutions for Cu, Ni, and Zn, 1 g/L were produced by dissolving their unpolluted metallic forms in either HCl or HNO_3, followed by dilution with DDW. Quality assurance and control procedures in this study incorporated the use of certified typical reference (GSS-1/RDMIB2023), method blanks, and replicate analyses to authenticate the precision and exactness of elemental quantification. No detectable concentrations of Potentially Toxic Elements (PTEs) were found in the blank samples. The recovery rates for analysed PTEs ranged from 94% to 112%, with Relative Standard Deviations (RSD) of replicate measurements below 5%. The method detection limits (MDLs, mg/L) for each element were as follows: Fe=0.0005, Pb=0.25, Zn=0.12, As=0.0017, Co = 0.00009, Cr=0.04, Cu=0.04, Cd=0.01, Mn=0.04, and Ni=0.05.

Positive matrix factorization (PMF)

Source apportionment of PTEs was carried out with the Positive Matrix Factorization (PMF) model using EPA PMF v 5.0.14 (6). In the PMF model, the observed concentration matrix is disintegrated into binary component matrices: factor profiles and factor contributions, which together represent the underlying source–receptor relationships. Source identification and characterization are subsequently performed by interpreting the derived factor profiles in conjunction with available emission inventory data and known source signatures [46, 47]. PMF was calculated by employing Eq. 1 [48].

$$X_{ij} = \sum_{k=1}^{p} g_{ik} f_{kf} + e_{ij} \tag{1}$$

Where x_{ij} denotes the concentration of the j^{th} PTE in the i^{th} sample, p represents the total number of resolved factors, g_{ik} corresponds to the contribution of factor k to sample i, f_{kj} signifies the concentration of the j^{th} PTE in factor profile k, and e_{ij} denotes the residual term (model error). The parameter g_{ik} and f_{kf} are iteratively optimized to minimize the objective function Q that quantifies the difference between observed and modelled concentrations. Q computation is specified in Eqs. 2 to 6.

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(\frac{e_{ij}}{u_{ij}}\right)^2 \tag{2}$$

Where n signifies the total number of samples; u_{ij} is the uncertainty of PTE j in sample i. PTEs concentration's uncertainty parameters are calculated using Equations 3 and 4. Equation 3 is applied when concentrations of PTEs are above the method detection limit (MDL), while Equation 4 is used for PTEs concentrations below MDL [29, 40, 49, 50].

$$Unc = \sqrt{\left(P_{ij} \times x_{ij}\right)^2 + (0.5 \times MDL)^2} \tag{3}$$

$$Unc = \frac{5}{6} MDL \tag{4}$$

P_{ij} is the error quantity (fraction) and x_{ij} denotes the PTEs concentration quantified in dust sample. Signal-to-Noise ratios below 2 are identified as 'weak' while above 2 are identified as 'strong' [51].

Assessment methods for PTEs

Contamination assessment techniques

The degree of PTE pollution and their possible ecological risks in vehicle interiors and outdoor parking dust samples were assessed using a combination of conventional and recently developed contamination indices. These include the EF, Igeo, CF, also referred to as Contamination Degree), ERI, NIPI and NIRI. Among these, the EF serves as a widely recognized metric for quantifying anthropogenic contributions to elemental concentrations by comparing observed levels against natural or background reference values [52, 53].

The EFs of PTEs in Abuja in-vehicle and outdoor park dusts were calculated using Eq. 5:

$$EF = \frac{\left[C_n / R_{ref}\right]_{sample}}{\left[B_n / B_{ref}\right]_{background}} \tag{5}$$

$[C_n / R_{ref}]_{sample}$ as well as $[B_n/B_{ref}]_{background}$ denote the ratios of the objective PTE to the corresponding reference PTE in the dust samples and background material. Fe, Zr, Ti,, Mn as well as Al are generally employed as reference PTEs to normalize PTE concentrations, serving as geochemical tracers for differentiating between natural (lithogenic) and anthropogenic sources of contamination [6]. In the present study, Fe was employed as the reference element due to its high natural abundance, relatively stable geochemical behaviour, limited association with other PTEs, and minimal susceptibility to anthropogenic perturbations [43, 54, 55]. Fe was excluded not only from NIRI but also from EF, Igeo, Contamination Factor, ERI, and NIPI. Fe concentrations are reported in the dataset, however owing to its low toxic-response and dominant crustal origin it was omitted from all ecological index calculations. to avoid biasing pollution and ecological-risk metrics. Furthermore, in the absence of pre-anthropogenic or baseline soil data specific to the study area, the average elemental composition of the continental crust reported by Bradl Bradl [56] was adopted as the geochemical background reference for the PTEs [57, 58]. The categorization of metal enrichment levels into five distinct pollution classes is provided in previous studies [29, 39, 59].

I_{geo} is a widely applied metric for assessing contamination levels, providing a comparative evaluation between the measured concentrations of PTEs and their corresponding background values, originally developed for use in sediment quality studies [29, 60]. I_{geo} serves as a conventional metric for quantifying contamination attributable to individual elements. It can also be applied to evaluate the extent of pollution in both in-vehicle and outdoor parking dust samples, as expressed in Eq. 6 [61, 62].

$$I_{geo} = log_2\left(\frac{C_n}{1.5B_n}\right) \quad (6)$$

C_n represents the quantified amount of a PTE in vehicle interior as well as outdoor park dust samples, while B_n symbolises the resultant geochemical background value (crustal average) of the PTE. Due to the absence of pre-industrial or baseline soil data for the Abuja area, the average continental crust composition reported by Bradl Bradl [56] was adopted as the background reference for the PTEs [57, 58]. A constant factor of 1.5 was incorporated into the calculation to account for potential variations in lithological composition among sediments [61]. The classification system for the Geo-Accumulation Index (Igeo) is provided in [59].

The ERI originally proposed by Hakanson [63] was applied in this study to evaluate the potential ecological threats associated with PTE contamination in in-vehicle and outdoor parking dust. This index has been extensively utilized in multi-element contamination assessments to quantify ecological risk across diverse environmental matrices [64-66]. The ERI values for PTEs were categorized into five distinct risk classes [59] and calculated using Eqs. 7–9 [39].

$$ERI = \sum_{i=1}^{n} E_r^i \quad (7)$$

$$E_r^i = T_r^i \times C_f^i \quad (8)$$

$$\mathrm{C_f^i} = \frac{\mathrm{C_{0-1}^i}}{\mathrm{C_n^i}} \quad (9)$$

Where C^i_f denotes the contamination factor (also referred to as the pollution index, PI) for each individual metal of interest; C^i_{0-1} signifies the measured concentration of the metal in the sample; C^i_n corresponds to the background concentration in soil; T^i_r signifies the toxic response factor of the metal; E^i_r indicates the potential ecological risk factor for a specific metal and ERI represents the aggregate potential ecological risk, obtained as the summation of all E^i_r values for the nine PTEs analysed. The background concentrations C^i_n adopted in this study based on upper continental crust values (µg/g) reported by Bradl [56] as well as the applied toxic response factors (T^i_r) followed those proposed by Du [67].

PTEs pollution levels in vehicle dust and outdoor park dusts were investigated using contamination factor and contamination degree [68]. Eq. 9 showed the C^i_f index of single element. The measure of pollution is the aggregate of C^i_f of the entire studied PTEs as indicated in Eq. 10:

$$C_{deg} = \sum C_f^i \quad (10)$$

C^i_f and C_{deg} are grouped into four categories as presented by [29].

In order to assess the integrated ecological risks of PTEs, which rely on the NIPI and ERI, this research applied a novel technique called NIRI, which was utilized by Men, Liu [28]. The NIPI was determined using the Eqs. 9 and 11 [28, 36, 69].

$$NIPI = \sqrt{\frac{(PI_{ave}^2 + PI_{max}^2)}{2}} \quad (11)$$

Where PI = C^i_f = the PTE pollution index (contamination factor) and PI_{ave} = PTEs PI average value and PI_{max} = PTEs PI maximum value.

According to Men, Liu [28], The NIRI addresses key limitations inherent in both the NIPI and ERI, notably the dependence of the ERI on the total quantity of PTEs as well as the omission of variations in toxic response factors within the NIPI framework. By integrating these considerations, the NIRI provides a more comprehensive and accurate evaluation of the cumulative ecological impacts associated with multiple PTEs. NIRI) was calculated as expressed in Eq. 12 [36].

$$NIRI = \sqrt{\frac{\left(E_{r\,ave}^{i\;2} + E_{r\,max}^{i\;2}\right)}{2}} \quad (12)$$

Where $E^i_{r\,max}$ and $E^i_{r\,ave}$ represent the corresponding highest and mean E^i_r for each element. The NIRI values were computed for Pb, Zn, As, Co, Cr, Cu, Cd, Mn, and Ni in this study. Iron (Fe) was excluded from the ecological risk evaluation because its concentrations typically approximate background levels and its toxicity in urban environments is considered negligible [28, 70, 71]. The classification thresholds applied for both the NIPI and the NIRI are provided by [29, 59]. In addition, the Average Daily Doses (ADD; mg/kg.day) for Abuja residents, stratified into children and adults, were quantified for ingestion (ADD_{ing}), inhalation (ADD_{inh}), and dermal absorption (ADD_{dermal}) exposure pathways, following the procedures detailed by [39, 59].

Results and discussion

Concentrations of PTEs in dusts of vehicles and outdoor parks

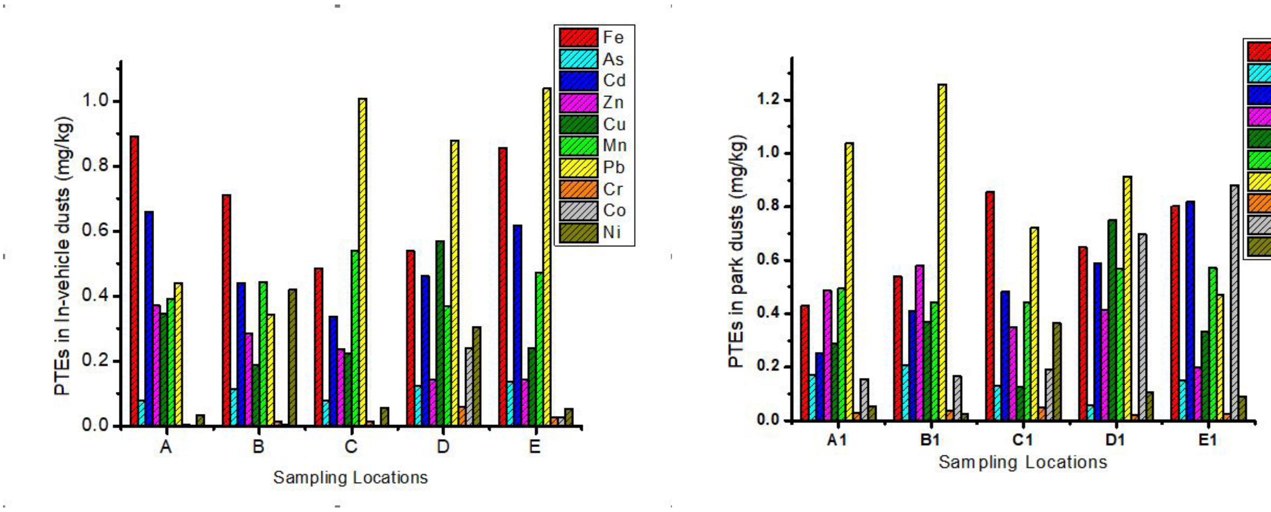
PTEs concentrations (in mg/kg) in vehicle and outdoor park dusts of Abuja metropolis and other information on the study area are described in Table 1.

Out of the 10 studied PTEs in this investigation, only the Cd concentration in Abuja indoor vehicle dusts surpassed its background concentration given by Bradl [56] by 1.67 folds. Likewise, the outdoor park dusts concentrations of all studied PTES were lower than their background concentrations except for Cd which was 1.70 folds larger than its background concentration, establishing strong effect of human activities with Cd sources on in-vehicle and outdoor park dusts in Abuja. Cd possible originates from multiple anthropogenic sources within Abuja's urban environment. Major contributors of Cd include vehicular emissions from fuel combustion and lubricating oil additives, as well as tire wear and brake abrasion, which release Cd-rich particulates into surrounding dust [72, 73].

Table 1. PTEs concentrations and descriptive statistics of in-vehicle and park dusts in Abuja

					PTEs compositions in vehicle (indoor) dusts (mg/kg)									
S/N	Location	Sample Code	Dust Type	Park Type	Fe	As	Cd	Zn	Cu	Mn	Pb	Cr	Co	Ni
1	Jabi Park, Abuja to Jos, Bauchi, Gombe	A	Invehicle dust	Interstate Park	0.892	0.079	0.66	0.371	0.347	0.392	0.438	0.003	0	0.034
2	Jabi Park, Abuja to Lagos, Ibadan	B	Invehicle dust	Interstate Park	0.711	0.115	0.44	0.284	0.189	0.443	0.344	0.012	0.003	0.42
3	Utako Park, Abuja to Port Harcorut	C	Invehicle dust	Interstate Park	0.485	0.079	0.335	0.237	0.225	0.539	1.006	0.013	0	0.056
4	Gwagwalada Park, Abuja to Onitsha	D	Invehicle dust	Interstate Park	0.539	0.122	0.461	0.143	0.57	0.37	0.88	0.06	0.241	0.305
5	Trailer Park, Lagos	E	Invehicle dust	Trailer Park	0.855	0.136	0.618	0.143	0.24	0.473	1.038	0.026	0.028	0.054
				Mean	0.696	0.106	0.503	0.236	0.314	0.443	0.741	0.023	0.054	0.174
				Minimum	0.485	0.079	0.335	0.143	0.189	0.37	0.344	0.003	0	0.034
				Maximum	0.892	0.136	0.66	0.371	0.57	0.539	1.038	0.06	0.241	0.42
				Median	0.711	0.115	0.461	0.237	0.24	0.443	0.88	0.013	0.003	0.056
				SD	0.182	0.026	0.134	0.097	0.155	0.067	0.327	0.022	0.105	0.177
				Skewness	-0.128	-0.218	0.064	0.457	1.543	0.507	-0.515	1.55	2.169	0.831
				Kurtosis	-2.685	-2.625	-1.805	-1.17	2.105	-0.611	-2.916	2.471	4.738	-1.977
				CV%	0.033	0.001	0.018	0.01	0.024	0.005	0.107	0.001	0.011	0.031

					PTEs compositions in park dust (mg/kg)									
S/N	Location	Sample Code	Dust Type	Park Type	Fe	As	Cd	Zn	Cu	Mn	Pb	Cr	Co	Ni
6	Jabi Park 1	A1	Park Dust	Interstate Park	0.43	0.172	0.252	0.486	0.29	0.495	1.038	0.03	0.153	0.054
7	Jabi Park 2	B1	Park Dust	Interstate Park	0.539	0.208	0.409	0.58	0.369	0.443	1.259	0.037	0.165	0.023
8	Utako Park	C1	Park Dust	Interstate Park	0.855	0.129	0.482	0.351	0.125	0.443	0.722	0.049	0.193	0.363
9	Gwagwalada Park	D1	Park Dust	Interstate Park	0.647	0.057	0.587	0.412	0.749	0.568	0.912	0.02	0.698	0.107
10	Trailer Park	E1	Park Dust	Trailer Park	0.801	0.151	0.818	0.197	0.333	0.57	0.47	0.023	0.881	0.089
				Mean	0.654	0.143	0.51	0.405	0.373	0.504	0.88	0.032	0.418	0.127
				Minimum	0.43	0.057	0.252	0.197	0.125	0.443	0.47	0.02	0.153	0.023
				Maximum	0.855	0.208	0.818	0.58	0.749	0.57	1.259	0.049	0.881	0.363
				Median	0.647	0.151	0.482	0.412	0.333	0.495	0.912	0.03	0.193	0.089
				SD	0.177	0.056	0.211	0.144	0.23	0.063	0.301	0.012	0.346	0.136
				Skewness	-0.121	-0.824	0.516	-0.459	1.274	0.173	-0.224	0.764	0.758	1.92
				Kurtosis	-1.908	1.128	0.545	0.232	2.648	-3.021	-0.375	-0.285	-2.416	3.937
				CV%	0.031	0.003	0.045	0.021	0.053	0.004	0.091	0.0001	0.119	0.018



(a) (b)

Fig. 2. PTEs concentrations in dusts of Abuja parks (a) In-vehicle dust and (b) park dust

Table 2. Comparison of Abuja PTE concentrations in road and park dust to other Cities

Country	Site	Concentration (mg/kg)										References
		Fe	As	Cd	Zn	Cu	Mn	Pb	Cr	Co	Ni	
Nigeria	Abuja (in-vehicle)	0.696	0.106	0.503	0.236	0.314	0.443	0.741	0.023	0.054	0.174	This Study
Nigeria	Abuja (Outdoor Park)	0.654	0.143	0.510	0.405	0.373	0.504	0.880	0.032	0.418	0.127	This Study
Namibia	Katima Mulilo	-	1.97	0.45	8.93	5	1.68	0.97	2.39	1.54	1.73	[74]
Kenya	-	-	0.7	0.06	9.3	2.01	-	1.92	0.84	-	0.58	[75]
Nigeria	Ibadan	41607.54	0.81	7.21	155.02	23.52	291.36	257.44	26.09	9.87	16.37	[6]
Nigeria	Osogbo	5030	-	2.80	49	15.14	80.52	1.77	6.81	1.98	1.31	[76]
China	Baotou	-	-	-	85.9	29.1	548.2	58.2	182.1	60.2	21.2	[77]
Iraq	Ramadi	-	-	2.206	-	49.520	-	21.032	34.742	-	29.275	[78]
China	Kunming	-	20.5	2.65	511	-	671	-	-	-	33.9	[79]
China	Baotou	-	6.5	0.3	49.7	26.9	504.4	36.2	154.1	52.9	25.1	[80]
Iran	Rafsanjan	-	105.3	3.1	252.6	791.4	-	123.1	18.4	-	28.4	[81]
China	Jiaozuo	-	23.08	1.25	374.30	49.85	473.77	55.26	112.07	25.27	51.70	[82]
India	Delhi	14338.9	-	-	346.7	61.5	507.4	35.9	-	10.3	61.5	[83]
Saudi Arabia	Riyadh	11125.25	-	-	162.94	10.88	175.68	3.37	28.20	5.84	8.75	[84]
Bosnia and Herzegovina	-	3150	-	3.18	81.72	30.01	236	52.49	33.17	-	73	[83]
South Africa	Pretoria	154540	2.68	0.7	556.76	215.21	2715.04	47.06	140.14	-	138.86	[85]
Egypt	Cairo	1181.12	2.76	-	201.36	26.07	-	66.10	26.00	14.78	32.42	[86[
Turkiye	Usak	-	24.3	0.1	50.6	20.2	-	21.9	139.9	-	217.1	[87]
Iraq	Hilla	-	3.44	-	5.6	3.95	0.74	11.44	109.16	-	6.45	[88]

Additional inputs may arise from informal waste burning, metal workshops, and roadside mechanical activities commonly observed in densely trafficked areas of the city [89-91].

Furthermore, the concentrations of all studied PTEs (Fe, As, Zn, Cu, Mn, Pb, Cr, Co and Ni) vehicle interiors and outdoor park dusts were smaller in comparison to their corresponding background concentrations. PTEs concentrations in dust within vehicles and surroundings of motor parks in Abuja are shown in Fig. 2.

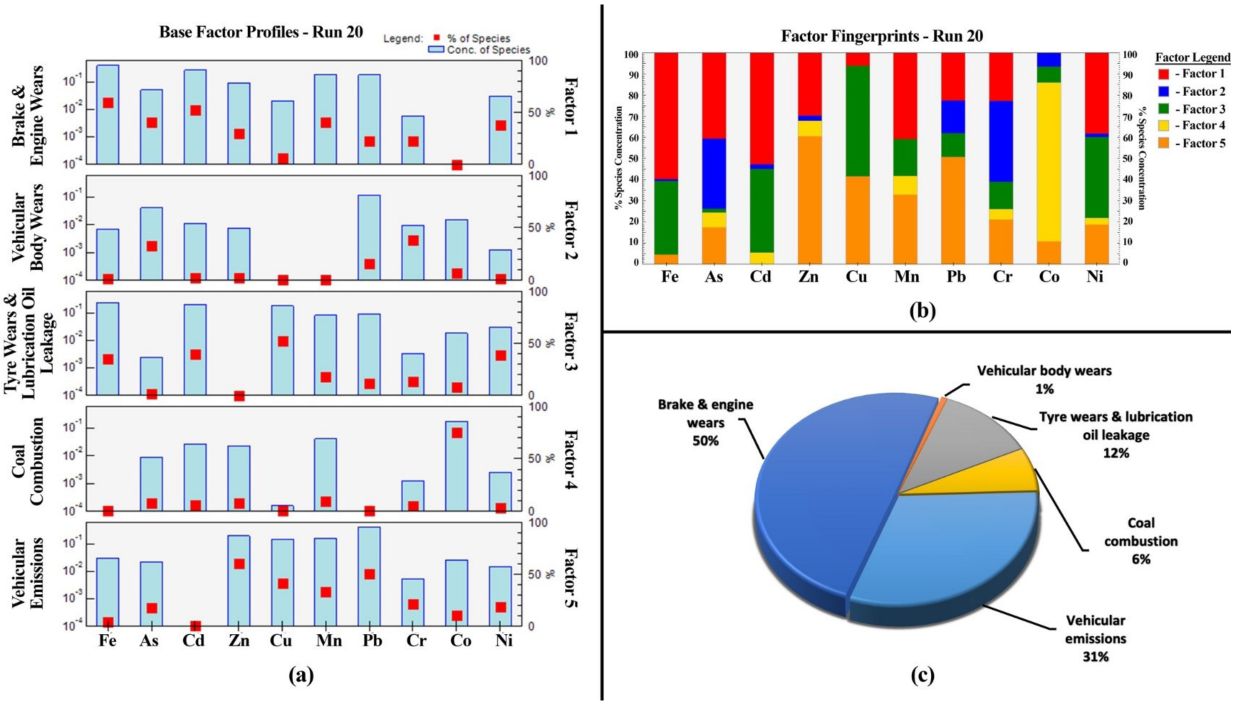
In comparison with different road and park dusts in different cities around the world, all PTEs analysed in this study apart from Cd have their mean concentrations lower than the mean concentrations of PTEs from different cities around the world (Table 2) [6, 76-79, 81-86, 88]. The mean concentrations of Cd which is 0.503±0.134 mg/kg for in-vehicle dust and 0.510±0.211 mg/kg for outdoor park dust are higher than Cd mean concentrations in Katima Mulilo, Namibia (0.45 mg/kg), some cities in Kenya (0.06 mg/kg), Baotou, China (0.3 mg/kg), in addition to Usak, Turkiye (0.1 mg/kg) [74, 75, 80, 87].

Source apportionment with PMF

Using the EPA PMF software, the PTEs ratios of signal-to-noise (S/N) ranged from 0.1 to 9.0. S/N values above 2 were classified as ‘strong’ while those below 2 were categorized as ‘weak’[6]. All PTEs in this analysis were expressed as ‘strong’ except for Cr and Ni, which had S/N ratios of 0.1 and 1.8, respectively, and were thus considered ‘weak’. Nevertheless, all ten PTEs were included in the PMF analysis to preserve the completeness of the dataset and capture potential source contributions from all measured elements. The PMF model was analysed using different factor numbers ranging from 4 to 8, with 20 runs per solution. The optimal number of factors was established by assessing statistical diagnostics and interpretability criteria. Both the robust and true Q values were examined to identify the solution with minimal and stable Q values across the 20 runs. Analyses of Bootstrap (BS) and Displacement (DISP) were further applied to assess the stability and uncertainty of factor profiles, confirming that no excessive factor swaps occurred and that the model solution was robust. The five-factor simulation produced an appropriate absolute scaled residual, with all PTE residuals falling within the range of –3 to +3, and minimal Q values across runs. Based on these diagnostics and the clear environmental interpretability of the identified sources, the five-factor model was chosen as the optimal solution explaining the accumulation of PTEs in the park environment.

The factor contribution of PTEs studied in Abuja Park illustrated in Fig. 3b showed Fe, Cd, Mn, and As as the main marker of factor 1 with concentrations of 59.7%, 52.8%, 40.8%, and 40.6%, respectively. Fe and Mn are associated with emissions from engine wears and brake (92, 93). Factor 2 accounted for 38.3% and 33.2% of Cr and As concentrations, respectively. Cr is associated with wears from the bodies of vehicles (6, 94). Hence, factor 2 was associated with vehicular body wears. Factor 3 was attributed to Cu, Cd, Ni, and Fe with concentrations of 52.3%, 39.6%, 38.2%, and 34.8%, respectively. A good source of Cu and Cd emissions in the park are from tyre wears and also leakage from lubricating oil [94-96].

Factor 4 was dominated with 75.3% concentration of Co. Co is released into the air from coal burning [95, 97]. Coal is used for cooking, frying, and roasting foods such as maize, meat, yam, and other snacks in the vicinity of the park, therefore, factor 4 is associated with coal combustion activities. Factor 5 contributed 60.5%, 50.7%, and 41.6% of the concentration of Zn, Pb, and Cu, respectively. Prior studies revealed Zn, Pb, and Cu as markers for emissions from vehicular exhausts [29, 95, 98].



(a) (b) (c)

Fig. 3. Source apportionment of PTEs in Abuja in-vehicle and outdoor park dusts (a) profiles of source, (b) fingerprints of factor, and (c) contributions of factors (%)

Five PTEs emission sources were ascertained using the PMF source profile presented in Figs. 3a and 3c. Factor 1 related to brake and engine wears having 50% source contribution, factor 2 was associated with vehicular body wears with a contribution of 1%, factor 3 emissions were from tyre wears and lubrication oil leakage with 12% contribution, factor 4 was attributed to coal combustion with 6% source contribution, and factor 5 was linked with vehicular emissions with source contribution of 31%. Brake and engine wears have the highest contribution accounting for half of the overall PTE’s emission in the parks, this showed the impact of anthropogenic activities on the surrounding environment.

Contamination assessment of PTEs in In-vehicle and outdoor park dusts

Enrichment factor (EF)

Using the EF categorisation standards adopted by [39, 59], the EFs of PTEs considered in vehicles and outdoor park dusts of Abuja ranged from deficiency to extremely high enrichment. The EFs of PTEs in vehicle and outdoor park dusts are presented in Table 3. The maximum EFs of in-vehicle dust and motor parks for all PTEs studied, were all higher than 2 (Tables 3) demonstrating that all studied PTEs originated from anthropogenic sources [9]. The mean EFs of As, Cd, Zn, Cu, Pb, Co, and Ni in Abuja in-vehicle were extremely high, mean EF of Mn was very high while the mean EF of Cr was just significant. The mean EFs of As, Cd, Zn, Cu, Pb, Co, and Ni in Abuja motor parks were extremely high whereas the mean EFs of Mn and Cr were very high. Generally, significant attention should be given to As, Cd, Zn, Cu, Pb, Co, and Ni, with extremely high enrichment in dusts sampled from vehicles and outdoor parks of Abuja.

Geoaccumulation index (Igeo)

Igeo values presented in Table 3 using the Igeo categorisation [59] specified that the Abuja public vehicles and outdoor parks were practically uncontaminated by Fe, As, Zn, Cu, Mn Pb, Cr, Co and Ni. However, Igeo of Cd for vehicles A, D, and E varied from uncontaminated to moderately contaminated. Likewise parks C1, D1 and E1 fluctuated from uncontaminated to moderately contaminated

I_{geo} estimates showed that dusts from vehicles interiors and motor parks of Abuja metropolis varied from uncontaminated to moderately contaminated. This may be due to air dispersion of dust and repeated washing of PTEs laden dust into topsoil by rain in the study area.

Contamination factor (C_f) and contamination degree (C_d)

PTE contamination factors (Cf) of in-vehicle and outdoor park dusts in Abuja, as shown in Table 3, exhibited trends consistent with those observed in the I_{geo} analysis. In general, all the studied PTEs had low contamination factor in-vehicle interior and outdoor park dusts except Cd. Moderate C_f of Cd were found in all vehicle samples and a motor park B1, C1, D1, and E1, vehicle A1 had low contamination of Cd. In this study, the PTEs degrees of Contamination (C_d) in dust from vehicles and motor parks were generally low.

Potential ecological risks

In vehicle dusts, potential ecological risk factor (E^i_r) less than 40 for Cd were observed at all the vehicles sampled (A, B, C, D, and E), signifying a low potential ecological risk for all vehicles sampled. Potential ecological risk of motor parks A1 is low, while ecological risk indexes of parks B1, C1, D1, and E1 were moderate.

In this study, both the I_{geo} and the individual E^i_r values for Cd were found to be greater than those of other PTEs in dust samples collected from vehicles and motor parks. This indicates that Cd warrants particular attention due to its elevated contamination and ecological risk potential. The elevated Cd concentrations are likely attributable to intense vehicular activity within Abuja, as Cd emissions can arise from diesel fuel and lubricant leaks, as well as from tyre wears generated through frictional interactions between tyres and road surfaces [6, 29].

Evaluation of contamination indices

The general outcomes for various PTEs contamination indicators in Abuja vehicle interiors and outdoor park dusts were very comparable (Table 3). Utilising the categorisation adopted by [59], overall mean EFs of As, Cd, Zn, Cu, Pb, Co, and Ni showed extremely high enrichments. Igeo of Cd in vehicles A, D, and E in addition to parks C1, D1, and E1 changed from uncontaminated to moderately contaminated while Igeo of As, Zn, Cu, Mn Pb, Cr, Co, and Ni signified they were practically uncontaminated in dusts of studied vehicles and motor parks.

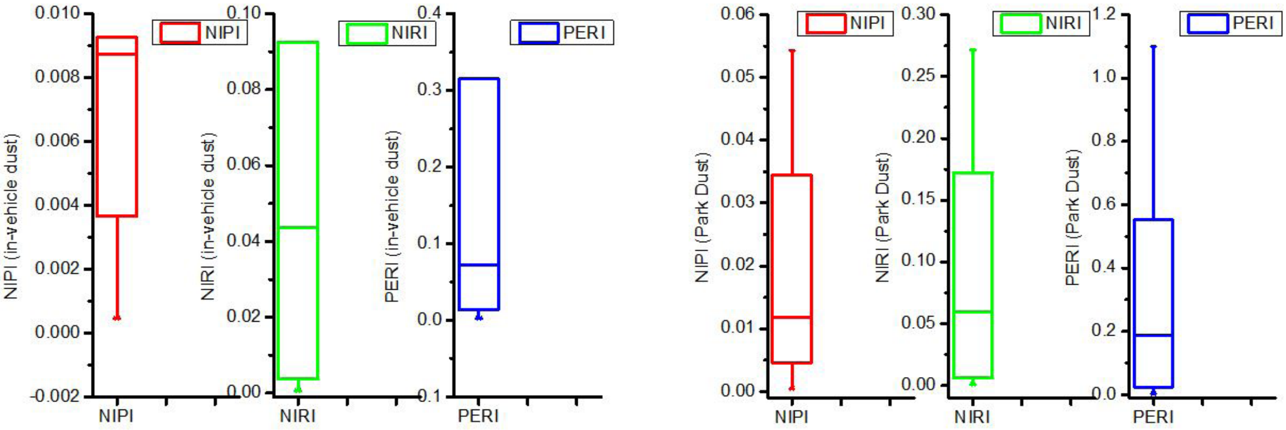
Apart from Cd, the ecological indexes of nine (9) PTEs presented in Table 3 were similar in this study. As, Zn, Cu, Pb, Co, Mn, Cr and Ni (8 PTEs) indicated low contamination factors indicating low pollution while the RI values of theses eight PTEs signified low potential ecological risk for sampled dusts in vehicles and outdoor parks studied. However, the values of PI and E^i_r for Cd revealed moderate contamination factor (i.e. moderate pollution) and moderate ERI, respectively in both in-vehicle and outdoor park dusts in Abuja. Generally, the different ecological indices (I_{geo}, PI, C_{deg} , E^i_r, and ERI) in this study showed that the in-vehicle and outdoor park dusts in Abuja suffered from no contamination to moderate pollution of PTEs.

NIPI and NIRI evaluation

NIPI estimates specified that Cd had low pollution in the Abuja in-vehicle and outdoor park dusts whereas NIPI values of other PTEs suggested dusts in vehicle and motor parks were unpolluted. NIPI and NIRI values for PTEs in Abuja are demonstrated in Fig. 4. The NIRI estimates for all studied PTEs were below 40, signifying these PTEs have low risks except Cd with moderate risks in dusts of Abuja public vehicles and motor parks.

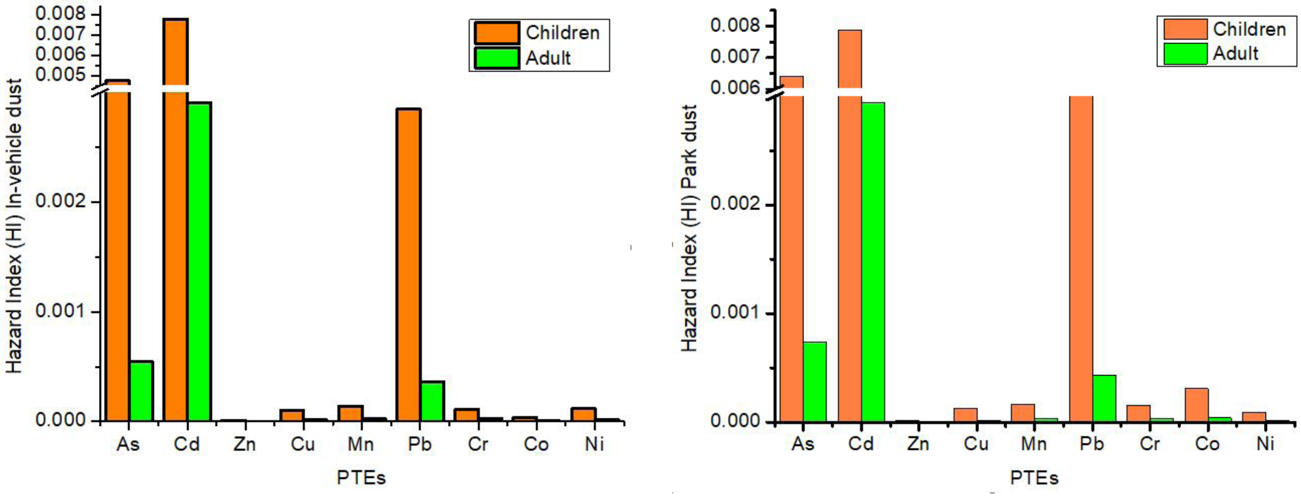
Table 3. Concentrations and contamination indicators of potentially toxic elements in dusts from vehicle interiors and motor park in Abuja

		In-vehicle Dust					**Park Dust**				
				Contamination Indices					Contamination Indices		
PTEs	Statistics	Concentration (in mg/kg)	EF	Igeo	PI or C_f (× 0.001)	E_r (× 0.001)	Concentration (in mg/kg)	EF	Igeo	PI or C_f (× 0.001)	E_r (× 0.001)
Pb	Mean	0.741	3007	-5.24	42.03	210.1	0.880	3871	-5.17	44.01	220.1
	Minimum	0.344	1234	-6.10	21.90	109.5	0.470	1496	-6.00	23.50	117.5
	Maximum	1.038	5289	-4.85	51.90	259.5	1.259	6156	-4.57	62.95	314.8
Zn	Mean	0.236	208.4	-9.18	2.772	2.772	0.405	420.0	-8.39	4.767	4.767
	Minimum	0.143	100.4	-9.80	1.682	1.682	0.197	147.6	-9.34	2.318	2.318
	Maximum	0.371	293.2	-8.42	4.365	4.365	0.580	678.1	-7.78	6.824	6.824
As	Mean	0.106	626.6	-6.09	7.865	78.65	0.143	952.0	-7.21	11.03	110.3
	Minimum	0.079	347.5	-7.95	6.077	60.77	0.057	345.6	-8.42	4.385	43.85
	Maximum	0.136	888.0	0.00	10.46	104.6	0.208	1569	-6.55	16.00	160.0
Co	Mean	0.054	246.9	-6.06	2.720	13.60	0.418	1564	-6.58	20.90	104.5
	Minimum	0.000	0.000	-13.3	0.000	0.000	0.153	575.6	-7.62	7.650	38.25
	Maximum	0.241	1140	0.00	12.05	60.25	0.881	2805	-5.09	44.05	220.3
Cr	Mean	0.023	19.25	-13.3	0.228	0.456	0.032	26.05	-12.3	0.318	0.636
	Minimum	0.003	1.720	-15.6	0.030	0.060	0.020	14.64	-12.9	0.200	0.400
	Maximum	0.060	56.77	-11.3	0.600	1.200	0.049	35.58	-11.6	0.490	0.980
Cu	Mean	0.314	501.2	-8.02	6.284	31.42	0.373	628.0	-7.87	7.464	37.32
	Minimum	0.189	271.1	-8.63	3.780	18.90	0.125	149.1	-9.23	2.500	12.50
	Maximum	0.570	1079	-7.04	11.40	57.00	0.749	1181	-6.65	14.98	74.90
Cd	Mean	0.503	123338	0.12	1676	50280	0.510	130461	0.07	1699	50960
	Minimum	0.335	105204	-0.43	1117	33500	0.252	95836	-0.84	840.0	25200
	Maximum	0.660	145399	0.55	2200	66000	0.818	173608	0.86	2727	81800
Mn	Mean	0.443	38.69	-11.6	0.493	0.493	0.504	46.25	-11.4	0.560	0.560
	Minimum	0.370	24.90	-11.8	0.411	0.411	0.443	29.36	-11.6	0.492	0.492
	Maximum	0.539	62.98	-11.3	0.599	0.599	0.570	65.23	-11.2	0.633	0.633
Ni	Mean	0.174	233.5	-9.73	2.897	14.48	0.127	147.8	-10.1	2.120	10.60
	Minimum	0.034	32.40	-11.4	0.567	2.833	0.023	36.27	-11.9	0.383	1.917
	Maximum	0.420	502.1	-7.74	7.000	35.00	0.363	360.9	-7.95	6.050	30.25



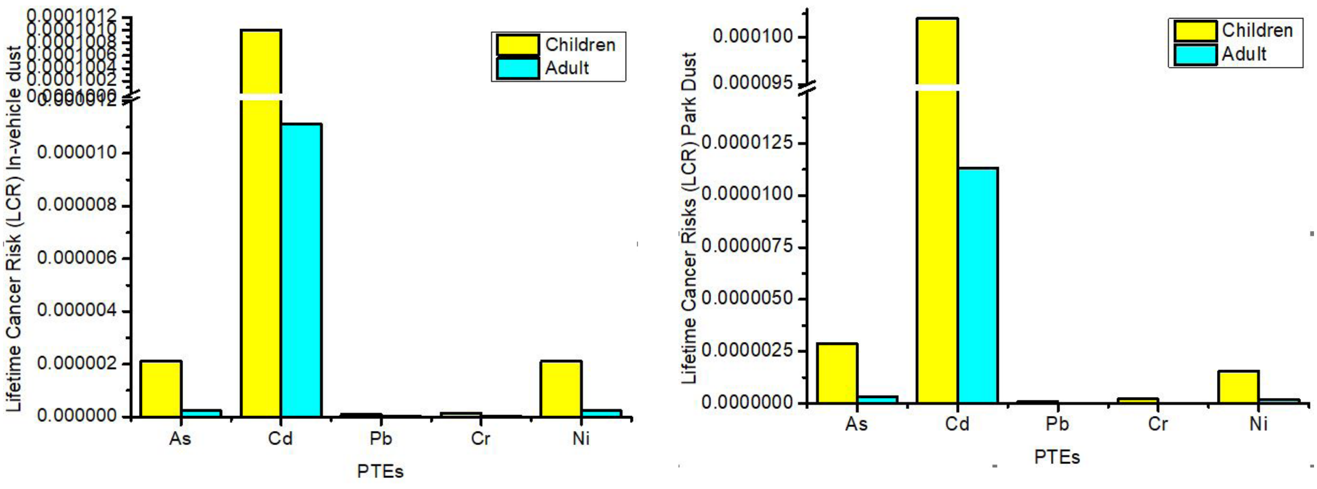
(a) (b)

Fig. 4. Risk indexes of PTEs at (a) In-vehicle dust (b) Park dust



(a) (b)

Fig. 5. Non-carcinogenic risks of residents in Abuja (a) In-vehicle dust (b) Park dust



(a) (b)

Fig. 6. Carcinogenic risks of residents in Abuja (a) In-vehicle dust (b) Park Dust

The outcomes of NIPI and NIRI were consistent with the findings derived from EF, Igeo, C_f, and individual E^i_r assessments. Among all the PTEs evaluated, Cd exhibited the highest NIPI and NIRI values, indicating its dominant contribution to overall pollution and ecological risk in Abuja metropolis.

Assessment of exposure risk

The potential health risks associated with children's and adults' exposure to PTEs in in-vehicle and outdoor park dust within Abuja were quantified through the three primary exposure pathways [29, 39, 59]. The corresponding Reference Doses (RfD) and Cancer Slope Factors (CSF) used in the assessment were stated in [59]. Out of the ten PTEs analysed, nine (Pb, Zn, As, Co, Cr, Cu, Cd, Mn, and Ni) were classified as non-carcinogenic, while five (Pb, As, Cr, Cd, and Ni) were identified as carcinogenic based on their toxicological profiles.

Assessment of Non-Carcinogenic risk

The contribution of the ingestion pathway (HQ_{ing}) to the total non-carcinogenic risk (HI) from PTEs in vehicle dust within Abuja accounted for 95.08% in children and 69.75% in adults. Similarly, for outdoor park dust, ingestion contributed 93.96% and 69.86% of the HI in children and adults, respectively. These findings indicate that ingestion represented the dominant exposure route for PTEs among both children and adults, followed by absorption via skin (dermal) and breathing (inhalation) pathways. Comparable exposure patterns have been documented in several previous studies [6, 29, 99, 100]. The estimated non-carcinogenic and carcinogenic health risks associated with PTEs in Abuja's in-vehicle and outdoor park dust for both age groups are illustrated in Figs. 5 and 6.

Furthermore, the percentage contributions of the ingestion pathway (HQ_{ing} and CR_{ing}) to the total non-carcinogenic (HI) and carcinogenic (CR) risks in vehicle dust were 82.41% and 98.44%, respectively. Comparable values of 82.40% and 98.44% were observed for motor park dust, demonstrating that the ingestion route contributed more substantially to CR than to HI in both environments. Additionally, the HQ values for children via ingestion, dermal contact, and inhalation pathways were approximately 9.33, 0.49, and 2.78 times higher than those for adults, respectively, across both in-vehicle and motor park dust samples.

The HI values for both children and adults Abuja vehicle and motor park dust were all below the safe threshold (HI < 1) (Fig. 5), indicating no immediate non-carcinogenic health risks. However, the HI for Cd in children exceeded 0.01 in vehicle dust, suggesting that although current exposure levels remain within safe limits, continuous or long-term accumulation of Cd could lead to potential health concerns if current contamination trends persist. Human kidney could be damaged by Cd toxicity. Thus, the potential non-cancer risk from toxic elements in Abuja's vehicle dusts should not be overlooked.

Carcinogenic risks

As a result of the unavailability of Slope Factor (SF) information for other PTEs, cancer risk assessment was limited to Pb, As, Cr, Cd, and Ni, following the procedures outlined in [29, 59]. Among these five PTEs (Fig. 6), Cd exhibited the highest carcinogenic risk in both in-vehicle and motor park dust samples (Fig. 6). The ingestion pathway (CR_{ing}) accounted for 99.84% and 97.04% of the total carcinogenic risk (CR) in children and adults, respectively. Furthermore, the hazard quotients via ingestion (HQ_{ing}), dermal contact (HQ_{dermal}), and inhalation (HQ_{inh}) were approximately 9.33, 0.49, and 2.78 times higher for children compared to adults in both environments. According to the international threshold standards established by the United States Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC) (67, 101, 102), the CR values for the five assessed PTEs in both age groups across Abuja ranged between 1 x 10^{-4} and 1 x 10^{-6} or lower than 1 x 10^{-6} (29), suggesting acceptable or negligible carcinogenic risks associated with dust from in-vehicle and motor park environments.

Overall, the human health risk assessment indicated that children were more susceptible to both carcinogenic and non-carcinogenic risks associated with PTE exposure from in-vehicle and outdoor park dusts in Abuja compared to adults (Figs. 5 and 6). This heightened vulnerability among children aligns with observations reported in several urban studies globally [1, 5, 6, 103, 104]. Children's increased exposure is primarily attributed to their behavioral patterns, including frequent outdoor play and hand-to-mouth activities, as well as bigger respiration rates relative to body weight. Consequently, they are more likely to inhale or ingest contaminated dust particles containing elevated PTE concentrations, leading to greater systemic accumulation and potential adverse health effects.

Conclusion

Among the ten PTEs analyzed in dust samples collected from five vehicles and five motor parks within Abuja City, Cd was the only element whose mean concentration exceeded its corresponding background value in both environments. PMF analysis identified five dominant sources contributing to PTE contamination in the examined vehicle and motor park dusts, with traffic-related emissions being the primary contributor. The mean EF values for As, Cd, Zn, Cu, Pb, Co, and Ni revealed extremely high enrichment levels, suggesting significant anthropogenic influence. Similarly, the I_{geo} results indicated higher pollution levels in in-vehicle dust compared to motor park dust. Both I_{geo} and PI values demonstrated comparable contamination trends, ranging from "no contamination" to "low contamination" for Fe, As, Zn, Cu, Mn, Pb, Cr, Co, and Ni. The individual E^i_r analysis showed low ecological risks for most PTEs, except Cd, which exhibited high to very high potential ecological risk levels. Consequently, continuous monitoring of Cd concentrations in vehicle and motor park dusts is strongly recommended to safeguard environmental and public health.

Furthermore, the outcomes of NIRI agreed (compartible) with outcomes of EF, Igeo, PI, and E^i_r results, reinforcing the observed contamination patterns across both sampling environments. Carcinogenic risk assessments for all PTEs revealed either acceptable or negligible risk levels for commuters (children and adults) exposed to vehicular and motor park dusts in Abuja metropolis. However, children exhibited greater susceptibility to both carcinogenic and non-carcinogenic risks than adults. Overall, this study highlights significant variations in human exposure to elevated PTE concentrations between in-vehicle and motor park microenvironments across Abuja Metropolis.

The findings of this study provide essential baseline data for future epidemiological and pollutant exposure studies across urban areas in Africa. The results highlight the urgent need for proactive interventions to minimize residents' exposure to PTEs within vehicles and motor parks in Abuja metropolis. To achieve this, relevant stakeholders should prioritize the implementation of stricter emission control regulations, routine monitoring of vehicular and roadside particulate pollution, and enforcement of vehicle maintenance standards. Additionally, improving fuel and lubricant quality, promoting the use of cleaner transportation technologies, and enhancing public awareness on the health implications of dust exposure are crucial. Collaborative efforts between government agencies, environmental regulators, and urban planners are recommended to develop sustainable strategies aimed at reducing traffic-related metal emissions and safeguarding public health in rapidly urbanizing environments.

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

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Ethical considerations
“Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors”.

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