Discover

Assessment of concentration of the potentially toxic elements and associated human health risk from particulate matter exposure along road intersections in Ibadan, southwestern Nigeria

Tesleem O. Kolawole[1] · Akinade S. Olatunji[2]

OPEN

Abstract
The harmful health effect of suspended particulate matter (PM_{10}) is mostly associated with its mass concentrations and chemical compositions. Therefore, this study focuses on the determination of the particulate matter (PM_{10}) concentrations and their potentially toxic elements (PTEs) composition from different road networks in Ibadan southwestern, Nigeria. In addition, human health risk assessment was estimated from the PTE data. The PM_{10} samples were collected from different road networks such as national highway roads (NHR), inner-city major roads (ICR), and remote roads (RRD) in Ibadan, Nigeria. The sampling was carried out with a high-volume air sampler (model #15000 manufactured by Science Resource, Walboro, USA) with a PM_{10} cut-off on a Whatman cellulose filter during the harmattan period. The PM_{10} concentrations and PTEs compositions (Al, Ba, Cd, Cu, Fe, La, Mo, Mn, Ni, Pb, V, and Zn) were determined by gravimetry and inductively coupled plasma-optical emission spectrometry (ICP-OES) methods (VISTA-MPX manufactured by Varian Incorporation), respectively. The PM_{10} concentrations in all three road networks were more than 3 folds higher than World Health Organization (WHO), United State Environmental Protection Agency (USEPA), and United Kingdom Environmental Protection Agency (UKEPA) standards (50 $\mu g/m^3$) for 24 h. The maximum average contents of Ba, Cd, Cu, La, Mn, Pb, and V, were observed at NHR, while that of Al, Fe, Mo, and Zn, were found at ICR. The principal component analysis (PCA) showed that PC1 (Ba, Cd, Cu, La, Mo, Pb, and V) and PC4 (Zn) were characterised by elemental markers of both exhaust emission and non-exhaust emissions, while PC2 (Mn) and PC3 (Al, Fe) were characterised by crustal elements. The Enrichment factor (EF) analysis classified all the PTEs as moderately to very highly enriched, especially in NHR and ICR, except Al, Fe, and to some extent Mn. Both the maximum and average hazard quotient (HQ) levels of Cd, Cu, Mn, Pb, and Zn were < 1, which was within the permissible level. Also, the carcinogenic risk (CR) was also within the permissible limit.

Keywords Exhaust emission · Non-exhaust emission · Particulate matter concentration

1 Introduction

Airborne Particulate matter (PM) is a complex mixture of primary and secondary aerosols mainly classified based on their sizes (diameter) into fine and coarse fractions. The fine fraction with an aerodynamic diameter of less than 2.5 μm is termed $PM_{2.5}$ and the coarse fraction with an aerodynamic diameter between 2.5 and 10 μm is termed PM_{10} [1]. $PM_{2.5}$ can penetrate into the lungs and the blood streams and affect human health. While PM_{10} can pass through

✉ Tesleem O. Kolawole, tesleem.kolawole@uniosun.edu.ng; Akinade S. Olatunji, akinadeshadrach@yahoo.com | [1]Department of Geological Sciences, Osun State University, Osogbo, Nigeria. [2]Department of Geology, University of Ibadan, Ibadan, Nigeria.

Springer

the nose and throat and cause irritations, nausea, and aggravate underlying health issues like asthma, especially in sensitive groups such elderly and children [2]. Natural and anthropogenic sources can pollute air quality. The natural sources include dust generated from volcanic eruption, windblown dust, and sea-salt spray [3]. Large volumes of particulate matter (PM) are also emitted into the atmosphere from different anthropogenic sources such as industrial and traffic-related product combustion, fugitive dust from construction projects, and waste incineration [4, 5]. However, traffic-related activity is one of the major causes of PM pollution in urban environments throughout the world including Nigeria. A link between air pollution and the severity of respiratory and cardiovascular diseases has been established from epidemiological and toxicological studies [6, 7]. This is due to an increase in vehicles, inefficient transportation, and poor urban planning. Several emissions from traffic-related activities including organic like organic carbon (OC) and polycyclic aromatic hydrocarbon (PAH) and inorganic (potentially toxic elements) substances, were caused by road wear, maintenance, and non-exhaust emissions from vehicle-related fluids, tires, and brake wear [8]. Particulate matter (PM), which is created during the burning of fuel, has been linked to more than 800,000 fatalities in urban areas around the world [9]. According to reports, non-exhaust emissions contribute primarily to PM_{10}, and exhaust-related emissions contribute to $PM_{2.5}$ [10, 11].

Generally, PM_{10} and $PM_{2.5}$ carry high concentrations of potentially toxic elements (PTEs) such as Pb, Zn, As, Cu, Cd, and Hg. It was established that as the particle size decreases the more the toxic metal will be absorbed. Therefore, $PM_{2.5}$ tends to have a higher concentration of toxic metals than PM_{10}. It was reported by Mohanral [12] that 70–90% of heavy metals are contained by PM_{10}. Consequently, According to studies by Hu [13], Pandey [14], and Xie [15], PTEs associated with inhalable particles have been linked to an increase in a number of disorders, including lung or cardiopulmonary damage. Similar to this, activities associated with traffic produce a range of pollutants such as PTEs that have a substantial impact on public health and the environment [4, 16, 17]. Certain PTEs like Ba, Zn, Cu, Mn, and Sb have been used as markers for non-exhaust emissions together with organic markers such as PAHs, and n-alkanes [18–20]. But they are unique from one region to the other based on traffic density and pattern, vehicle types and characteristics, driving pattern, and rock and soil in the area [21–23]. For instance, Jandacka [24] worked on the particulate matter in the vicinity of urban roads in Zilina, Slovakia in order to identify the sources of the particles and to determine the abundance of their constituent metals. It was observed from their study that the non-combustion emission which was associated with some metals such as Na, Fe, Mn, Ni, Zn, Mo, Sb, Cd, and Pb were the major contributor, followed by combustion emissions from vehicles which were associated Mg, Ca, and Ba. Also, a similar study was carried out by Tian [25] in Beijing, China in order to characterise the toxicity of PM. The finding suggests that the chemical substances (PAH and trace elements) were higher near the road than those off-road and attributed this to differing physicochemical characteristics. Most of these investigations emphasised particle concentrations and their chemical constituents without paying attention to the human health risk index arising from the PTEs in the atmosphere. Hence, this study assesses the human health risk associated with the potentially toxic elements in PM_{10} in the study area.

The study area, Ibadan, is one of Nigeria's biggest cities and also one of the fast-growing cities in sub-Saharan Africa with a total population greater than 3.7 million people according to the 2006 National Census [26]. This growth has increased the concentration of commercial and industrial activities in the urban center and often lead to traffic lock jam, which is becoming a typical scenario especially, during the rush hours of working days [27, 28]. Though there are numerous sources of air pollution in Ibadan, (such as open-air burning of waste and biomass [29], industrial activities [30, 31]), and domestic cooking fires [32], traffic-related activities are significant contributors to the pollution of the environment. This is due to rising road congestion, the prevalence of old cars, poor vehicle maintenance, and the use of low-quality fuels [33]. The majority of buses and trucks burn diesel fuel with a high sulfur content (5000 ppm S) as SO_2, which contributes to the level of pollution in the environment [32]. Consequently, roadway emissions significantly affect human health, especially for the significant numbers of people who got exposed to congested highways. In Ibadan, 49% of daily travels were made on foot or on a motorcycle. Another big issue concerns groups of people who spend their days on crowded highways and roadside areas, such as traffic cops and street merchants [27].

Therefore, the main objectives of this investigation were to (1) determine the concentrations of the particulate matter (PM_{10}), (2) determine the concentrations of the potentially toxic elements (PTEs) in the PM_{10}, (3) assess the enrichment factor (EF) of the PTEs in PM_{10}, (4) carry out preliminary human health risk associated with the PTEs.

2 Methodology

2.1 Sampling site

The study area is located within the Ibadan metropolis, southwestern Nigeria. Ibadan is well-known for its hilly and undulating topography, which also contains plains, valleys, and rivers. The hills, which make up less than 20% of the total surface area and range in elevation from 180 to 210 m above sea level, are the most noticeable features [34]. However, the plains are the most abundant in the study area. According to the work of Okunlola [35], Olayinka [34]; Tijani [36], quartzites, banded gneisses, augen gneisses, and migmatites are the dominant rock groups in the research area. These rocks have intrusions from pegmatite, quartz vein, aplite, and dioritic dykes. Amphibolites and pegmatites are minor rocks with significant covering. However, most of the areas are covered by regolith.

   This research was carried out on a segment of national highway roads (NHR), inner-city major roads (ICR), and remote roads (RRD) in Ibadan, Southwestern Nigeria for their PM_{10} assessments. The NHR is the inter-state Highway and was monitored at the intersection between the south (Iwo Road) and the north (Ojoo Road) roads. This six-lane highway (3 northbound, 3 southbound) supports over 10,000 vehicles per hour [37] during the study. Around 15% of the daily traffic on this highway was made up of heavy-duty diesel trucks, with most of the remaining vehicles being light-duty gasoline passenger cars and buses. Two other major inner-city roads (Beere and Mokola) were monitored (Fig. 1). These areas are ideal for such a study, because various parks, busy junctions, and road constructions represent point sources for atmospheric pollution. Mobile air monitoring sampler was located in each of the locations. The sampler was placed between 60 and 100 m away from the road, depending on the predominant upwind direction for seven days each, during the Dry season. However, two remote roads (RRD) area (with a low settlement, low traffic, and other minimal activities) was also monitored for the same periods. The samples were collected for 4–6 h. A total of forty-two (42) samples were collected from all the locations. 14 samples were collected from each of the three different road networks (NHR, ICR, RRD).

Fig. 1 Illustration map of the sampling points and the traffic and infrastructure network in the sampling region
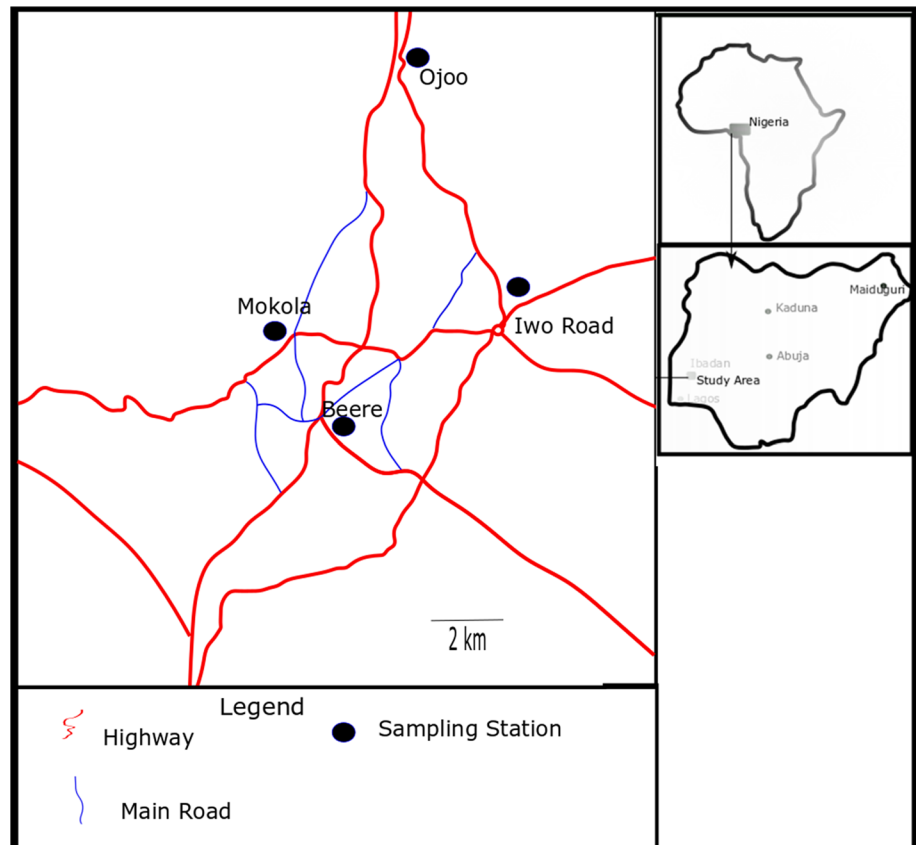
2.2 Sample collection

The particulate matter (PM$_{10}$) was collected with a high-volume air sampler (HAS) model #15000 manufactured by Science Resource, Walboro, USA with a flow rate of 630 l/m with a cellulose filter. The filters were equilibrated at 25 °C and 50% relative humidity (RH) before and after their insertion into the sampler. The concentration of PM$_{10}$ was determined gravimetrically. The detail of the working principle, set-up, and filter has been reported [27].

2.3 Meteorological information capturing

The Nigerian Airport Authority's meteorological unit, which is based in Samonda, Ibadan, Nigeria, provided information on pertinent meteorological factors like temperature, RH, precipitation, wind direction, and wind speed. The information received covered the time frame depicted in Table 1 for the investigation.

2.4 Determination of metal concentration

According to EPA's 1999 proposal, elemental analysis of the filters entailed hot acid digestion of the filters. In a Pyrex tube containing 5 cm^3 of the sample material, 5 ml of HNO$_3$ (Merck Suprapur 65%), 2 ml of HCl (Merck Suprapur 36%), and 10 ml of ultra-pure water were added. The tube was then held still for 2 h at 95 °C on a heating plate. A Whatman n° 41 (WH1441-110) filter was used to filter the extracted solution, which was then diluted to 50 ml with ultrapure water and stored in clean plastic bottles in the refrigerator for analysis. The same procedure was used to process filter and reagent blanks. Less than 8% of the sample's average metal concentration was found in the blanks for Ca, Mg, K, Na, Mo, Mn, Fe, Zn, Cu, Co, Ni, Al, and Pb. Inductively coupled plasma optical emission spectroscopy (CP-OES) VISTA-MPX manufactured by Varian Incorporation was employed for the determination of the PTEs.

3 Result and discussion

3.1 PM$_{10}$ concentration

The statistical summary of the result of PM$_{10}$ concentration is presented in Table 2 and Fig. 2. The average concentration of PM$_{10}$ at NHR, ICR, and RRD were 260, 134, and 120 µg/m^3, respectively. These values were in multiple folds higher than WHO, USEPA, and the UKEPA, which have set their standard at 50 µg/m^3 for 24 h. However, the minimum PM concentration of PM at RRD (27 µg/m^3) was lower than this standard for some of the days, due to low vehicular movement and low wind speed.

There is a significant variation of PM concentrations on the basis of their minimum and maximum values at NHR (101–375 µg/m^3), ICR (62–298), and (27–196). Therefore, high PM concentrations were observed at NHR, and ICR, while the minimum value was found at RRD. These areas correspond to a high average traffic density of about 3000 vehicles per hour (vph) according to Etim [37]. Similarly, during the sampling period, intense road construction was very prominent. The lowest PM concentration that was observed at RRD had relatively low traffic density (< 200 vph) [37]. This investigation was consistent with the findings of some research work in the study area [38] and elsewhere in Nigeria [39]. The studies found a positive correlation between traffic volume and PM concentration. They also opined the fact that the daily peak period of PM$_{10}$ concentrations is arguable during the daytime/afternoon when the traffic volume normally reaches its highest points. Therefore, the PM concentration at NHR and ICR stations contributed most to the budget of the particles in the areas, which is attributed to high traffic volume. Because vehicular movement generates air turbulence,

Table 1 Metrological data of the study area	Collection location	Average daily temperature (°C)	Average daily humidity (%)	Average wind speed (kmph)	Wind direction
	NHR	32.2	72.5	8	SW
	ICR	28.9	71.3	7	SW
	RRD	30.6	72.5	8	SSW

Table 2 PM$_{10}$ concentrations (μg/m^3) and their PTEs concentrations (ng/m^3) in the different road networks of the study area

|	NHR			ICR			RRD		
	Mean ± Std	Range	EF	Mean ± Std	Range	EF	Mean ± Std	Range	EF
PM	260 ± 85	101–375	–	134 ± 92	62–298	–	120 ± 53	27–196	–
Al	1504 ± 526	977–2840	–	7232 ± 1438	3404–9708	–	4654 ± 2789	1198–8313	–
Ba	6.84 ± 4.50	1.55–17.95	0.59	1.60 ± 0.71	0.56–2.46	0.03	1.16 ± 1.14	0.11–3.48	0.09
Cd	43.86 ± 39.41	12.10–119	1080	10.84 ± 13.17	0.28–41.00	50.75	0.43 ± 0.66	Bld-2.20	1.60
Cu	49.71 ± 34.90	12.10–121	98	5.33 ± 3.48	0.32–11.32	2.21	1.16 ± 1.18	Bld-2.72	0.78
Fe	4244 ± 3486	1117–11,243	4.23	5986 ± 2166	1125–8405	1.29	2401 ± 568	1187–3281	1.36
La	2.49 ± 3.27	0.23–12.10	3.67	0.80 ± 0.45	0.11–1.31	0.31	0.10 ± 0.11	Bld-0.33	0.11
Mo	5.54 ± 3.12	0.10–11.21	286	5.71 ± 2.31	1.12–8.63	64.77	0.58 ± 1.04	Bld-2.99	5.58
Mn	309 ± 148	113–580	19	218 ± 115	70–389	3.02	210 ± 161	85–539	8.56
Pb	48.68 ± 45.13	10.38–142.01	144	20.9 ± 10.84	11.00–42.50	15.11	0.14 ± 0.36	Bdl-1.33	0.20
V	57.61 ± 28.17	11.29–112.00	33.43	32.35 ± 17.27	8.23–53.50	4.11	0.65 ± 0.68	Bdl-2.30	0.14
Zn	289 ± 211	54–795	274	313 ± 232	88–910	54.66	49 ± 21	20–89	28.37

PM: particulate matter; NHR: National Highway Road; ICR: Inner-city Road; RRD: Remote Road

Fig. 2 Statistical summary of the PM$_{10}$ concentrations in the study area
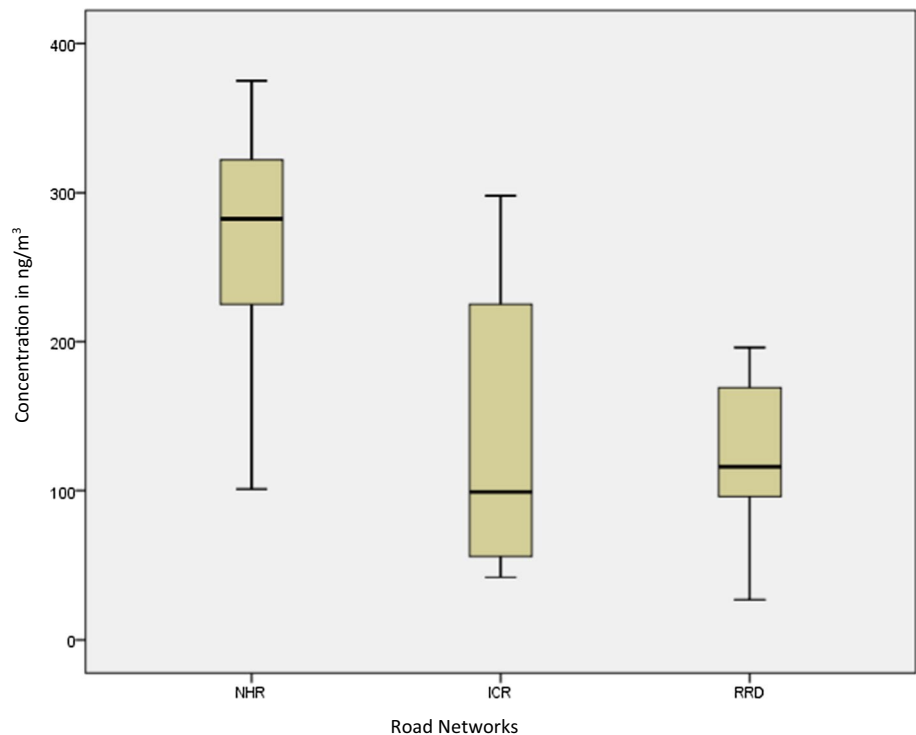
which usually stirs the deposition of a coarse fraction such as vehicular wear and roadside soil dust-resuspension into the immediate atmospheric environment and also generates other forms of combustion processes that are prevalent in the area, this also is in agreement with the work of Odeshi [27]. Consequently, the area was adjudged non-attainment status when compared with the global standards.

This result was also compared with the average concentration reported in the study areas and elsewhere in Nigeria (Fig. 3). The highest average PM$_{10}$ concentration in this study (260 μg/m^3) was higher than the values reported by Akinlade [40], and Obioh [41]; at Ibadan (146 μg/m^3) and Port Harcourt (192 μg/m^3) Nigeria, respectively. However, the average PM concentration was lower than the value reported by Odeshi [27] (500.00 μg/m^3) at Ibadan, Ilorin (800 μg/m^3), Aba

Fig. 3 Comparison of average PM concentration of the study area with other previous works
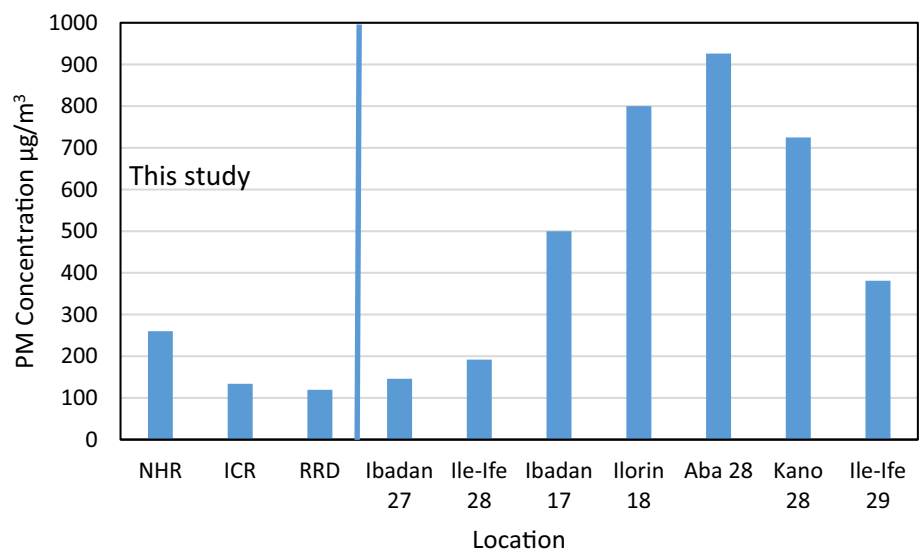
(926 µg/m^3) and Kano (725 µg/m^3) [28, 41] Ile-Ife (381 µg/m^3) [42]. The studies similarly attributed the high PM values to traffic density, road construction, and vehicular emission, coupled with wind seed and low precipitation.

3.2 Distribution of PTEs in the PM_{10}

The statistical summary of the PTEs in PM_{10} is presented in Table 2. The maximum average concentration of Ba (6.84 ng/m^3), Cd (43.86 ng/m^3), Cu (49.71 ng/m^3), La (2.49 ng/m^3), Mn (309 ng/m^3), Pb (48.68 ng/m^3), and V (57.61 ng/m^3) were observed at NHR. While the maximum average concentrations of Al (7,232 ng/m^3), Fe (5,986 ng/m^3), Mo (5.71), and Zn (313 ng/m^3) were observed at ICR. All these trace elements had their lowest concentration at RRD. Largely, in terms of the mean concentrations, the metals decrease as follows: Al > Fe > Zn > Mn > V > Cu > Pb > Cd > Ba > Mo > La. Furthermore, there is a significant variation of Ba, Cd, Cu, La, Mo, Pb, V, and Zn from their lowest and the highest value, but lesser/moderate variation was observed in the values of the crustal elements (Al, Fe, and Mn) (Table 2). This suggests the heterogeneity in the level of anthropogenic activities that emit the particles into the atmospheric environment of the study area. These PTEs were fundamental indicators for emissions from vehicles' exhaust systems caused by the burning of fuel and lubricants, catalytic converters, particle filters, and engine corrosion [43, 44].

Several reports have shown higher emission rates of Ba and V, which were attributed to fossil fuel emissions [45]. Also, Ba is used as barium sulfate ($BaSO_4$) in diesel fuel to suppress smoke generation and filler material in brake lining [46, 47]. There are two major vehicle types in this area (NHR) based on the fuel they consumed. Small vehicles (cars and buses) are the most abundant and operate on gasoline and heavy vehicles (mostly trucks) rely on diesel engines. Therefore, their contribution from the vehicular exhaust cannot be overemphasized. Zinc (Zn) compounds are added to engine oil to reduce wear and oxidation [48]. Zinc (Zn) is also sourced from roadside traffic-related activities non-exhaust emissions such as tire wear [49] and brake wear [45] and oil combustion [11]. There were also reports that the concentrations of Zn, Pb, and Cu were higher in road dust and surface wear than in background soil in Ibadan [33, 50]. The environmental effects of Pb are common all over the world as they cause various diseases, especially in sensitive groups such as children, elderly people, and pregnant women [51]. But children, in particular, face a greater risk not only because they are smaller, but also because they have faster metabolic rates. They are less able physically to handle toxic chemicals [51]. Lead (Pb) origin could be possibly linked to their presence in the roadside soil that was resuspended into the atmosphere. Although, Pb-gasoline had been banned in Nigeria and elsewhere in the world its elevated content in roadside soil was recently reported by Fashae [52] who attributed their presence to traffic activities in the area. Copper (Cu) compounds are also used in engine oil to reduce wear and oxidation. Hjortenkrans [53] and Canepari [54] reported that Cu and other elements were present in the brake. High level of Cu has been reported to cause respiratory diseases [55]. Cadmium (Cd) compound had been reported to originate from oil combustion, industrial processes, and coal burning [27]. Therefore, Cd in this study was a result of exhaust emission. However, WHO reported that even at low concentration values if inhaled can have severe health impacts [56, 57].

The mean concentrations of these elements were used in the comparison of the average elemental concentration of other previous research work both in the study area and other regions Table 3). Although, there were few previous research works in the study area, however, the average concentrations of Cu, Mn, Pb, V, and Zn in this study, especially at NHR and ICR, were more than two folds higher than the one reported in the study area by Akinlade [40], and lower than the results of Odeshi et al., 2014 [27] (Table 3). This result is also higher than the similar findings in Lagos (57). However, Ezeh [58] reported a higher mean concentration of Cd (135 ng/m^3) in the Lagos traffic section, which was higher than the result of this study (43.86 ng/m^3). The mean concentration of Mo and La in this study were lower than 35.85 ng/m^3 and 28.08 ng/m^3, respectively, reported by Owoade [42]. Equally, the result of the study area was compared with previous work in Beijing, China [25], Bogota, Colombia [1], Zilina City, Slovakia [24], and Madras, India (50). Generally, the result of the mean content of Cu, Mn, and Zn of this study was greater than the corresponding elements in the four cities, except Beijing and Madras, which had a higher value of Zn (677 ng/m^3) (Table 3). Meanwhile, the average concentrations of Ba and Mo were lower than the ones reported in the four cities except for Zilina for Ba (14 ng/m^3). The average concentrations of Pb and V were consistent with the work of Tian [25], Ramirez [1], and Srimuruganandam and Nagendram, [59] (Table 3).

3.3 Elemental relationship and sourcing of the PM

The main influencing factors for the PTEs and any related sources of the PTEs were identified using principal component analysis (PCA). Table 4 displays the PTE content of PM$_{10}$ PCA results. The variation was broken down into four major components, which accounted for 88% variance. Ba, Cd, Cu, La, Mo, Pb, and V were the dominant elements in the first PC, which made up around 47% of the overall variance. These PTEs are elemental markers for both exhaust (fossil fuel combustion) and non-exhaust emissions, like brake wear and the rusting of metallic automotive portions, which have been established in previous sections [45–48]. Therefore, the source of these metals was attributed to anthropogenic sources from traffic-related activities. The PC2 and PC3 explain similar total variance (14% each) and are composed of Mn; Al and Fe, respectively. These elements were believed to be crustal elements and generally had very high concentrations across all the different road networks. Therefore, their contributions were mainly attributed to natural/geogenic sources. They originated from the entrained soil dust by vehicular movement and wind from unpaved roads and construction earthy materials. Although PC4 only accounts for around 13% of the total variance, it is substantially positively loaded with Zn (0.96), which is important in depicting that non-exhaust emission from tire wear has an anthropogenic origin in the study area.

To further establish the source identification of PTEs, the relationships between the PTEs based on the first three principal components are illustrated by a loading plot (Fig. 4a) and score plot (Fig. 4b). The first cluster in the loading plot (Fig. 4a) demonstrated the relationship of the PC1 (Ba, Cd, Cu, La, Mo, Pb, and V) and PC4 (Zn) elements, which were the most prevalent at NHR and ICR. Their contributions were attributed to both exhaust and non-exhaust emissions. While the isolation of Mn on one side and Fe on the other side were attributed to geogenic origin. Four groups of samples are shown in the factor score (Fig. 4b) based on the abundance and sourcing of the various elements. The first and the second groups were characterised by samples from NHR, which had a relatively very high concentration of all the PTEs, except Al. while the third and fourth groups were composed of samples mainly from ICR and RRD and were characterised by relatively high Al and low to moderate concentrations of the other PTEs. Therefore, the contributions of the PTEs were mainly derived from the NHR and ICR, because of the level of traffic-related activities in the study area.

4 Environmental assessment of PTEs in PM

In order to assign the amount of contamination of the elements using the enrichment factor (EF), the environmental assessment of the elements in the study region was determined.

To provide information on potential sources of the elements, EFs of the elements in PM$_{10}$ were calculated by comparing the concentration of each element in the atmosphere of the study area against the concentration of a reference element [60]. There is no set rule for selecting the reference element; typically, Si, Al, Fe, or Mn are employed. Al was employed as the reference for the estimations of the enrichment factor. Aluminum (Al) was a good choice, as evidenced by its more significant spread in the crust.

Table 3 Average elemental composition of PM of this study and previous work (all values in ng/m³)

Elements	This study			Akinlade [40]	Odeshi [27]	Ezeh [57]	Ezeh [58]	Tian et [25]	Ramirez [1]	Jandacka [24]	Srimurugananadam and Nagendram [59]
	NHR	ICR	RRD	Ibadan, Nigeria	Ibadan, Nigeria	Lagos, Nigeria	Lagos, Nigeria	Beijing, China	Bogota, Colombia	Zilina, Slovakia	Madras, India
Ba	6.8	1.60	1.16	–	1700	–	–	72	43	14	150
Cd	43.86	10.84	0.43	–	–	135	–	3	0	–	45
Cu	49.71	5.33	1.16	10	1600	50	8	127	84	20	150
La	2.49	0.80	0.10	–	–	–	–	–	–	–	–
Mo	5.54	5.71	0.58	–	–	–	–	116	–	10	45
Mn	309	218	210	100	5500	20	19	–	–	1	300
Pb	48.68	20.9	0.14	12	5600	18	10	199	–	14	1
V	57.61	32.35	0.65	10	–	9	7	33	4	–	45
Zn	289	313	49	100	–	58	60	677	108	73	300

Table 4 Principal component analysis PTEs

	PC1	PC2	PC3	PC4
Al	−0.39	−0.49	0.72	−0.05
Ba	0.91	0.29	−0.08	−0.09
Cd	0.93	0.13	−0.15	0.18
Cu	0.76	0.42	0.03	0.19
Fe	0.34	0.23	0.80	0.24
La	0.81	0.30	0.33	−0.02
Mn	0.20	0.94	0.04	0.09
Mo	0.59	0.07	0.42	0.48
Pb	0.89	0.11	0.19	0.00
V	0.89	0.01	0.09	0.28
Zn	0.05	0.08	0.09	0.96
Eigen value	5.18	1.55	1.54	1.38
% Variance	47.06	14.11	13.99	12.50
Cumulative %	47.06	61.17	75.16	87.66

Fig. 4 PCA loading plot (**a**) Graphic score plot in the study area (**b**)
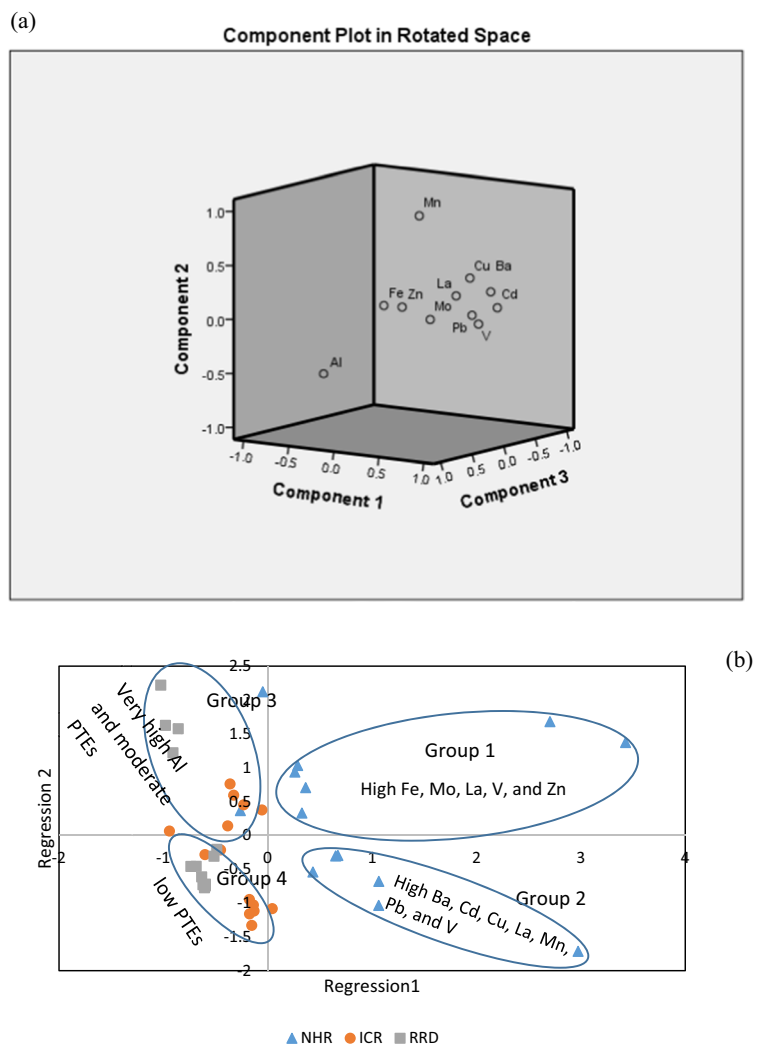
$$EF = \frac{\left(\frac{B_i}{B_{ref}}\right)air}{\left(\frac{C_i}{C_{ref}}\right)crust} \tag{1}$$

where B_i is the concentration of elements of interest and B_{ref} is the concentration of reference element in PM (Al). While C_i is the crustal abundance of the element of interest and C_{ref} is the crustal abundance of reference element by Rudnick and Gao [61]. Typically, the enrichment factor was linked to five classes of contamination (Table 5).

The average enrichment factor (EF) values obtained (Table 2) of PM at NHR were very high to extremely high in Cd, Cu, Mo, Pb, V, and Zn, significant in Mn, moderate in La and Fe, and low in Ba. Also, it was found from ICR that Cd, Mo, and Zn EF values were within extremely high enrichment. While Pb was significantly enriched, Cu, Mn, and V had moderate enrichment, and the enrichment of Ba and La was low at ICR. The result of the EF in this study is consistent with the work of Ezeh [58], their study also observed extremely high enrichment of Cd, Cu, Zn, and Pb in the city of Lagos. They attributed the sources of their enrichment to petroleum oil product combustion. Meanwhile, their study also identified low EF values for Al and Fe among other crustal elements and ascribed their contributions to natural sources from entrained or resuspension soil dust. At RRD, the EF values of Ba, Cd, Cu, Fe, La, Pb, and V had low enrichment, however, some of the PTEs (Mo, Mn, and Zn) were moderately enriched. The low enrichment in this region was a result of the remoteness of the area in terms of low traffic density. The reason for the moderate enrichment in this region could be a result of the emission from the few vehicles that ply the route. The result was consistent with results obtained in the remote area in Cape Verde [3].

5 Human health risk assessment

5.1 Health risk assessment

5.1.1 Non-carcinogenic risk

In this study, the non-carcinogenic risk was determined by taking into account inhalation pathway, which is how humans are exposed to PTEs through PM [62–64, 66, 67]. This was accomplished by calculating the hazard quotients (HQs) for some selected PTEs and the hazard index (HI) for children, adult males and females exposed in the research area.

For chronic daily intake (CDI) for inhalation pathway:

$$CDI_{Inh} = \left(C * IRi * EF * ED \times 10^{-6}\right)/(BW*AT) \tag{2}$$

$$HQ = CDI_{Inh}/RfD_{inh} \tag{3}$$

$$HI = \Sigma HQ = \Sigma(CDI/RfD) \tag{4}$$

The individual terms in Eqs. 2, 3 and 4 and their values are defined in Tables 6 and 7.

The statistical summary of non-carcinogenic (HQ and HI) indices performed on selected elements such as Cd, Mn, Mo, Cu, Pb, and Zn in PM$_{10}$ for adult males, females, and children are presented in Table 8. On the basis of average values of HQ of metals in adult males, females, and children, the elements generally decrease in the following order:

Table 5 Thresholds for soil and sediment quality classification for multi-element indices

Class	Qualification	EF
1	Unpolluted	Ef < 2
2	Moderate enrichment	2 < Ef < 5
3	Significant enrichment	5 < Ef < 20
4	Very high enrichment	20 < Ef < 40
5	Extreme high enrichment	Ef > 40

Qingjie [65]

Table 6 Definitions of parameters and values of the variables for estimating human exposure to soil and sediment

Symbols	Units	Definition value	Value
CDIinh	mg kg^{-1} day^{-1}	Chronic daily dose through inhalation	–
C	mg kg^{-1}	Concentration of heavy metal in substrate	–
InhR	m^3 day^{-1}	soil inhalation rate for receptor resident	7.63 (child) 20 (adult)
EF	d yr^{-1}	Exposure frequency	350 (resident) 75 (recreations)
ED	yr	Exposure duration	30 (resident, recreation); 6 child (resident)
BW	kg	Average body weight	42.4 (child) 62.7 (adult males) 54.4 (adult females)
AT$_{nc}$	D	Average time for non-carcinogenic effects	ED X 365 (resident and recreation)
RfDinh	mg m^{-3}	Chronic inhalation reference dose concentration	Table 7
HQ	–	Hazard quotient	Table 8
HI	–	Hazard index	Table 8
CSFo		Oral slope factor	Table 7

Table 7 Reference dose (RfDinh) values of heavy metals. Jia [62]

Metal	RfDinh	CSFo
Cd	0.00001	6.3
Cu	0.0024	/
Mn	0.000005	/
Pb	0.0015	0.0085

Table 8 the result of health quotient (HQ) of metals and health index (HI) of adult male and female, and children in PM$_{10}$ for non-carcinogenic risk assessment

		HQ			CR
		Adult male	Adult female	Children	
Cd	Average	1.5E−05	1.3E−05	3.7E−05	8.48E−06
	Min	0	6.6E−06	1.9E−05	0
	Max	2.8E−05	2.4E−05	6.8E−05	9.23E−05
Mn	Average	1.5E−04	1.3E−04	3.7E−04	
	Min	5.8E−05	4.9E−05	1.4E−04	
	Max	2.9E−04	2.5E−04	7.1E−04	
Cu	Average	1.4E−06	1.2E−06	3.4E−06	
	Min	6.9E−07	5.9E−07	1.7E−06	
	Max	2.8E−06	2.4E−06	6.9E−06	
Zn	Average	1.7E−05	1.4E−05	4.1E−05	
	Min	9.8E−06	8.4E−06	2.4E−05	
	Max	3.3E−05	2.9E−05	8.2E−05	
Pb	Average	2.7E−04	2.3E−04	6.5E−04	8.49E−07
	Min	7.6E−05	6.5E−05	1.9E−04	0
	Max	6.2E−04	5.3E−04	1.5E−03	8.58E−06
HI	Average	4.6E−04	3.9E−04	1.1E−03	
	Min	1.6E−04	1.4E−04	3.9E−04	
	Max	9.9E−04	8.5E−04	2.4E−03	

Cd > Pb > Cu > Mn > Zn > Mo. Both the lowest and the highest HQ values of all the metals were less than the acceptable permissible HQ values (1), which pose no significant non-carcinogenic risk to humans. But, when considering the results for the non-carcinogenic risk for the three age groups it was observed that children had a higher potential risk. Furthermore, the highest average HQ values were observed for Pb (6.5×10^{-4}) in PM_{10}. Therefore, Pb contributed more to the non-carcinogenic risk for all age groups. This result can be explained by the elevated Pb concentrations at this site, as well as by its high intoxication and respective RfD value. The same trend was observed for the HQ values of the other metals, though with lesser HQ values (Table 8). Therefore, progressive exposure to PTEs in the study area might enhance the non-carcinogenic risk.

Consequently, the HI values of both the size fraction and seasons were less than 1, which indicated that they may pose no significant non-carcinogenic risk. The highest average (1.1×10^{-3}) and maximum (2.43×10^{-3}) HI values were observed in children. These values were more than 6–60 times greater than the HI values found in adult males and females. Despite the fact that the HI values fell within acceptable non-carcinogenic risk, HI for children is higher than both adults, this indicated that children were more susceptible to the effect of the PTEs.

5.1.2 Carcinogenic risk

The CR was estimated using the formula below:

$$CR = CD_{inh} \times SF$$

where SF is the carcinogenic slope factor. The slope factor for of Cd and Pb are 6.3 and 0.0085 per (mg/kg/day) (Table 7), respectively.

The carcinogenic risk (CR) were estimated for Cd and Pb for the inhalation pathway in the study area (Table 8). For Cd, the highest average CR value was discovered to be 8.48×10^{-6}. Risk values below 1×10^{-6} suggest no substantial health impacts, while values above 1×10^{-4} imply unacceptable carcinogenic health hazards for humans. A CR value in the range of 1×10^{-6} to 1×10^{-4} implies an acceptable total risk (53, 54). Consequently, both the maximum average CR values observed for Cd in the study area and the highest singular CR value of 9.23×10^{-6} (Cd) were within the permissible limit of carcinogenic risk. The CR values decreased as follows: Cd > Pb. Although the CR results obtained for Cd are higher than Pb, it does not really pose a major carcinogenic risk due to the fact that the metals are still within the threshold levels for both adults and children were also within acceptable limits.

6 Conclusion

This investigation revealed that the PM_{10} concentration is particularly higher in the NHR and ICR and lower in RRD due to their corresponding level of traffic volume, the former had high volume traffic while the latter had low traffic volume. However, their average values were all higher than the global standards and their air quality can be adjudged non-attainment status. The potentially toxic elements (PTEs) such as Ba, Cd, Cu, La, Mn, Mo, Ni, Pb, V, and Zn, were elemental makers for both non-exhaust emission and emission from road vehicles and their concentrations in the PM_{10} were high, especially in NHR and ICR road networks. The principal component analysis (PCA) attributed the sources of the PTEs, from PC1 (Ba, Cd, Cu, La, Mo, Pb, and V), PC2 (Mn), PC3 (Al, Fe), and PC4 (Zn) to be exhaust emission, non-exhaust emissions both. While PC2 and PC3 were characterised by crustal elements. The Enrichment factor (EF) analysis classified all the PTEs as moderately to very highly enriched, especially in NHR and ICR, except Al, Fe, and to some extent Mn. Both the maximum and average Hazard quotient (HQ) values of Cd, Cu, Mn, Pb, and Zn were less than the acceptable permissible HQ value (1), which poses no significant non-carcinogenic risk to humans. But the high value of children is worrisome. Also, the carcinogenic risk (CR) was also within the permissible limit.

This work recommends that an assessment of $PM_{2.5}$ should be carried out in the study area in order to complement the present study for proper policy on environmentally sound transportation systems and road networking.

Author contributions TOK, the first and corresponding author designed the study, took part in the fieldwork, data analysis, data interpretation, and wrote the manuscript. While ASO, the second author also took part in designing this work, the fieldwork, and manuscript review. Both authors read and approved the final manuscript.

Declarations

Competing interests The authors declare no competing interests.

References

1. Ramírez O, de la Campa AMS, Sánchez-Rodas D, de la Rosa JD. Hazardous trace elements in thoracic fraction of airborne particulate matter: assessment of temporal variations, sources, and health risks in a megacity. Sci Total Environ. 2020;710(2020): 136344.
2. Kaupp H, McLachlan MS. Distribution of polychlorinated dibenzo-P-dioxins and dibenzifurans (PADD/Fs) within the full size range of atmospheric particles. Atmos Environ. 2000;34:73–83.
3. Fomba KW, Muller K, van Pinxteren D, Herrmann H. Aerosol size-resolved trace metal composition in remote northern tropical Atlantic marine environment: case study Cape Verde islands. Atmos Chem Phys. 2013;2013(13):4801–14.
4. Wang H, Cai L, Wang H, Hu G, Chen L. A comprehensive exploration of risk assessment and source quantification of potentially toxic elements in road dust: a case study from a large Cu smelter in central China. CATENA. 2021;196: 104930.
5. Cheng Z, Chen L-J, Li H-H, Lin J-Q, Yang Z-B, Yang Y-X, Xu X-X, Xian J-R, Shao J-R, Zhu X-M. Characteristics and health risk assessment of heavy metals exposure via household dust from urban area in Chengdu, China. Sci Total Environ. 2018;619:621–9.
6. Seposo X, Ueda K, Sugata S, Yoshino A, Takami A. Short-term effects of air pollution on daily single- and co-morbidity cardiorespiratory outpatient visits. Sci Total Environ. 2020. https://doi.org/10.1016/j.scitotenv.2020.138934.
7. Zoran MA, Savastru RS, Savastru DM, Tautan MN. Assessing the relationship between surface levels of PM2.5 and PM10 particulate matter impact on COVID-19 in Milan, Italy. Sci Total Environ. 2020;738(738): 139825.
8. Aljazzar T, Kocher B. Monitoring of contaminant input into roadside soil from road runoff and airborne deposition. Transp Res Procedia. 2016;14(2016):2714–23.
9. Pope CA III, Dockery DW. Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc. 2006;56:709–42.
10. Kam W, Liacos JW, Schauer JJ, Delfino RJ, Sioutas C. Size-segregated composition of particulate matter (PM) in major roadways and surface streets. Atmos Environ. 2012;55:90–7.
11. Pant P, Harrison RM. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. Atmos Environ. 2013;77:78–97.
12. Mohanral R, Azeez PA, Priscilla T. Heavy metal in airborne particulate matter of urban Coimbatore. Arch Environ Contam Toxicol. 2004;47B:162–7.
13. Hu X, Zhang Y, Ding Z, Wang T, Lian H, Sun Y, et al. Bioaccessibility and health risk of (Cd Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2.5 in Nanjing, China. Atmos Environ. 2012;57:146–52.
14. Pandey P, Patel DK, Khan AH, Barman SC, Murthy RC, Kisku GC. Temporal distribution of fine particulates (PM2.5, PM10), potentially toxic metals, PAHs and Metal-bound carcinogenic risk in the population of Lucknow City, India. J Environ Sci Health A Tox Hazard Subst Environ Eng. 2013;48(7):730–45.
15. Xie DH, Yang TB, Liu ZY, Wang H. Epidemiology of birth defects based on a birth defect surveillance system from 2005 to 2014 in Hunan province, China. PLoS ONE. 2016;11:673.
16. Zhang J, Hua P, Krebs P. Influences of land use and antecedent dry-weather period on pollution level and ecological risk of heavy metals in road-deposited sediment. Environ Pollut. 2017;228:158–68.
17. Wang S, Cai L-M, Wen H-H, Luo J, Wang Q-S, Liu X. Spatial distribution and source apportionment of heavy metals in soil from a typical county-level city of Guangdong Province, China. Sci Total Environ. 2019;655:92–101.
18. Gietl JK, Lawrence R, Thorpe AJ, Harrison RM. Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road. Atmos Environ. 2010;44(2):141–6.
19. Oliveira C, Martins N, Tavares J, Pio C, Cerqueira M, Matos M, Silva H, Oliviera S, Camoes F. Size distribution of polycyclic aromatic hydrocarbons in a roadway tunnel in Lisbon, Portugal. Chemosphere. 2011;83(11):1588–96.
20. Kwon EE, Castaldi MJ. Mechanistic understanding of polycyclic aromatic hydrocarbons (PAHs) from the thermal degradation of tires under various oxygen concentration atmospheres. Environ Sci Technol. 2012;46(23):12921–6.
21. Amato F, Pandolfi M, Moreno T, Furger M, Pey J, Alastuey A, Bukowiecki N, Prevot ASH, Baltensperger U, Querol X. Sources and variability of inhalable road dust particles in three European cities. Atmos Environ. 2011;45(37):6777–87.

22. Duong TT, Lee BK. Determining contamination level of heavy metals in road dust from busy traffic areas with different characteristics. J Environ Manage. 2011;92(3):554–62.

23. Birmili, W., Hoffmann, T., 2006. Environmental pollutants. Particulate and dust pollution, inorganic and organic compounds. In: Encyclopedia of Respiratory Medicine. Academic Press, Oxford, pp. 110–120.

24. Jandacka D, Durcanska D, Bujdos M. The contribution of road traffic to particulate matter and metals in air pollution in the vicinity of an urban road. Transp Res Part D. 2017;50(2017):397–408.

25. Tian H, Zhao D, Cheng K, Lu L, He M, Hao J. Anthropogenic atmospheric emissions of antimony and its spatial distribution characteristics in China. Environ Sci Technol. 2012;46:3973–80.

26. Nigerian Population Commission (NPC), 2006. Legal Notice on Publication of the Details of Breakdown of the National and State, 2006 Census, Federal Republic of Nigeria Official Gazette.

27. Odeshi TA, Ana GR, Sridhar MK, Olatunji AO, Abimbola AF. Outdoor air particle-bound trace metals in four selected communities in Ibadan, Nigeria. Environ Geochem Health. 2014;36:755–64. https://doi.org/10.1007/s10653-014-9593-8.

28. Adeniran JA, Yusuf RO, Olajire AA. Exposure to coarse and fine particulate matter at and around major intra-urban traffic intersections of Ilorin metropolis, Nigeria. Atmos Environ. 2017. https://doi.org/10.1016/j.atmosenv.2017.07.041.

29. Ana GREE, Odeshi TA, Sridhar MKC, Ige MO. Outdoor respirable particulate matter and the lung function status of residents of selected communities in Ibadan, Nigeria. Royal Soc Public Health. 2014;134:169–75.

30. Olatunji AS, Kolawole TO, Oloruntola M, Günter G. Evaluation of pollution of soils and particulate matter around metal recycling factories in southwestern Nigeria. J Health Pollution. 2018;8:20–30. https://doi.org/10.5696/2156-9614-8.17.20.

31. Kolawole TO, Olatunji AS, Jimoh MT, Fajemila OT. Heavy metal contamination and ecological risk assessment in soils and sediments of an industrial area in Southwestern Nigeria. J Health Pollut. 2018;8: 180906. https://doi.org/10.5696/2156-9614-8.19.180906.

32. Ana G, Adeniji B, Ige O, Oluwole O. Exposure to emissions from firewood cooking stove and the pulmonary health of women in Olorunda community, Ibadan, Nigeria. Air Qual Atmos Health. 2012;6:465–71. https://doi.org/10.1007/s11869-012-0183-6.

33. Kolawole TO, Ajibade OM, Olajide-Kayode JO, Fomba KW. Level, distribution, ecological, and human health risk assessment of heavy metals in soils and stream sediments around a used-automobile spare part market in Nigeria. Environ Geochem Health. 2022. https://doi.org/10.1007/s10653-022-01283-z.

34. Olayinka AI, Abimbola AF, Isibor RA, Rafiu AR. A geoelectrical-hydrogeochemical investigation of shallow groundwater occurrence in Ibadan, southwestern Nigeria. Environ Geol. 1999;37(1–2):31–9. https://doi.org/10.1007/s002540050357.

35. Okunlola OA, Adeigbe OC, Oluwatoke OO. Compositional and petrogenetic features of schistose rocks of Ibadan Area, Southwestern Nigeria. Earth Sci Res J. 2009;13(2):119–33.

36. Tijani MN, Okunlola OA, Abimbola AF. Lithogenic concentrations of trace metals in soils and saprolites over crystalline basement rocks: a case study from SW Nigeria. J Afr Earth Sci. 2006;46(5):427–38.

37. Etim EU. Air pollution emission inventory along a major traffic route within Ibadan Metropolis, southwestern Nigeria. Afr J Environ Sci Technol. 2016;10:432–8.

38. Iyogun K, Lateef SA, Ana GR. Lung function of grain millers exposed to grain dust and diesel exhaust in two food markets in Ibadan Metropolis, Nigeria. Saf Health Work. 2019;10(2019):47–53.

39. Taiwo AM, Michael JO, Gbadebo AM, Oladoyinbo FO. Pollution and health risk assessment of road dust from Osogbo metropolis, Osun State, Southwestern Nigeria. Hum Ecol Risk Assess. 2019. https://doi.org/10.1080/10807039.2018.1563478.

40. Akinlade GO, Olaniyi HB, Olise FS, Owoade OK, Almeida SM, Almeida-Silva M, Hopke PK. Spatial and temporal variations of the particulate size distribution and chemical composition over Ibadan, Nigeria. Environ Monit Assess. 2015;187:544.

41. Obioh IB, Ezeh GC, Abiye OE, Alpha A, Ojo EO, Ganiyu AK. Atmospheric particulate matter in Nigerian megacities. Toxicol Environ Chem. 2013;95:379–85.

42. Owoade KO, Hopke PK, Olise FS, Ogundele LT, Fawole OG, Olaniyi BH, Jegede OO, Ayoola MA, Bashiru MI. Chemical compositions and source identification of particulate matter (PM2.5 and PM2.5–10) from a scrap iron and steel smelting industry along the Ife-Ibadan highway, Nigeria. Atmos Pollut Res. 2015;6(1):107–19.

43. Pulles T, van der Gon H, Appelman W, Verheul M. Emission factors for heavy metals from diesel and petrol used in European vehicles. Atmos Environ. 2012;61:641–51.

44. Varrica D, Bardelli F, Dongarra G, Tamburro E. Speciation of Sb in airborne particulate matter, vehicle brake linings and brake pad wear residues. Atmos Environ. 2012;64:18–24.

45. Peltier RE, Cromar KR, Ma Y, Fan Z-H, Lippmann M. Spatial and seasonal distribution of aerosol chemical components in New York City: (2) road dust and other tracers of traffic-generated air pollution. J Eposure Sci Environ Epidemiol. 2011;21(5):484–94.

46. Chellam S, Kulkarni P, Fraser MP. Emissions of organic compounds and trace metals in fine particulate matter from motor vehicles: a tunnel study in Houston, Texas. J Air Waste Manag Assoc. 2005;55:60–72.

47. Sternbeck J, Sjödin Å, Andréasson K. Metal emissions from road traffic and the influence of resuspensiond results from two tunnel studies. Atmos Environ. 2002;36(30):4735–44.

48. Sorme L, Bergback B, Lohm U. Goods in the anthroposphere as metal emissions source—a case study of Stockholm, Sweden. Water Air Soil Pollut. 2001;1:213–27.

49. Ondráček J, Schwarz J, Zdímal V, Andelová L, Vodicka P, Bízek V, Tsai C-J, Chen S-C, Smolik J. Contribution of the road traffic to air pollution in the Prague city (busy speedway and suburban crossroads). Atmos Environ. 2011;45(29):5090–100.

50. Afolabi OO, Olatunji AS. Unraveling the source(s) and fate of Pb in urban soils and sediments of Ibadan metropolis using lead isotopes. Environ Geochem Health. 2022. https://doi.org/10.1007/s10653-022-01274-0.

51. Wani AL, Ara A, Usmani JA. Lead toxicity: a review. Interdiscip Toxicol. 2015;8(2):55–64.

52. Fashae OA, Olusola AO, Orekan P. Assessing Heavy Metal Distribution and Contamination of Soil in Ogere Trailer Terminal, Ogun State (Southwestern Nigeria). In: Boughdiri M, Badenas B, Selden P, Jailard E, Bengtoson P, Granier B. Eds. Paleobiodiversity and Tectono-Sedimentary Records in the Mediterranean Tethys and Related Eastern Areas, Advances in Science, Technology & Innovation.

53. Hjortenkrans DST, Bergbäck BG, Häggerud AV. Metal emissions from brake linings and tires: case studies of Stockholm, Sweden 1995/1998 and 2005. Environ Sci Technol. 2007;41(15):5224–30.

54. Canepari S, Perrino C, Olivieri F, Astolfi ML. Characterisation of the traffic sources of PM through size-segregated sampling, sequential leaching and ICP analysis. Atmos Environ. 2008;42(35):8161–75.

55. Manalis N, Grivas G, Protonotarios V, Moutsatsou A, Samara C, Chaloulakou A. Toxic metal content of particulate matter (PM10), within the greater area of Athens. Chemosphere. 2005;60(4):557–66.

56. World Health Organisation (WHO). Guidelines for air quality. Geneva: WHO Global Update; 2006.

57. Ezeh GC, Obioh IB, Asubiojo OI, Abiye OE. PPIXE characterization of PM10 and PM2.5 particulate sizes collected in Ikoyi Lagos, Nigeria. Toxicol Environ Chem. 2012;94(5):884–94.

58. Ezeh GC, Obioh IB, Asubiojo OI, Chiari M, Nava S, Calzolai G, Lucarelli F, Nuviadenu C. The complementarity of PIXE and PIGE techniques: a case study of size segregated airborne particulates collected from a Nigeria city. Appl Radiat Isotopes. 2015;103(2015):82–92.

59. Srimuruganandam B, Nagendra SMS. Characteristics of particulate matter and heterogeneous traffic in the urban area of India. Atmos Environ. 2011;45:3091–102.

60. Zhang X, Yang L, Li Y, Li H, Wang W, Ye B. Impacts of lead/zinc mining and smelting on the environment and human health in China. Environ Monit Assess. 2012;184(4):2261–73.

61. Rudnick RL, Gao S. Composition of the continental crust. In: Rudnick RL, editor. treatise on geochemistry: the crust. Oxford: Elsevier; 2003. p. 683.

62. Jia Z, Li S, Wang L. Assessment of soil heavy metals for eco-environment and human health in a rapidly urbanization area of the upper Yangtze Basin. Sci Rep. 2018;8:3256.

63. Baltas H, Sirin M, Gokbayrak E, Ozcelik AE. A case study on pollution and a human health risk assessment of heavy metals in agricultural soils around Sinop province. Turkey Chemosphere. 2020;2020(241): 125015.

64. Agyeman PC, Ahado SK, John K, Kebonye NM, Vašát R, Borůvka L, Němeček K. Health risk assessment and the application of CF-PMF: A pollution assessment–based receptor model in an urban soil. J Soils Sediments. 2021;21(9):3117–36.

65. Qingjie G, Jun D, Yunchuan X, Qingfei W, Liqiang Y. Calculating pollution indices by heavy metals in ecological geochemistry assessment and a case study in parks of Beijing. J China Univ Geosci. 2008;19:230–41.

66. Saraswat A, Nath T, Omeka ME, Unigwe CO, Anyanwu IE, et al. Irrigation suitability and health risk assessment of groundwater resources in the Firozabad industrial area of north-central India: an integrated indexical statistical and geospatial approach. Front Environ Sci. 2023. https://doi.org/10.3389/fenvs.2023.1116220.

67. Omeka ME, Egbueri JC. Hydrogeochemical assessment and health-related risks due to toxic element ingestion and dermal contact within the Nnewi-Awka urban areas, Nigeria. Environ Geochem Health. 2023;45:2183–211. https://doi.org/10.1007/s10653-022-01332-7.