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Assessment of potentially toxic elements concentration and distribution in soils at automobile mechanic workshops across different geological environments: a review

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ABSTRACT

This study reviewed previous works on potentially toxic elements (PTEs) in soils at automobile mechanic workshops (AMWs) across different geological environments in Nigeria, with the aim to investigate the extent of PTEs pollution, ecological risks and potential human health hazards. The results from previous studies (thirty-six published articles) revealed significant variation in PTEs distribution in the soils around the workshops, with higher levels compared to control soils. The mean concentration of PTEs (mg/kg) including Pb (0.28 to 1689.56), Cr (0.11 to 137.08), Cd (0.008 to 51.47), and Zn (0.56 to 424.4) was used to calculate the pollution indices, human health risk and statistical relationship between PTEs and geological environments. The mean geo-accumulation index (mIgeo: 0.00–4.44), pollution load index (PLI: 0.01–32.57) and potentially ecological risk factor (RI: 0.59–1200.8) revealed that the pollution levels in AMW soils range from unpolluted to extremely polluted across the three geological environments. Human health risk assessment indicated that children and adults are not at risk of developing non-cancer and cancer diseases. Pairwise relationships among PTEs particularly for Cu-Mn and Fe-Mn showed strong correlation across the three environments. Based on the research findings, regular monitoring and strategic urban planning are essential to mitigate pollution and health hazards.

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1. Introduction

Automotive activities at automobile mechanic workshops (AMWs) in developing countries are known to release potentially toxic elements (PTEs) into the surrounding soil and environment (Mohiuddin et al. 2011; Kawo et al. 2018; Ale et al. 2024a). These PTEs include lead (Pb), cadmium (Cd), copper (Cu) and zinc (Zn) which are commonly found in soil around AMW (Sawyer 1998; Dolan et al. 2006) and are associated with motor vehicle performance such as fuel burning, worn-out tires, leakage of oils, corrosion of batteries and radiator metallic parts (Adelekan and Abegunde 2011). The used engine oil from engine combustion processes contains a mixture of chemicals which include complex polycyclic aromatic hydrocarbons (PAHs), PTEs, chlorinated biphenyls and additives resulting from wearing of the engine parts (Wang et al. 2000; Kidman and Boehlecke 2011). The additives from used lubricating oil (e.g. vehicles' engines, gear boxes and brake containers) are discharged intentionally or accidentally into the soil and are leached into the subsurface soil through rainfall and wind (Mohammed et al. 2005). They have become an epidemic environmental issue to be addressed (Odjegba and Sadiq 2002; Akbar et al. 2006; Adewole and Uchegbu 2010).

The dark oil-stained lateritic soil around automobile mechanic workshops (AMWs) can absorb carbon monoxide (CO) from vehicle exhaust systems, further contributing to soil pollution in these areas. The combination of oil pollution and CO emissions can lead to both short-term (irritation of the eyes) and long-term health risks, particularly for respiratory and skin health (Shilpa et al. 2023) with lower health risks in adults compared to children (Issac and Kandasubramanian 2021). Edible plants and grasses that grow in contaminated soil negatively impact the ecosystems by passing PTEs to the food chain (Vicente-Martorell et al. 2009; Musilova et al. 2016; Adetutu et al. 2020). Higher concentrations of PTEs in environmental components (soils, sediments and water) can threaten the existence of fauna and flora in the ecosystem due to their bioaccumulation and toxicity (Ahamad et al. 2024; Razzaq et al. 2024; Zhao et al. 2024; Tiabou et al. 2024). Furthermore,

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agricultural soil affected by PTEs suffers degradation due to loss of essential physicochemical, mineralogical and biological properties, resulting in reduced fertility and diminished productivity (Suh et al. 2025).

Studies conducted in Nigeria have found high concentrations of polycyclic aromatic hydrocarbons (PAHs) sourced from both petrogenic and pyrogenic origins in borehole water samples (Onydinma et al. 2021), PTEs in soil samples (Odoh et al. 2011; Yahaya et al. 2023), and increased levels of toxic metals in topsoil around automobile mechanic workshops (Omofonmwan and Osa-Edoh 2008; Pam et al. 2013a). Other studies conducted in Cameroon, Pakistan and China have found significant contents of PTEs in stream sediments and other sample media with harmful effects on the ecosystem (Gao et al. 2016; Ahamed et al. 2020; Enowakwen et al. 2023; Yiika et al. 2024). PTEs are released into the water ecosystem through waste effluents from anthropogenic activities such as mining, automobile emission, electroplating, power transmission and agricultural activities (Muhammad et al. 2011; Sun et al. 2015; Yiika et al. 2023). The toxicity of PTEs in the environment is influenced by factors such as chemical type and properties, total accumulation, metal binding condition among others (Damian et al. 2008). Several researchers have highlighted the significant importance of pollution indices to include monitoring of soil quality and degradation, estimation of environmental risk and potential sources of PTEs (Caeiro et al. 2005; Adamu and Nganje 2010; Ogunkunle and Fatoba 2013; Ripin et al. 2014; Ale and Ogunribido 2024; Ale et al. 2024b).

The increase in population, transportation industry growth and rapid urbanisation in developing countries like Nigeria have driven an increase in automotive activities at AMWs, resulting in concerns over the release of PTEs and hydrocarbon polymers into the environment. The pollution has shown increasingly serious impacts on the agricultural soil, groundwater and nearby streams,hence, the need to review the activities of automobile mechanic workshops on near surface soil across different geological terrains. This will safeguard our environment so that future generations will not inherit these losses. This review provides a comprehensive study of PTEs in automobile mechanic workshop soils as well as the relationships and trends of pollution in different geological environments. The assessment was based on (i) geo-accumulation index (Igeo), contamination factor (CF) and ecological risk factor (ERF) of PTEs (ii) potential human health risks associated with exposure to PTEs through inhalation, and (iii) statistical relationship between PTEs across geological terrains. The findings provide valuable insights for policymakers and environmentalists in Nigeria and other developing countries to address the anthropogenic sources of PTEs in automobile mechanic workshop soils in order to protect human health and environment.

2. Study area

Nigeria is a country in West Africa on the Gulf of Guinea with an estimated population of over 200 million people (World Bank 2022). Nigeria lies between latitudes 4°N and 14°N and longitudes 3°E and 15°E of the Greenwich meridian (Figure 1). The study area is surrounded by Benin to the west, Niger to the north, Chad to the northeast, Cameroon to the east and north of Gulf of Guinea. Nigeria is covered by three types of vegetation namely forests, savannahs and montane land with a varied landscape. In the south, the tropical rainforest climate has annual rainfall of between 1,500 and 2,000 mm (60 to 80 in) per year, which is limited to between 500 and 1,500 mm (20 and 60 in) per year in the savannah (Akinseye 2010).

Geology of Nigeria is divided into three: precambrian basement complex, younger granite and sedimentary basins. The precambrian basement complex is further divided into igneous and metamorphic rocks that were deformed during the Pan-African orogeny. They occupy about 40% of the land mass of Nigeria and they include migmatite-gneiss, schist belts and older granites (Rahaman 1988; Obaje 2009; Tijani 2023). Sedimentary rock is further divided into two environments: cretaceous and tertiary-recent ages which fill the interior depression created in the crystalline basement to form non-conformity. The sedimentary basins are the Bida basin, Benin basin, Anambra basin, Sokoto basin, Benue trough, Chad basin and Niger-Delta basin (Figure 1). Overall, the geology of Nigeria was divided into five environments based the geology age classification: Precambrian basement, Jurassic younger granite, cretaceous, tertiary volcanic and tertiary-recent sediment environments (Nigerian Geological Survey Agency NGSA 2006) (Figure 1). Sedimentary units are up to 15 km wide and 15–30 m thick along the channels of the rivers Niger and Benue, as well as along the courses of major ephemeral streams and fadamas, especially in the northern parts of Nigeria (Obaje 2009; Tijani 2023). A review of the geotechnical properties of the soils in the southwest and other parts of Nigeria showed that they have poor to good geotechnical ratings (Vincent et al. 2020; Omeiza et al. 2022; Ale et al. 2023).

3. Data analysed from previous works

In an attempt to evaluate the pollution status of soil impacted by automotive activities, such as vehicle repairs and panel beating in different geological settings across Nigeria with a special focus on human health risk assessment. Thirty-six articles published in

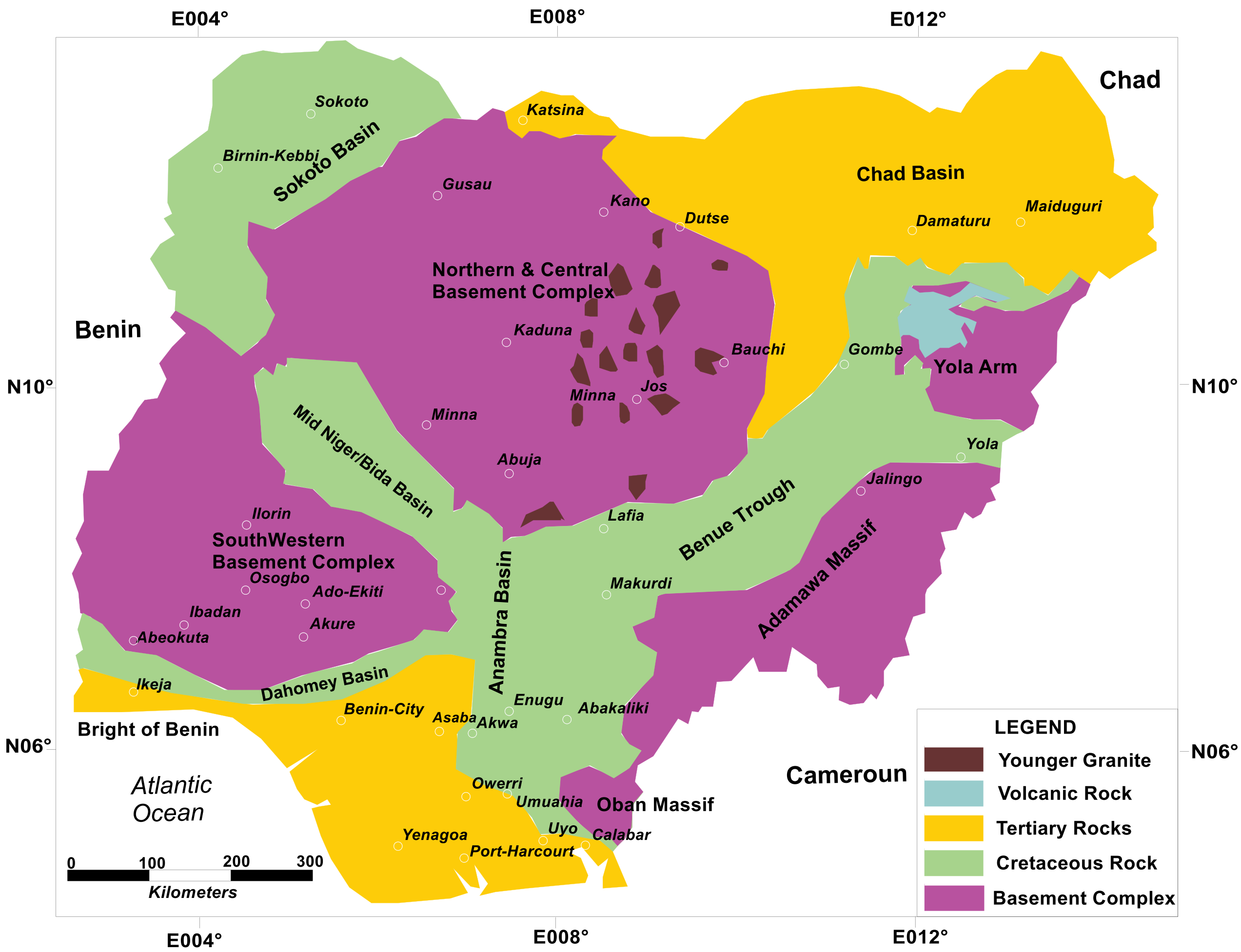

Figure 1. Geological map of Nigeria (Nigerian Geological Survey Agency NGSA 2006).

the literature (secondary data) were reviewed and divided into three groups based on the geological environments of the workshops: basement, cretaceous and tertiary. Eleven articles considered automobile mechanic workshops in basement environments, nine articles covered cretaceous environments and the remaining sixteen articles covered tertiary environments (Figure 2). Articles that did not include tables showing the concentration values of PTEs in soil were not included in the review. The reviewed articles were published between 2008 and 2023, and focused on the concentrations of eight (8) PTEs namely: lead (Pb), chromium (Cr), copper (Cu), cadmium (Cd), iron (Fe), manganese (Mn), nickel (Ni) and zinc (Zn). In the previous studies, the authors carried out experimental research on the near surface soils by determining the concentrations of PTEs in laboratories around the world. The samples collected were analysed using analytical techniques, including X-ray fluorescence (XRF), atomic absorption spectrophotometer (AAS) and inductively coupled plasma mass spectrometry (ICP-MS). All tests were conducted following the guidelines set by the American Public Health Association (APHA 2005). The authors and the publication years of the reviewed articles, the number of automobile mechanic workshop sites, the geological environments of the workshop sites and the mean concentration values of PTEs in the soils are presented in Table 1 and represented in Figure 2. To ascertain the pollution levels in each geological environment, the mean concentration values of PTEs from the reviewed studies were used to calculate several pollution indices, including the contamination factor (CF), ecological risk factor (ERF), geo-accumulation index (I_{geo}) and potential ecological risk index (RI). Additionally, statistical analyses using Pearson's correlation coefficient (PCC) and analysis of variance (ANOVA) were carried out to assess the relationship between the different PTEs and geological environments. PCC and ANOVA were preferred for this study because PCC measures linear relationships between two continuous variables (PTEs) while ANOVA compares the mean of three conditions (different geological environments) in the analysis of PTEs. The data processing and analysis were performed using Microsoft Excel and Surfer software packages.

3.1. Soil sampling in previous studies

Soil samples in the previous studies were collected from various automobile mechanic workshops located

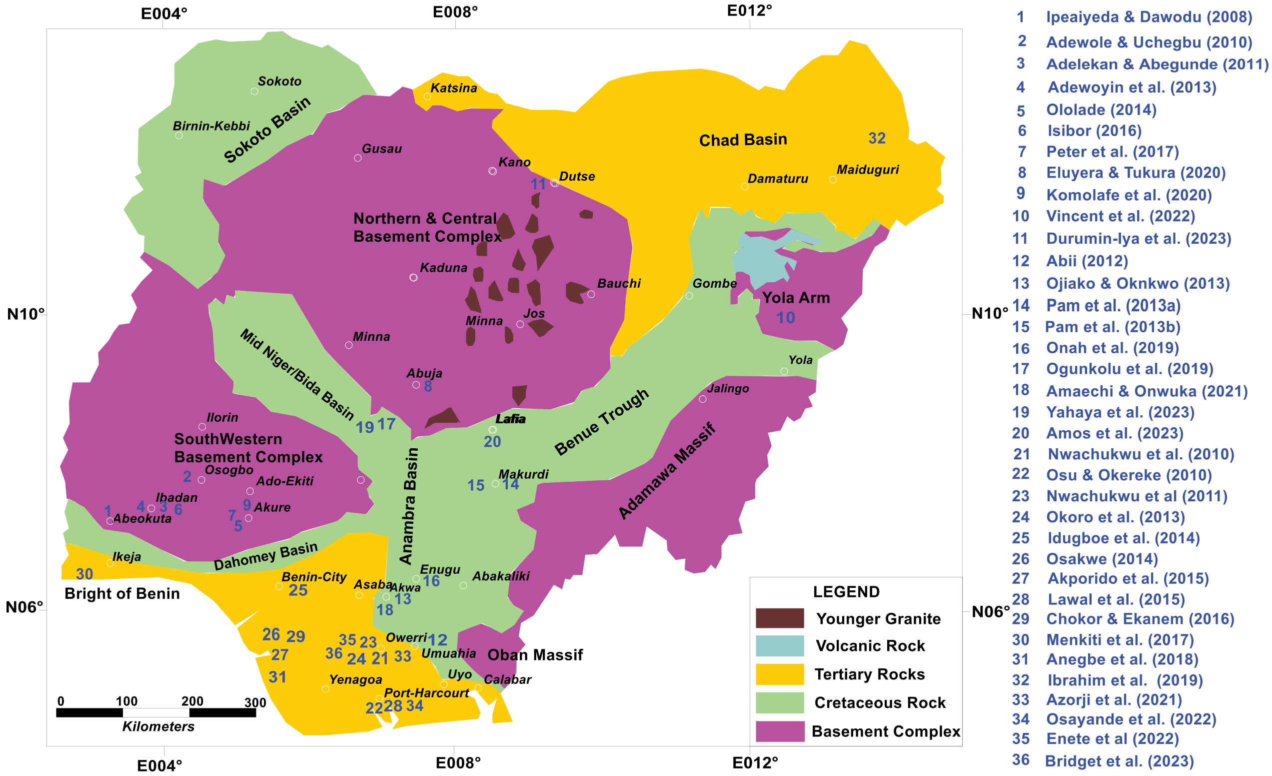

Figure 2. Geological map of Nigeria showing sampling locations for the 36 reviewed articles (geological map digitized after Nigerian Geological Survey Agency NGSA 2006).

across different geological environments in Nigeria and within 150 cm depth of the subsurface, mostly at 15 cm interval spacing. The soil samples were collected at the depth range 0–45 cm (18 articles: 50%), 0–60 cm (13 articles: 36%) and 0->100 cm (5 articles: 14%) respectively (Figure 3). The coordinates of the sample points were recorded with a hand-held geographic positioning system (GPS). As expected, all the PTEs tested in the soil samples from automobile mechanic workshop sites had higher values compared to the control sites (Ololade et al. 2015; Ale et al. 2024a). Thirty-five (35) out of thirty-six (36) articles analysed Pb while thirty-two articles tested for Cd concentration. Copper (Cu) and nickel (Ni) concentrations were analysed in twenty-six articles, while Zn, Cr, Fe and Mn concentrations were tested in twenty-four, twenty-one, eighteen and thirteen articles respectively (Table 1). In addition to the AMW soil samples, authors of nineteen reviewed articles took control samples at distances (200–500 m) away from these workshops (Table 2). The range, mean and standard deviation values of PTEs in control samples are presented in Table 2 and were used as a reference point for calculating multi-pollution indices.

3.2. PTEs in the previous studies

The mean concentration values of PTEs in soils at various automobile mechanic workshops across the different geological environments ranged from 0.28 to 1689.56 mg/kg (Pb), 0.11 to 137.08 mg/kg (Cr), 0.008 to 51.47 mg/kg (Cd), 0.03 to 801.1 mg/kg (Cu), 1.03 to 49,295 mg/kg (Fe), 0.09 to 104.17 mg/kg (Ni), 0.17 to 1157.3 mg/kg (Mn) and 0.56 to 424.4 mg/kg (Zn) respectively (Table 1). Majority of the workshops exhibited low concentrations of PTEs in their soils, most of which were within the recommended limits set by NESREA (2021). Remarkably, twenty-two (91.7%) out of twenty-four workshop soils had Zn concentration levels within the recommended limit of 421 mg/kg set by NESREA (2021) while twenty-one (80.8%) and twenty-five (96.2%) out of twenty-six workshop soils had Cu and Ni concentration levels within the acceptable standards of NESREA. Others are: 76.9% of workshop (10 out of 13) soils had Mn concentrations, 66.7% (12 out of 18) had Fe concentrations, 62.5% (20 out of 32) had Cd concentrations, 79.4% (23 out of 30) had Pb concentrations and 81% (17 out of 21) had Cr concentrations within the acceptable limits set by NESREA.

3.3. Sources of PTEs in auto-mechanic workshops

PTEs such as lead (Pb), manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), cadmium (Cd) and nickel (Ni) have been persistent in the automobile repair workshop soils due to their toxicity. Previous studies have found that the topsoil is a better indicator of metal contamination as it tends to accumulate more contaminants before it reaches the subsurface

Table 1. List of reviewed works, number of obtained samples, environments, average values of potentially toxic elements.

S/No	Author & year	Site	Location	Environment	Pb mg/Kg	Cr mg/Kg	Cu mg/Kg	Fe mg/Kg	Cd mg/Kg	Mn mg/Kg	Ni mg/Kg	Zn mg/Kg
1	Ipeaiyeda and Dawodu (2008)*	5	Iwo, Ogun State	Basement	104.27	4.45	–	–	–	–	8.77	0.61
2	Adewole and Uchegbu (2010)*	3	Ile-ife Osun State	Basement	1.76	–	–	1173.88	–	–	–	19.55
3	Adelekan and Abegunde (2011)*	7	Ibadan-Oyo	Basement	900.26	9.94	50.63	–	0.98	–	7.48	–
4	Adewoyin et al. (2013)*	3	Ibadan-Oyo	Basement	206.3	–	–	199.07	0.51	–	–	–
5	Ololade (2014)	3	Ikare-Ondo State	Basement	15.83	60.83	282.93	208.03	51.47	–	58.07	205.03
6	Isibor, (2016)	12	Oyo town, Oyo	Basement	1233.50	137.08	86.33	–	0.53	1157.33	26.92	306.67
7	Peter et al. (2017)*	2	Akure Ondo State	Basement	147.68	103.88	59.67	2954.2	5.93	–	50.84	–
8	Eluyera and Tukura (2020)*	5	F.C.T. Abuja	Basement	5.59	2.28	1.19	607.69	0.28	17.76	2.08	17.47
9	Komolafe et al. (2020)	3	Owo-Ondo State	Basement	55.24	–	46.91	–	0.34	–	–	146.03
10	Vincent et al. (2022)	6	Yola-Adamawa	Basement	2.02	–	–	2.91	0.17	–	3.67	4.79
11	Durumin-Iya et al. (2023)*	10	Dutse-Jigawa	Basement	0.73	1.07	0.39	1.03	0.90	1.21	2.15	0.28
12	Abii (2012)	4	Umuahia Abia	Cretaceous	96.75	24.6	–	–	22.26	–	–	–
13	Ojiako and Okonkwo (2013)	5	Onitsha Anambra	Cretaceous	10.41	0.63	1.43	–	0.044	–	0.56	–
14	Pam et al. (2013a)	1	Makurdi Benue	Cretaceous	123.0	–	24.6	–	0.60	92.0	8.44	42.7
15	Pam et al. (2013b)	2	Gboko & Markurdi	Cretaceous	474,350	–	801.1	–	11.6	165.5	29.3	424.4
16	Onah et al. (2019)	3	Enugu- Enugu	Cretaceous	3.01	1.40	–	–	0.26	–	0.69	–
17	Ogunkolu et al. (2019)*	1	Anyigba, Kogi State	Cretaceous	1.32	0.21	3.80	6.31	0.30	1.77	0.35	4.08
18	Amaechi and Onwuka (2021)	4	Awka, Anambra	Cretaceous	23.94	129.61	84.5	1230.05	2.04	7.54	6.37	18.42
19	Yahaya et al. (2023)	3	Lokojo-Kogi	Cretaceous	–	–	–	35.38	0.26	–	0.88	19.27
20	Amos et al. (2023)*	4	Lafia Nasarawa	Cretaceous	0.62	–	1.66	1.61	1.04	–	0.07	10.41
21	Nwachukwu et al. (2010)*	3	Owerri Imo State	Tertiary	586.33	30	643.67	60.44	33.17	744.67	19.83	–
22	Osu and Okereke (2010)	6	Port Harcourt, River	Tertiary	46.34	–	–	–	14.32	–	0.38	–
23	Nwachukwu et al. (2011)	2	Owerri Imo State	Tertiary	1162	–	385	49295	20	864	40	824
24	Okoro et al. (2013)*	2	Owerri Imo State	Tertiary	1689.56	14.39	391.22	–	12.91	–	–	–
25	Idugboe et al. (2014)*	3	Benin Edo State	Tertiary	0.93	0.49	1.15	291.27	0.062	14.52	0.181	11.71
26	Osakwe (2014)*	4	Abraka Delta	Tertiary	–	–	0.66	40.05	–	34.39	–	16.74
27	Akporido et al. (2015)*	1	Effurun Delta	Tertiary	67.75	–	10.2	–	34.35	–	104.17	–
28	Lawal et al. (2015)	1	Obio/Akpor River	Tertiary	91.03	–	–	–	5.63	–	–	–
29	Chokor and Ekanem (2016)	6	Sapele, Delta	Tertiary	24.56	24.19	68.73	–	5.39	–	–	–
30	Menkiti et al. (2017)*	13	Lagos State	Tertiary	19.5	15.89	31.93	–	9.45	–	8.29	153.12
31	Anegbe et al. (2018)*	5	Oghara, Delta	Tertiary	4.77	–	35.15	622.43	1.37	–	–	41.24
32	Ibrahim et al. (2019)	10	Biu-Borno State	Tertiary	91.28	126.91	38.34	–	0.98	56.14	37.06	53.94
33	Azorji et al. (2021)*	3	Imo State	Tertiary	1.35	0.27	12.69	66.33	0.49	–	0.93	156.13
34	Osayande et al. (2022)*	1	Port Harcourt, River	Tertiary	32.79	5.35	–	–	2.87	–	–	74.17
35	Enete et al. (2022)	6	Owerri, Imo State	Tertiary	0.28	0.11	0.03	16	0.008	0.17	0.09	0.56
36	Bridget et al. (2023)*	2	Nekede & Orji Owerri Imo State	Tertiary	15.78	–	10.24	–	–	–	2.11	40.83

Pb, lead; Cr, chromium; Cu, Copper; Fe, iron; Cd, Cadmium; Mn, manganese; Ni, nickel; Zn, zinc; Author name*, authors who took control samples.

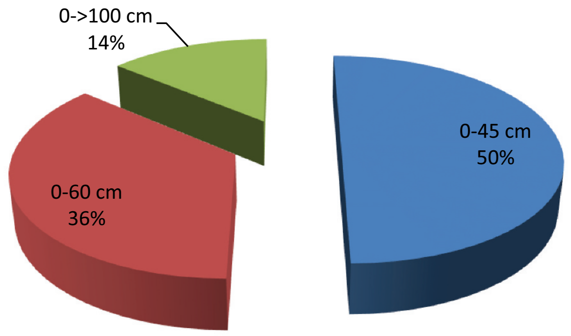

Figure 3. Sampling depths of previous studies on the impacts of automobile mechanic workshops on soil.

(Nyangababo and Hamya 1986; Ale et al. 2024b). Adewole and Uchegbu (2010) and Ogunkolu et al. (2019) attributed the high concentration of iron (Fe) observed in the soil around automobile mechanic workshop sites to both natural (laterisation) and anthropogenic sources. Automotive activities in automobile workshops such as the use of spent oil, welding of metallic parts, body damage repair and crankshaft wear also contribute to the increased Fe content in the soil (Osakwe 2014; Ogunkolu et al. 2019). The high concentration of lead (Pb) observed in the soil around automobile mechanic workshops was attributed to the quantity of waste oil, vehicle fumes and the improper disposal of expired motor batteries (Pam et al. 2013b; Ojiako and Okonkwo 2013; Ogunkolu et al. 2019). According to Osakwe (2014), the manganese (Mn) level in the soil of automobile mechanic workshops was caused by abandoned metal rails, expired batteries, machinery components, welding waste, and vehicle spray paint. On the other hand, copper (Cu) in soil was sourced from corroding vehicle trash, copper pipe electrodes, and scattered copper wires (Nwachukwu et al. 2011; Durumin-Iya et al. 2023). The activities and materials used by panel beaters and spray painters in these workshops released zinc (Zn) into the soil (Onder et al. 2003; Abechi et al. 2010). Other sources of Zn include brake lining wear and vehicle exhaust (Pam et al. 2013b; Osakwe 2014). Researchers (Dabkowska-Naskret 2004; Udousoro et al. 2010; Pam et al. 2013b; Ogunkolu et al. 2019, Eluyera and Tukura 2020; Durumin-Iya et al. 2023) identified polyvinyl chloride (PVC) plastics, motor engine oil, glass, vehicle wheels, nickel-Cd batteries, paint pigments, welding electrodes and metal alloys as the most likely sources of cadmium (Cd) and nickel (Ni) in automobile mechanic workshop soils. There was no consistent pattern in PTEs distribution across the three geological environments. Less expensive waste materials such as agricultural and/less agricultural by-products, industrial wastes, construction and demolition wastes (sugarcane straw, sawdust ash, fly ash, silica fume, hydrated lime, fibre-reinforced, waste-tire-derived aggregate and different forms of rubber wastes) should be incorporated into the soil in the right proportion so as to explore its soil-binding potential and to immobilised the contaminants in the soil (Ogunribido 2012; Ojuri et al. 2017; Soltani et al. 2017; Şahin et al. 2020; Akbarimehr and Fakharian 2021; Bascetin et al. 2022; Eker and Bascetin 2022; Ogunribido et al. 2022; Ale 2022, 2023a, 2023b).

3.4. Assessment of pollution indices

3.4.1. Contamination factor (CF)

The contamination factor (CF) was used to estimate the level of pollution in soils. CF was classified as: CF < 1, low contamination; 1 ≤ CF ≤ 3, moderate contamination; 3 ≤ CF ≤ 6, very high contamination (Seshan et al. 2010). The CF calculation was achieved using eq. 1.

$$CF = \frac{C_s}{C_b} \tag{1}$$

Where: C_s, elemental concentrations in the soil samples; C_b, background values of the element (control sample).

3.4.2. Ecological risk factor (ERF)

ERF was used to assess the negative consequences that pollutants have on people and the environment. ERF was classified as: ERF > 320, very high ecological risk; 160 < ERF < 320, high ecological risk; 80 < ERF < 160, considerable ecological risk; 40 < ERF < 80, moderate ecological risk and ERF < 40, low ecological risk (Suresh et al. 2012; Ale et al. 2024c 2024a). The ERF for a single metal was calculated using eq.2..

$$ERF = Tri \times CF \tag{2}$$

Where Tri, toxic-response factor for a given element; CF, contamination factor of an element

Tri: 30 for Cd, 5 for Cu, 5 for Pb, 5 for Ni, 2 for Cr, 1 for Zn, 1 for Mn and 1 for Fe (Weihua et al., 2010).

3.4.3. Geo-accumulation index (I_{geo})

The geo-accumulation index (I_{geo}) was used to determine the status of soil contamination level. I_{geo} was classified as: I_{geo} >5, extremely polluted; 4< I_{geo} ≤5,

Table 2. Control values for potentially toxic elements in the reviewed works.

	Pb mg/Kg	Cr mg/Kg	Cu mg/Kg	Fe mg/Kg	Cd mg/Kg	Mn mg/Kg	Ni mg/Kg	Zn mg/Kg
Range	0.01–292.3	0.004–22	0.21–223.3	0.32–311.1	0.00–17.5	0.16–198.7	0.00–15.7	0.11–146.6
Mean	31.19	3.78	21.52	101.87	1.95	36.72	2.57	25.82
Standard Deviation	81.7	6.9	58.5	129.9	4.6	79.5	5.0	44.0

Table 3. Inhalation parameters used for the health risk estimations via inhalation.

Parameter	Unit	Child	Adult	References
Body Weight (BW)	Kg	15	70	Heidari et al. (2021)
Expusure Frequency (EF)	Days/Years	350	350	Xia et al. (2020)
Exposure Duration (ED)	Year	6	24	Heidari et al. (2021)
Soil Inhalation Rate (IRIhn)	Mg/day	7.5	15	Rehman et al. (2018)
Average Time (AT) for Carcinogenic	Days/Years	365 × 70	365 × 70	Rehman et al. (2018)
Average Time (AT) for non-carcinogenic	Days/Years	365 × ED	365 × ED	Rehman et al. (2018)
Particular Emission Factor (PEF)		1.36×10^9	1.36×10^9	Wang et al. (2022)

Calculating the non-carcinogenic risk involves determining how PTEs from soil affect non-carcinogenic effects in humans. Non-carcinogenic risk was calculated using Equations (7)-(8).

highly to extremely polluted; 3< I_{geo} ≤4, highly polluted; 2< I_{geo} ≤3, moderately to highly polluted; 1< I_{geo} ≤2, moderately polluted; 0< I_{geo} ≤1, unpolluted to moderately polluted; and I_{geo} ≤0, unpolluted (Nowrouzi and Pourkhabbaz 2014; Gupta et al. 2014; Ogundele et al. 2017). I_{geo} was calculated using eq. 3.

$$I_{geo} = Log_2\left(\frac{C_n}{1.5B_n}\right) \quad (3)$$

Where: C_n, concentration of the element in the soil samples; B_n, geochemical background concentrations (control); 1.5, lithospheric background effect/correlation matrix factor.

3.4.4. Pollution load index (PLI)

The pollution load index (PLI) was used to determine the samples' overall pollution status. The PLI was classified as: PLI ≤ 1, unpolluted; 1 ≤3, moderately polluted; 3<PLI ≤5, highly polluted; and PLI > 5, very highly polluted (2734” class=“cross-reference”>Atiemo et al. 2012; Likuku et al. 2013). PLI was computed using eq. 4.

$$PLI = (CF1 \times CF2 \times CF3 \times .... \times CFn)1/n \quad (4)$$

Where: CF, contamination factor of metal, n, specific metal contamination factor.

3.4.5. Potential ecological risk index (RI)

The potential ecological risk index (RI) was used to evaluate soil-related environmental concerns (Tisha et al. 2020). The RI was classified as: RI < 150, low risk; 150≤ RI < 300, moderate risk; 300≤ RI < 600, considerable risk; and RI ≥ 600, high risk (Kang et al. 2020). RI was calculated using Eq. 5:

$$\mathrm{RI} = \sum_{i=1}^{n} \mathrm{ERF} \quad (5)$$

Where: ERF, ecological risk factor.

3.4.6. Human health risk assessment (HHRA)

The HHRA was used to estimate the quantity of PTEs that people (most especially the workers) breathe in contaminated soil at automobile mechanic workshops (El FadEl Fadili et al. 2022). The average time (AT) for non-carcinogenic risk is calculated by multiplying the value of exposure duration (ED) by the number of days in a year, or 365, whereas the AT for carcinogenic risk is calculated by multiplying the average life expectancy (LT) of 70 by the number of days in a year. Average daily dose (ADD/CDI) was calculated using Eq. 6.

$$ADD_{inh} = \frac{\mathrm{C} \times \mathrm{InhR} \times \mathrm{ED} \times \mathrm{EF}}{\mathrm{BD} \times \mathrm{PEF} \times \mathrm{AT}} \quad (6)$$

Where: C, concentration of heavy metal in soil; InhR, inhalation rate; EF, exposure frequency; ED, exposure duration; PEF, particular emission factor; BW, body weight; AT, average time (shown in the supplementary File, Table 3).

$$HQ_{inh} = \frac{\mathrm{ADD}_{inh}}{\mathrm{RfD}_{inh}} \quad (7)$$

$$\mathrm{HI}_{inh} = \sum_{i=1}^{n} \mathrm{HQ}_{inh} \quad (8)$$

Where: HQ_{inh}, hazard quotient; ADD_{inh}, average daily dose; RfD_{inh}, reference dose for each of the heavy metals; n, number of heavy metals; and HI_{inh}, hazard index. If HI or HQ value is greater than one (HI ˃ 1), it implies Hunan's health is at risk while HI value less than one (HI ˂ 1) implies that the level of threat to human life is insignificant (Adewumi 2022).

The potential carcinogenic effects of PTEs on human health are measured by two parameters: carcinogenic risk (CR) and total carcinogenic risk (TCR). CR and TCR were calculated using Equations (9)-(10)

$$\mathrm{CR}_{inh} = \mathrm{CDI}_{inh} \times \mathrm{CSF}_{inh} \quad (9)$$

$$\mathrm{TCR}_{inh} = \sum_{i=1}^{n} \mathrm{CR}_{inh} \quad (10)$$

Where: n, number of heavy metals; CSF, cancer slope factor; TCR_{inh}, total carcinogenic risk; and CR_{inh} is the carcinogenic risk (shown in the supplementary File, Table 4). A TCR or CR value less than 10^{-6} implies that people are not at risk of developing carcinogenic

Table 4. Reference dose and cancer slope factor for PTEs via inhalation.

PTE	*RfD* ($mg.kg^{-1}.day^{-1}$)	CSF ($kg.day.mg^{-1}$)	References
Cr	2.86×10^{-5}	42	Heidari et al. (2021)
Ni	2.06×10^{-2}	0.84	Xia et al. (2020)
Pb	3.52×10^{-3}	4.2×10^{-2}	Heidari et al. (2021)
Mn	1.43×10^{-5}	–	Heidari et al. (2021)
Fe	2.2×10^{-4}	–	Heidari et al. (2021)
Cu	4.02×10^{-2}	–	Heidari et al. (2021)
Cd	1×10^{-5}	–	Heidari et al. (2021)
Zn	3×10^{-1}	–	Heidari et al. (2021)

diseases; a value between 1×10^{-6} and 1×10^{-4} means that people are at a marginal or tolerable risk; and if the value is greater than 10^{-4}, people are at risk of getting infested, which is therefore unacceptable (Zhou et al. 2022).

4. Discussion

4.1. Multi-pollution indices

The calculated I_{geo} values and mean I_{geo} values are presented in Table 5 and represented as histogram (Figure 4). The mean I_{geo} values revealed a range of pollution levels, ranging from unpolluted to moderately-to-highly polluted for basement and cretaceous environments and from unpolluted to highly-to-extremely polluted in tertiary environments. Overall, mean I_{geo} values showed that there are 10 unpolluted sites, 5 moderately polluted sites, 12 unpolluted-to-moderately polluted sites, 7 moderately-to-highly polluted sites, 1 highly polluted site and 1 highly-to-extremely polluted site of AMW (Table 5 and Figure 4). The degree of I_{geo} contamination of PTEs (mean) values in soils around AMW in the basement, cretaceous, and tertiary environments follows the decreasing order of Cr (1.86) > Ni (1.57) > Mn (1.46) > Fe (1.43) > Pb (1.29) > Cu (0.95) > Zn (0.91) > Cd (0.57); Cr (1.33) > Cu (1.00) > Fe (0.75) > Pb (0.72) > Zn (0.60) > Ni (0.59) > Mn (0.58) > Cd (0.55); and Fe (1.61) > Ni (1.49) > Cr (1.31) > Mn (1.29) > Cd (1.27) > Pb (1.06) > Cu (1.0) > Zn (0.80) respectively (Figure 4). The concentration of I_{geo} values for Fe and Cd was high in some workshops in tertiary environments and the concentration values for Ni, Cr, and Pb were high in basement environments. This implies that soil samples from AMW in cretaceous environments are the least contaminated, while soil samples from AMW in basement environments are the most contaminated.

Similarly, the degree of ERF contamination (mean) values of AMW soils in basement, cretaceous, and tertiary environments follow the decreasing order of Cd (104.46) > Pb (38.95) > Ni (38.81) > Cr (23.98) > Cu (17.52) > Mn (10.68) > Fe (7.22) > Zn (3.4); Cd (65.66) > Cu (35.51) > Cr (16.56) > Pb (13.1) > Ni (11.35) > Zn (3.37) > Fe (3.13) > Mn (1.82); and Cd (166.29) > Fe (70.67) > Ni (45.86) > Pb (40.98) > Cu (31.30) > Cr (12.29) > Mn (7.78) > Zn (5.35) respectively (Table 6 and Figure 5). The results indicated significant spatial variability in PTE concentration with higher levels of Cd, Pb, Zn, Ni, Fe and Cu recorded in tertiary environments while Cr and Mn were observed in basement environments. Notably, cretaceous soils were the least contaminated, while tertiary soils were the most contaminated. Based on Potential Ecological Risk Factor (RI), the study area's

Table 5. Geo-accumulation index values and status of the PTEs (mg/Kg) in AMW soils in Nigeria.

Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn	Mean Igeo	I_{geo} Class & Classification
Ipeaiyeda and Dawodu (2008)	Basement	1.16	0.00	–	–	–	–	1.19	0.00	0.59	Unpolluted to moderately poll.
Adewole and Uchegbu (2010)	Basement	0.00	–	–	2.94		–	–	0.00	0.98	Unpolluted to moderately poll.
Adelekan and Abegunde (2011)	Basement	4.27	0.81	0.65		0.00	–	0.96	–	1.34	Moderately polluted
Adewoyin et al. (2013)	Basement	2.14	–	–	0.38	0.00	–	–	–	0.84	Unpolluted to moderately poll.
Ololade (2014)	Basement	0.00	3.42	3.13	0.45	4.14	–	3.91	2.40	2.49	Moderately to highly polluted
Isibor (2016)	Basement	4.72	4.60	1.42	–	0.00	4.39	2.80	2.99	2.99	Moderately to highly polluted
Peter et al. (2017)	Basement	1.66	4.20	0.89	4.27	1.02	–	3.72		2.63	Moderately to highly polluted
Eluyera and Tukura (2020)	Basement	0.00	0.00	0.00	1.99	0.00	0.00	0.00	0.00	0.25	Unpolluted to moderately poll.
Komolafe et al. (2020)	Basement	0.24	–	0.54	–	0.00	–	–	1.92	0.68	Unpolluted to moderately poll.
Vincent et al. (2022)	Basement	0.00	–	–	0.00	0.00	–	0.00	0.00	0.00	Unpolluted
Durumin-Iya et al. (2023)	Basement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Unpolluted
Abii (2012)	Cretaceous	1.05	2.12	–	–	2.93	–	–	–	2.03	Moderately to highly polluted
Ojiako and Okonkwo (2013)	Cretaceous	0.00	0.00	0.00	–	0.00	–	0.00	–	0.00	Unpolluted
Pam et al. (2013a)	Cretaceous	1.39	–	0.00	–	0.00	0.74	1.13	0.15	0.57	Unpolluted to moderately poll.
Pam et al. (2013b)	Cretaceous	3.34	–	4.63	–	1.99	1.59	2.93	3.46	2.99	Moderately to highly polluted
Onah et al. (2019)	Cretaceous	0.00	0.00	–	–	0.00	–	0.00	–	0.00	Unpolluted
Ogunkolu et al. (2019)	Cretaceous	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Unpolluted
Amaechi and Onwuka (2021)	Cretaceous	0.00	4.51	1.39	3.01	0.00	0.00	0.72	0.00	1.20	Moderately polluted
Yahaya et al. (2023)	Cretaceous	–	–	–	0.00	0.00	–	0.00	0.00	0.00	Unpolluted
Amos et al. (2023)	Cretaceous	0.00	–	0.00	0.00	0.00	–	0.00	0.00	0.00	Unpolluted
Nwachukwu et al. (2010)	Tertiary	3.65	2.40	4.32	0.00	3.50	3.76	2.36	–	2.86	Moderately to highly polluted
Osu and Okereke (2010)	Tertiary	0.00	–	–	–	2.29	–	0.00	–	0.76	Unpolluted to moderately poll.
Nwachukwu et al. (2011)	Tertiary	4.63	–	3.58	8.33	2.77	3.97	3.38	4.42	4.44	Highly to extremely polluted
Okoro et al. (2013)	Tertiary	5.17	1.34	3.60		2.14	–	–	–	3.06	Highly polluted
Idugboe et al. (2014)	Tertiary	0.00	0.00	0.00	0.93	0.00	0.00	0.00	0.00	0.12	Unpolluted to moderately poll.
Osakwe (2014)	Tertiary	–	–	0.00	0.00	–	0.00	–	0.00	0.00	Unpolluted
Akporido et al. (2015)	Tertiary	0.53	–	0.00	–	3.55	–	4.76	–	2.21	Moderately to highly polluted
Lawal et al. (2015)	Tertiary	0.96	–	–	–	0.94	–	–	–	0.95	Unpolluted to moderately poll.
Chokor and Ekanem (2016)	Tertiary	0.00	2.09	1.09	–	0.88	–	–	–	1.02	Moderately polluted
Menkiti et al. (2017)	Tertiary	0.00	1.49	0.00	–	1.69	–	1.10	1.99	1.05	Moderately polluted
Anegbe et al. (2018)	Tertiary	0.00	–	0.12	2.03	0.00	–	–	0.10	0.45	Unpolluted to moderately poll.
Ibrahim et al. (2019)	Tertiary	0.96	4.48	0.25	–	0.00	0.03	3.27	0.49	1.35	Moderately polluted
Azorji et al. (2021)	Tertiary	0.00	0.00	0.00	0.00	0.00	–	0.00	0.00	0.00	Unpolluted
Osayande et al. (2022)	Tertiary	0.00	0.00	–	–	0.00	–	–	0.95	0.24	Unpolluted to moderately poll.
Enete et al. (2022)	Tertiary	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Unpolluted
Bridget et al. (2023)	Tertiary	0.00	–	0.00	–	–	–	0.00	0.08	0.02	Unpolluted to moderately poll.

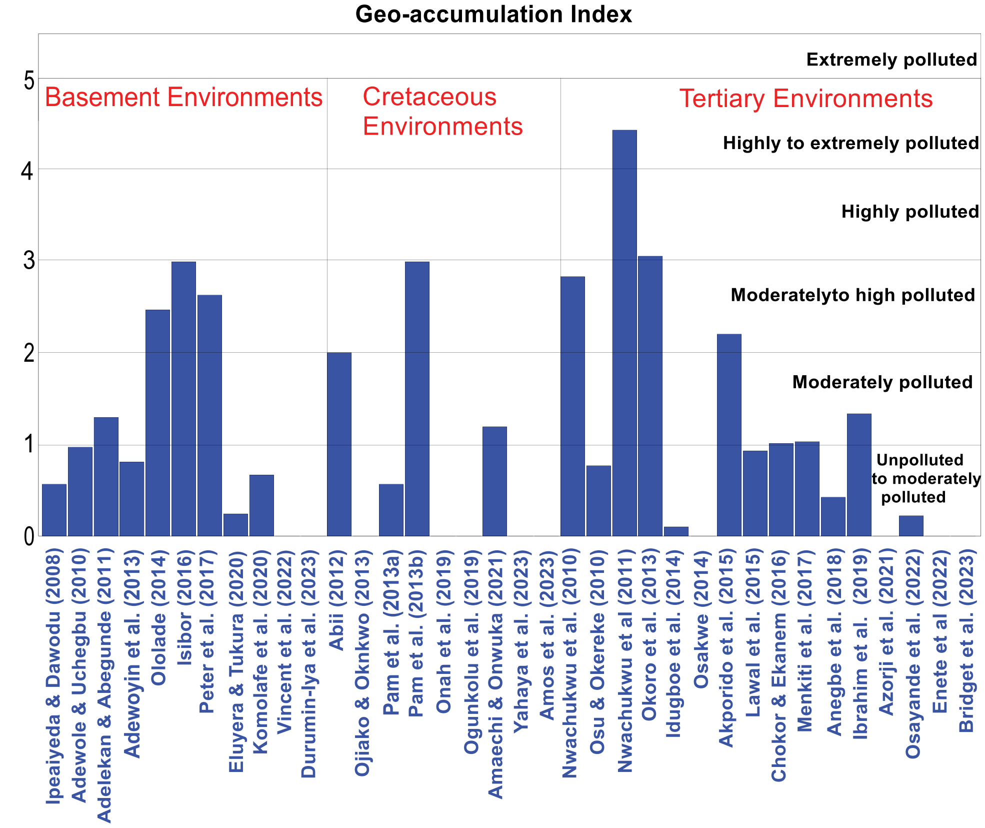

Figure 4. Geo-accumulation index (mean) of PTEs concentrations in AMW soils across three geological environments.

Table 6. Ecological risk factor values (ERF), potentially ecological risk factor (RI) and status of the PTEs (mg/Kg) in AMW soils in Nigeria.

		Ecological Risk Factor (ERF)									
Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn	RI	RI classification
Ipeaiyeda and Dawodu (2008)	Basement	16.72	1.18	–	–	–	–	17.06	0.02	34.98	Low risk
Adewole and Uchegbu (2010)	Basement	0.28	–	–	11.52	–	–	–	0.76	12.57	Low risk
Adelekan and Abegunde (2011)	Basement	144.3	5.26	11.76	–	15.08	–	14.55	–	190.97	Moderate risk
Adewoyin et al. (2013)	Basement	33.07	–	–	1.95	7.85	–	–	–	42.87	Low risk
Ololade (2014)	Basement	2.54	32.16	65.74	2.04	791.8	–	113.0	7.91	1015.2	Low risk
Isibor (2016)	Basement	197.7	72.53	20.06	–	8.15	31.52	52.37	11.94	394.31	Considerable risk
Peter et al. (2017)	Basement	23.67	54.96	13.86	29.00	91.23	–	98.1	–	311.64	Considerable risk
Eluyera and Tukura (2020)	Basement	0.90	1.21	0.28	5.97	4.31	0.48	4.05	0.68	17.86	Low risk
Komolafe et al. (2020)	Basement	8.86	–	10.90	–	5.23	–	–	5.69	30.67	Low risk
Vincent et al. (2022)	Basement	0.32	–	–	0.03	2.62	–	7.14	0.19	10.29	Low risk
Durumin-Iya et al. (2023)	Basement	0.12	0.57	0.09	0.01	13.85	0.03	4.18	0.01	18.86	Low risk
Abii (2012)	Cretaceous	15.51	13.02	–	–	342.5	–	–	–	370.99	Considerable risk
Ojiako and Okonkwo (2013)	Cretaceous	1.67	0.33	0.33	–	0.68	–	1.09	–	4.10	Low risk
Pam et al. (2013a)	Cretaceous	19.72	–	5.72	–	9.23	2.51	16.42	1.66	55.25	Low risk
Pam et al. (2013b)	Cretaceous	76.04	–	186.1	–	178.5	4.50	57.00	16.53	518.67	Considerable risk
Onah et al. (2019)	Cretaceous	0.48	0.74	–	–	4.00	–	1.34	–	6.57	Low risk
Ogunkolu et al. (2019)	Cretaceous	0.21	0.11	0.88	0.06	4.62	0.05	0.68	0.16	6.77	Low risk
Amaechi and Onwuka (2021)	Cretaceous	3.83	68.58	19.63	12.07	31.38	0.21	12.39	0.72	148.82	Low risk
Yahaya et al. (2023)	Cretaceous	0.34	–	–	0.35	4.00	–	1.71	0.75	6.81	Low risk
Amos et al. (2023)	Cretaceous	0.10	–	0.39	0.02	16.00	–	0.14	0.41	17.04	Low risk
Nwachukwu et al. (2010)	Tertiary	93.99	15.87	149.6	0.59	510.3	20.28	38.58	–	829.18	High risk
Osu and Okereke (2010)	Tertiary	7.43	–	–	–	220.3	–	0.74	–	228.48	Moderate risk
Nwachukwu et al. (2011)	Tertiary	186.3	–	89.45	483.9	307.7	23.53	77.82	32.09	1200.8	High risk
Okoro et al. (2013)	Tertiary	270.8	3.08	90.90	–	198.6	–	–	–	564.17	Considerable risk
Idugboe et al. (2014)	Tertiary	0.15	0.26	0.27	2.86	0.95	0.40	0.35	0.46	5.69	Low risk
Osakwe (2014)	Tertiary		–	0.15	0.39	–	0.94	–	0.65	2.13	Low risk
Akporido et al. (2015)	Tertiary	10.86	–	2.40	–	528.5	–	202.7	–	744.36	High risk
Lawal et al. (2015)	Tertiary	14.59	–	–	–	86.62	–	–	–	101.21	Low risk
Chokor and Ekanem (2016)	Tertiary	3.94	12.80	15.97	–	82.92	–	–	–	115.63	Low risk
Menkiti et al. (2017)	Tertiary	3.13	8.41	7.42	–	145.4	–	16.13	5.96	186.43	Moderate risk
Anegbe et al. (2018)	Tertiary	0.76	–	8.17	6.11	21.08	–	–	1.61	37.72	Low risk
Ibrahim et al. (2019)	Tertiary	14.63	67.15	8.91	–	15.08	1.53	72.10	2.10	181.50	Moderate risk
Azorji et al. (2021)	Tertiary	0.22	0.14	–	0.65	–	–	–	6.08	19.39	Low risk
Osayande et al. (2022)	Tertiary	5.26	2.83	–	–	44.15	–	–	2.89	55.13	Low risk
Enete et al. (2022)	Tertiary	0.05	0.06	0.01	0.16	0.12	0.00	0.18	0.02	0.59	Low risk
Bridget et al. (2023)	Tertiary	2.53	–	2.38		–		4.11	1.59	10.60	Low risk

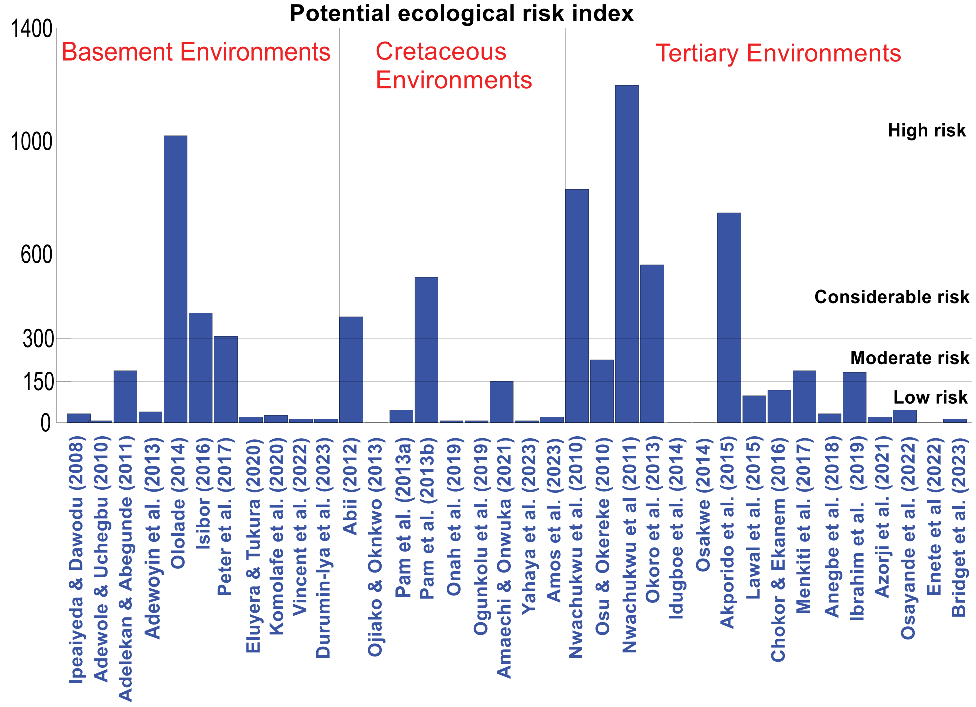

Figure 5. Potentially ecological risk factor (RI) of PTEs concentrations in AMW soils across three geological environments.

soils were divided into four groups: 24 low-risk sites, 5 considered-risk sites, 4 moderate-risk sites and 3 high-risk sites (Table 6 and Figure 5). In cretaceous environments, the soils showed low to considerable risk, while soils in basement and tertiary environments exhibited low to moderate risk and low to high risk respectively.

The mean CF values are presented in Table 7. CF values follow the decreasing order of Cr (12.16) > Mn (10.68) > Pb (7.79) > Ni (7.78) > Fe (7.21) > Cu (3.51) > Cd (3.48) > Zn (3.4) for basement environments; Cr (8.28) > Cu (7.10) > Zn (3.71) > Fe (3.13) > Pb (2.94) > Ni (2.27) > Cd (2.19) > Mn (1.82) for the cretaceous environments; and Fe (70.67) > Ni (8.29) > Pb (8.20) > Mn (7.78) > Cr (6.40) > Cu (5.82) > Zn (5.35) > Cd (5.16) for tertiary environments respectively (Table 7). Cr and Mn contributed significantly to the pollution levels in the basement environments while Pb, Ni, Fe, Cd, Zn and Cu were identified as major pollutants in tertiary environments exhibiting high CF values. The observed pattern aligns with findings of the researches carried out (Okoro et al. 2013; Ololade 2014; Isibor 2016; Peter et al. 2017). The PLI values revealed that 15 sites were unpolluted, 9 sites were moderately polluted, 2 sites were highly polluted and 10 sites were very highly polluted within the different geological environments (Table 7 and Figure 6). Each of the three geological environments has unpolluted to very highly polluted ratings. The pollution levels reported by various indices in this review are similar to the results of previous studies on automobile mechanic soils in Ghana as reported by Sadick et al. (2015), Gyimah et al. (2022) and Konadu et al. (2023a).

4.2. Risk implications of potentially toxic elements (PTEs) in soils

The variability in the level of risk revealed by pollution indices (Igeo, CF, EF and RI) across the different geological environments highlights the complex interplay between geology and PTE contamination (Tables 5–7). Soil contamination may render agricultural soil infertile, leading to loss of valuable farmland. Additionally, consumption of vegetables grown in soil contaminated with PTEs can lead to serious health hazards. The concentrations of PTEs in the soils around AMWs pose serious threat to groundwater resources in shallow aquifers, especially in basement environments due to shallow overburden coverage (Raji and Abdulkadir 2020; Onydinma et al. 2021; Akingboye et al. 2023; Ale et al. 2025). Despite the low to moderate pollution levels observed in some workshops, it is recommended that groundwater be thoroughly remediated before being used for agriculture and domestic purposes.

4.3. Statistical analyses

The Pearson's correlation coefficient (PCC) results were presented using modified Rollinson (1993) and Ale et al. (2022) classifications. Their merged classifications were reclassified into three: $0 \leq PCC < +(-)0.5$, weak correlation; $+(-)0.5 \leq PCC < +(-)0.7$, moderate correlation; and $+(-)0.7 \leq PCC \leq +(-)1$ strong correlation. Strong pairwise relationships of Cr-Fe (0.7086), Fe-Mn (0.9998), Cd-Ni (0.7422) were observed in basement environments while strong pairwise relationships of Cu-Ni (0.9396), Fe-Mn (0.8416), Fe-Zn

Table 7. Contamination factor and pollution load index (PLI) values and status of the PTEs (mg/Kg) in AMW soils in Nigeria.

Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn	PLI	PLI Class & Degree
Ipeaiyeda and Dawodu, ((2008)	Basement	3.34	1.78	–	–	–	–	3.41	0.02	0.75	Unpolluted
Adewole and Uchegbu (2010)	Basement	0.06	–	–	11.5	–	–	–	0.76	0.79	Unpolluted
Adelekan and Abegunde (2011)	Basement	28.9	2.63	2.35	–	0.50	–	2.91	–	3.04	Highly polluted
Adewoyin et al. (2013)	Basement	6.61	–	–	1.95	0.26	–	–	–	1.50	Moderately polluted
Ololade, (2014)	Basement	0.51	16.09	13.15	2.04	26.39	–	22.60	7.91	7.23	Very highly polluted
Isibor, (2016)	Basement	39.55	36.26	4.01	–	0.27	31.52	10.47	11.94	9.33	Very highly polluted
Peter et al. (2017)	Basement	4.73	27.48	2.77	29.00	3.04	–	19.78	–	9.26	Very highly polluted
Eluyera and Tukura, (2020)	Basement	0.18	0.60	0.06	5.97	0.14	0.48	0.81	0.68	0.44	Unpolluted
Komolafe et al. (2020)	Basement	1.77	–	2.18	–	0.17	–		5.69	1.40	Moderately polluted
Vincent et al. (2022)	Basement	0.06	–	–	0.03	0.09	–	1.43	0.19	0.13	Unpolluted
Durumin-Iya et al. (2023)	Basement	0.02	0.28	0.02	0.01	0.46	0.03	0.84	0.01	0.06	Unpolluted
Abii (2012)	Cretaceous	3.10	6.51	–	–	11.42	–		–	6.13	Very highly polluted
Ojiako and Okonkwo, (2013)	Cretaceous	0.33	0.17	0.07	–	0.02	–	0.22	–	0.11	Unpolluted
Pam et al. (2013a)	Cretaceous	3.94	–	1.14	–	0.31	2.51	3.28	1.66	1.63	Moderately polluted
Pam et al. (2013b)	Cretaceous	15.21	–	37.21	–	5.95	4.50	11.40	16.53	11.91	Very highly polluted
Onah et al. (2019)	Cretaceous	0.10	0.37	–	–	0.13		0.27	–	0.19	Unpolluted
Ogunkolu et al. (2019)	Cretaceous	0.04	0.06	0.18	0.06	0.15	0.05	0.14	0.16	0.09	Unpolluted
Amaechi and Onwuka (2021)	Cretaceous	0.77	34.29	3.93	12.07	1.05	0.21	2.48	0.72	2.16	Moderately polluted
Yahaya et al. (2023)	Cretaceous	–	–	–	0.35	0.13	–	0.34	0.75	0.33	Unpolluted
Amos et al. (2023)	Cretaceous	0.02	–	0.08	0.02	0.53	–	0.03	0.41	0.07	Unpolluted
Nwachukwu et al. (2010)	Tertiary	18.80	7.94	29.91	0.59	17.01	20.28	7.72	–	9.51	Very highly polluted
Osu & Okereke (2010)	Tertiary	1.49	–	–	–	7.34	–	0.15	–	1.17	Moderately polluted
Nwachukwu et al (2011)	Tertiary	37.26	–	17.89	483.9	10.26	23.53	15.56	32.09	32.57	Very highly polluted
Okoro et al. (2013)	Tertiary	54.17	3.81	18.18	–	6.62	–	–	–	5.40	Very highly polluted
Idugboe et al. (2014)	Tertiary	0.03	0.13	0.05	2.86	0.03	0.40	0.07	0.46	0.15	Unpolluted
Osakwe (2014)	Tertiary	–	–	0.03	0.39		0.94	–	0.65	0.29	Unpolluted
Akporido et al. (2015)	Tertiary	2.17	–	0.47	–	17.62	–	40.53	–	5.21	Very highly polluted
Lawal et al. (2015)	Tertiary	2.92	–	–	–	2.89	–	–	–	2.90	Moderately polluted
Chokor and Ekanem (2016)	Tertiary	0.79	6.40	3.19	–	2.76	–	–	–	6.67	Very highly polluted
Menkiti et al. (2017)	Tertiary	0.63	4.20	1.48	–	4.85	–	3.23	5.96	2.67	Moderately polluted
Anegbe et al. (2018)	Tertiary	0.15	–	1.63	6.11	0.70	–	–	1.61	1.11	Moderately polluted
Ibrahim et al. (2019)	Tertiary	2.93	33.57	1.78	–	0.50	1.53	14.42	2.10	3.28	Highly polluted
Azorji et al. (2021)	Tertiary	0.04	0.07	0.59	0.65	0.25	–	0.36	6.08	0.35	Unpolluted
Osayande et al. (2022)	Tertiary	1.05	1.42	–	–	1.47	–	–	2.89	1.59	Moderately polluted
Enete et al. (2022)	Tertiary	0.01	0.03	0.00	0.16	0.00	0.00	0.04	0.02	0.01	Unpolluted
Bridget et al. (2023)	Tertiary	0.51	–	0.48	–	–	–	0.82	1.59	0.75	Unpolluted

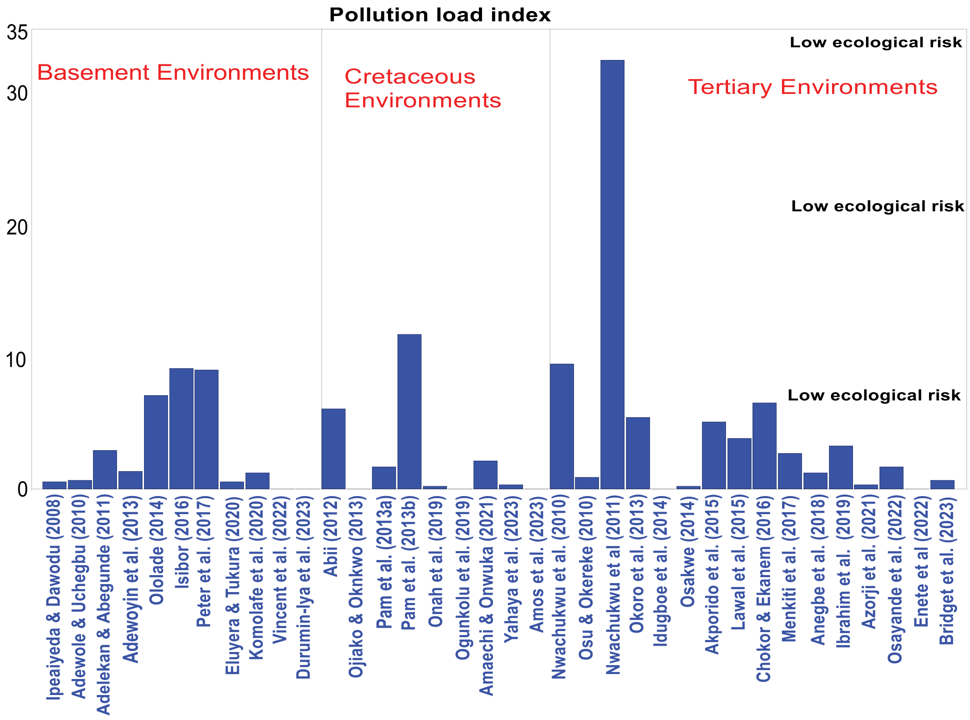

Figure 6. Pollution load index (PLI) of PTEs concentrations in AMW soils around geological environments of Nigeria.

(0.9952) and Mn-Zn (0.8847) were observed in cretaceous environments and Cu-Mn (0.7398) relationship in tertiary environments. This indicates that the distribution of PTEs in soil is linked to a common source of automotive activities within the automobile mechanic workshops across the three geological environments (Zhai et al. 2008). Cu-Mn (−0.6086, −0.5395 and 0.7398) and Fe-Mn (0.9998, 0.8416 and 0.6989)

Table 8. Pairwise correlation coefficient (Pearson's) of PTEs in AMW soils around basement environment.

	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn
Pb	1	−0.1885	−0.1521	−0.3163	0.4776	−0.4184	0.1382	**0.5162**
Cr		1	−0.2281	**0.7086**	0.1704	**−0.5847**	**0.6907**	**0.6115**
Cu			1	−0.1257	0.0145	**−0.6086**	−0.1896	−0.0624
Fe				1	−0.228	**0.9998**	0.1226	**0.5819**
Cd					1	**0.5039**	**0.7422**	0.381
Mn						1	−0.4914	**−0.5811**
Ni							1	0.4006
Zn								1

Table 9. Pairwise correlation coefficient (Pearson's) of PTEs in AMW soils around cretaceous environments.

	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn
Pb	1	−0.3108	−0.2286	−0.3475	0.3454	**−0.5077**	−0.2076	−0.2011
Cr		1	−0.2127	−0.3474	−0.2281	0.2089	−0.4037	−0.2990
Cu			1	−0.2853	−0.3246	**−0.5395**	**0.9396**	−0.2411
Fe				1	**−0.5595**	**0.8416**	−0.04	**0.9952**
Cd					1	−0.0643	−0.3095	−0.2404
Mn						1	−0.3468	**0.8847**
Ni							1	−0.0156
Zn								1

Table 10. Pairwise correlation coefficient (Pearson's) of PTEs in AMW soils around tertiary environments.

	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn
Pb	1	−0.1046	0.2861	−0.31.65	0.3776	−0.32.75	−0.0915	0.2071
Cr		1	−0.1493	−0.1625	**0.6832**	−0.2584	−0.1602	**0.0522**
Cu			1	0.2901	**0.6206**	**0.7398**	−0.0421	**0.6641**
Fe				1	−0.104	**0.6989**	−0.3477	−0.259
Cd					1	0.1901	−0.2595	**0.5254**
Mn						1	−0.346	0.4938
Ni							1	−0.0206
Zn								1

pairwise were strongly correlated across the different geological environments (Tables 8–10). The strong negative relationship of Cu-Mn pairwise in basement and cretaceous environments was caused by two sources of either both natural (weathering/mineralisation in basement) and anthropogenic sources or two different sources of automotive activities while Cu-Mn in tertiary environments and Fe-Mn pairwise (0.9998, 0.8416 and 0.6989) in the three geological environments are linked to a common source of automotive activities (body fillers and paints) within the automobile mechanic workshops (Iwegbue et al. 2024).

The ANOVA $F_{statistical}$, P_{value} and $F_{crtical}$ values for the three geological environments range from 0.195997 (Zn) to 1.681071 (Pb), 0.202704 (Pb) to 0.823501 (Zn) and 3.304817 (Pb) to 4.102821 (Mn) respectively (Table 11). The $F_{statistical}$ values of PTEs were higher than the alpha level of 0.05 which implies that the null hypothesis was accepted for all. This is an indication that the level of soil pollution is nearly the same across the different geological environments with very little variation, which may be as a result of the age of automobile mechanic workshop, volume of work done, types of repairs and lubricants used (Nwachukwu et al. 2011; Ololade 2014).

Table 11. Estimated ANOVA values for PTEs in AMW soils in Nigeria's geological environments.

S/No.	F stat.	P-value	F crit.
Pb	1.681071	0.202704	3.304817
Cr	0.374002	0.693198	3.554557
Cu	0.218868	0.805084	3.422132
Fe	0.678013	0.522518	3.68232
Cd	0.61093	0.549685	3.327654
Mn	0.58953	0.572761	4.102821
Ni	1.00846	0.380348	3.422132
Zn	0.195997	0.823501	3.4668

4.4. Human risk assessment (inhalation route)

The average daily intake (ADI) for children non-carcinogenic risk, adults non-carcinogenic risk, children carcinogenic risk and adults carcinogenic risk ranges from 2.82×10^{-12} (Cd of Pam et al. 2013a) to 1.74×10^{-5} (Fe of Osakwe 2014), 1.21×10^{-12} (Cd of Pam et al. 2013a) to 7.17×10^{-5} (Pb of Eluyera and Tukura 2020), 2.32×10^{-7} (Ni of Ojiako and Okonkwo 2013) to 0.571 (Cr of 2854i" class="cross-reference">Osakwe 2014) and 1.04×10^{-12} (Ni of Ojiako and Okonkwo 2013) to 2.55 × 10–6 (Cr of Osakwe 2014) respectively (Tables 12, 13 , 16 and 17). The average daily intake of PTEs by people working at AMW sites is considered tolerable (Zhou et al. 2022). The general ADD or CDI trend was in the following order: Basement environments > Tertiary environments > Cretaceous environments for adults and

Table 12. Average daily dose of non-carcinogenic disease for children in Nigeria.

		Children							
		Average daily dose for non-carcinogenic disease							
Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn
Ipeaiyeda & Dawodu (2008)	Basement	2.57×10^{-10}	3.77×10^{-10}	1.37×10^{-10}	3.63×10^{-10}	3.17×10^{-10}	4.27×10^{-10}	7.58×10^{-10}	9.87×10^{-11}
Adewole and Uchegbu (2010)	Basement	7.27×10^{-8}	–	–	7.02×10^{-8}	1.8×10^{-10}	–	–	–
Adelekan and Abegunde (2011)	Basement	3.22×10^{-8}	4.47×10^{-8}	1.35×10^{-8}	–	3.45×10^{-10}	1.98×10^{-8}	1.31×10^{-8}	1.9×10^{-8}
Adewoyin et al. 2013)	Basement	3.17×10^{-7}	3.5×10^{-9}	1.78×10^{-8}	–	3.45×10^{-10}	–	2.64×10^{-9}	–
Ololade (2014)	Basement	1.95×10^{-8}	–	1.65×10^{-8}	–	1.2×10^{-10}	–	–	5.15×10^{-8}
Isibor (2016)	Basement	–	–	–	1.25×10^{-8}	9.17×10^{-11}	–	3.1×10^{-10}	6.79×10^{-9}
Peter et al. (2017)	Basement	7.12×10^{-10}	–	–	1.03×10^{-9}	5.99×10^{-11}	–	1.29×10^{-9}	1.69×10^{-9}
Eluyera & Tukura (2020)	Basement	1.67×10^{-5}	–	2.82×10^{-7}		4.09×10^{-9}	5.83×10^{-8}	1.03×10^{-8}	1.5×10^{-7}
Komolafe et al. (2020)	Basement	6.2×10^{-10}	–	–	4.14×10^{-7}	–	–	–	6.89×10^{-9}
Vincent et al. (2022)	Basement	3.68×10^{-8}	1.57×10^{-9}	–	–	–	–	3.09×10^{-9}	2.15×10^{-10}
Durumin-Iya et al. (2023)	Basement	3.41×10^{-8}	8.67×10^{-9}	–	–	7.85×10^{-9}	–	–	–
Abii (2012)	Cretaceous	5.56×10^{-9}	–	3.61×10^{-9}	–	–	–	7.44×10^{-10}	1.44×10^{-8}
Ojiako & Oknkwo (2013)	Cretaceous	4.65×10^{-10}	7.4×10^{-11}	1.34×10^{-9}	2.22×10^{-9}	1.06×10^{-10}	6.24×10^{-10}	1.23×10^{-10}	1.44×10^{-9}
Pam et al. (2013a)	Cretaceous	3.28×10^{-10}	1.73×10^{-10}	4.05×10^{-10}	1.03×10^{-7}	2.19×10^{-11}	5.12×10^{-9}	6.38×10^{-11}	4.13×10^{-9}
Pam et al. (2013b)	Cretaceous	9.87×10^{-11}	3.88×10^{-11}	1.06×10^{-11}	5.64×10^{-9}	2.82×10^{-12}	5.99×10^{-11}	3.17×10^{-11}	1.97×10^{-10}
Onah et al. (2019)	Cretaceous	1.97×10^{-9}	8.04×10^{-10}	4.2×10^{-10}	2.14×10^{-7}	9.87×10^{-11}	6.26×10^{-9}	7.33×10^{-10}	6.16×10^{-9}
Ogunkolu et al. (2019)	Cretaceous	8.66×10^{-9}	8.53×10^{-9}	2.42×10^{-8}	–	1.9×10^{-9}	–	–	–
Amaechi and Onwuka (2021)	Cretaceous	1.68×10^{-9}	–	1.24×10^{-8}	2.19×10^{-7}	4.83×10^{-10}	–	–	1.45×10^{-8}
Yahaya et al. (2023)	Cretaceous	8.44×10^{-9}	4.57×10^{-8}	2.98×10^{-8}	4.34×10^{-7}	7.19×10^{-10}	2.66×10^{-9}	2.25×10^{-9}	6.49×10^{-9}
Amos et al. (2023)	Cretaceous	–	–	2.33×10^{-10}	1.41×10^{-10}	–	1.21×10^{-8}		5.9×10^{-9}
Nwachukwu et al. (2010)	Tertiary	2.39×10^{-8}	–	3.6×10^{-9}	–	1.21×10^{-8}	–	3.67×10^{-8}	–
Osu and Okereke (2010)	Tertiary	3.21×10^{-8}	–	–	–	1.98×10^{-9}	–	–	–
Nwachukwu et al. (2011)	Tertiary	3.67×10^{-9}	2.22×10^{-10}	5.04×10^{-10}	–	1.55×10^{-11}	–	1.97×10^{-10}	–
Okoro et al. (2013)	Tertiary	4.34×10^{-8}		8.67×10^{-9}	–	2.12×10^{-10}	3.24×10^{-8}	2.98×10^{-9}	1.51×10^{-8}
Idugboe et al. (2014)	Tertiary	5.96×10^{-7}	5.07×10^{-9}	1.38×10^{-7}	–	4.55×10^{-9}	–	–	–
Osakwe (2014)	Tertiary	4.1×10^{-7}		1.36×10^{-7}	1.74×10^{-5}	7.05×10^{-9}	3.05×10^{-7}	1.41×10^{-8}	2.9×10^{-7}
Akporido et al. (2015)	Tertiary	2.07×10^{-7}	1.06×10^{-8}	2.27×10^{-7}	2.13×10^{-8}	1.17×10^{-8}	2.63×10^{-7}	6.99×10^{-9}	–
Lawal et al. (2015)	Tertiary	6.87×10^{-9}	5.6×10^{-9}	1.13×10^{-8}	–	3.33×10^{-9}	–	2.92×10^{-9}	5.4×10^{-8}
Chokor and Ekanem (2016)	Tertiary	1.63×10^{-8}	–	–	–	5.05×10^{-9}	–	1.34×10^{-10}	–
Menkiti et al. (2017)	Tertiary	5.21×10^{-8}	3.66×10^{-8}	2.1×10^{-8}	1.04×10^{-6}	2.09×10^{-9}	–	1.79×10^{-8}	–
Anegbe et al. (2018)	Tertiary	4.35×10^{-7}	4.83×10^{-8}	3.04×10^{-8}	–	1.87×10^{-10}	4.08×10^{-7}	9.49×10^{-9}	1.08×10^{-7}
Ibrahim et al. (2019)	Tertiary	1.06×10^{-9}	4.94×10^{-10}	–	–	9.17×10^{-11}	–	2.43×10^{-10}	–
Azorji et al. (2021)	Tertiary	4.76×10^{-10}	9.52×10^{-11}	4.47×10^{-9}	2.34×10^{-8}	1.73×10^{-10}	–	3.28×10^{-10}	5.5×10^{-8}
Osayande et al. (2022)	Tertiary	2.19×10^{-10}	–	5.85×10^{-10}	5.68×10^{-10}	3.67×10^{-10}	–	2.47×10^{-11}	3.67×10^{-9}
Enete et al. (2022)	Tertiary	5.58×10^{-9}	2.14×10^{-8}	9.97×10^{-8}	7.33×10^{-8}	1.81×10^{-8}	–	2.05×10^{-8}	7.23×10^{-8}
Bridget et al. (2023)	Tertiary	1.16×10^{-8}	1.89×10^{-9}	–	–	1.01×10^{-9}	–	–	2.61×10^{-8}

Table 13. Average daily dose of non-carcinogenic disease for adults in Nigeria.

		Adults							
		Average daily dose for non-carcinogenic disease							
Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn
Ipeaiyeda & Dawodu (2008)	Basement	$1. \times 10^{-10}$	1.62×10^{-10}	5.89×10^{-11}	1.56×10^{-10}	1.36×10^{-10}	1.83×10^{-10}	3.25×10^{-10}	4.23×10^{-11}
Adewole and Uchegbu (2010)	Basement	3.12×10^{-8}	–	–	3.01×10^{-8}	7.71×10^{-11}	–	–	–
Adelekan and Abegunde (2011)	Basement	1.38×10^{-8}	1.92×10^{-8}	5.79×10^{-9}	–	1.48E $\times 10^{-10}$	8.48×10^{-9}	5.6×10^{-9}	8.15×10^{-9}
Adewoyin et al. (2013)	Basement	1.36×10^{-7}	1.5×10^{-9}	7.65×10^{-9}	–	1.48×10^{-10}	–	1.13×10^{-9}	–
Ololade (2014)	Basement	8.35×10^{-9}	–	7.09×10^{-9}	–	5.14×10^{-11}	–	–	2.21×10^{-8}
Isibor (2016)	Basement		–	–	5.35×10^{-9}	3.93×10^{-11}	–	1.33×10^{-10}	2.91×10^{-9}
Peter et al. (2017)	Basement	3.05×10^{-10}	–	–	4.4×10^{-10}	2.57×10^{-11}	–	5.54×10^{-10}	7.24×10^{-10}
Eluyera & Tukura (2020)	Basement	7.17×10^{-5}	–	1.21×10^{-7}		1.75×10^{-9}	2.5×10^{-8}	4.43×10^{-9}	6.41×10^{-8}
Komolafe et al. (2020)	Basement	2.66×10^{-10}	–	–	1.77×10^{-7}	–	–		2.95×10^{-9}
Vincent et al. (2022)	Basement	1.58×10^{-8}	6.72×10^{-10}	–	–	–	–	1.33×10^{-9}	9.22×10^{-11}
Durumin-Iya et al. (2023)	Basement	1.46×10^{-8}	3.72×10^{-9}	–	–	3.36×10^{-9}	–	–	–
Abii (2012)	Cretaceous	2.38×10^{-9}	–	1.55×10^{-9}	–	–	–	3.19×10^{-10}	6.17×10^{-9}
Ojiako & Oknkwo (2013)	Cretaceous	1.99×10^{-10}	3.17×10^{-11}	5.74×10^{-10}	9.53×10^{-10}	4.53×10^{-11}	2.67×10^{-10}	5.29×10^{-11}	6.16×10^{-10}
Pam et al. (2013a)	Cretaceous	1.41×10^{-10}	7.4×10^{-11}	1.74×10^{-10}	4.4×10^{-8}	9.37×10^{-12}	2.19×10^{-9}	2.73×10^{-11}	1.77×10^{-9}
Pam et al. (2013b)	Cretaceous	4.23×10^{-11}	1.66×10^{-11}	4.53×10^{-12}	2.42×10^{-9}	1.21×10^{-12}	2.57×10^{-11}	1.36×10^{-11}	8.46×10^{-11}
Onah et al. (2019)	Cretaceous	8.45×10^{-10}	3.44×10^{-10}	1.8×10^{-10}	9.18×10^{-8}	4.23×10^{-11}	2.68×10^{-9}	3.14×10^{-10}	2.64×10^{-9}
Ogunkolu et al. (2019)	Cretaceous	3.71×10^{-9}	3.65×10^{-9}	1.04×10^{-8}	–	8.14×10^{-10}	–	–	–
Amaechi and Onwuka (2021)	Cretaceous	7.21×10^{-10}	–	5.31×10^{-9}	9.4×10^{-8}	2.07×10^{-10}	–	–	6.23×10^{-9}
Yahaya et al. (2023)	Cretaceous	3.62×10^{-9}	1.96×10^{-8}	1.28×10^{-8}	1.86×10^{-7}	3.08×10^{-10}	1.14×10^{-9}	9.62×10^{-10}	2.78×10^{-9}
Amos et al. (2023)	Cretaceous	–	–	9.97×10^{-11}	6.05×10^{-9}	–	5.2×10^{-9}	–	2.53×10^{-9}
Nwachukwu et al. (2010)	Tertiary	1.02×10^{-8}	–	1.54×10^{-9}	–	5.19×10^{-9}	–	1.57×10^{-8}	–
Osu and Okereke (2010)	Tertiary	1.38×10^{-8}	–	–	–	8.51×10^{-10}	–	–	–
Nwachukwu et al. (2011)	Tertiary	1.57×10^{-9}	9.52×10^{-11}	2.16×10^{-10}	–	6.65×10^{-12}	–	8.46×10^{-11}	–
Okoro et al. (2013)	Tertiary	1.86×10^{-8}		3.72×10^{-9}	–	9.07×10^{-11}	1.39×10^{-8}	1.28×10^{-9}	6.45×10^{-9}
Idugboe et al. (2014)	Tertiary	2.55×10^{-7}	2.17×10^{-9}	5.91×10^{-8}	–	1.95×10^{-9}	–	–	–
Osakwe (2014)	Tertiary	1.76×10^{-7}		5.82×10^{-8}	7.45×10^{-6}	3.02×10^{-9}	1.31×10^{-7}	6.04×10^{-9}	1.24×10^{-7}
Akporido et al. (2015)	Tertiary	8.86×10^{-8}	4.53×10^{-9}	9.73×10^{-8}	9.13×10^{-9}	5.01×10^{-9}	1.13×10^{-7}	3×10^{-9}	–
Lawal et al. (2015)	Tertiary	2.95×10^{-9}	2.4×10^{-9}	4.82×10^{-9}	–	1.43×10^{-9}	–	1.25×10^{-9}	2.31×10^{-8}
Chokor and Ekanem (2016)	Tertiary	7×10^{-9}	–	–	–	2.16×10^{-9}	–	5.74×10^{-11}	–
Menkiti et al. (2017)	Tertiary	2.23×10^{-8}	1.57×10^{-8}	9.02×10^{-9}	4.46×10^{-7}	8.96×10^{-10}	–	7.68×10^{-9}	–
Anegbe et al. (2018)	Tertiary	1.86×10^{-7}	2.07×10^{-8}	1.3×10^{-8}	–	8.01×10^{-11}	1.75×10^{-7}	4.07×10^{-9}	4.63×10^{-8}
Ibrahim et al. (2019)	Tertiary	4.55×10^{-10}	2.12×10^{-10}	–	–	3.93×10^{-11}	–	1.04×10^{-10}	–
Azorji et al. (2021)	Tertiary	2.04×10^{-10}	4.08×10^{-11}	1.92×10^{-9}	1×10^{-8}	7.4×10^{-11}	–	1.41×10^{-10}	2.36×10^{-8}
Osayande et al. (2022)	Tertiary	9.37×10^{-11}	–	2.51×10^{-10}	2.43×10^{-10}	1.57×10^{-10}	–	1.06×10^{-11}	1.57×10^{-9}
Enete et al. (2022)	Tertiary	2.39×10^{-9}	9.19×10^{-9}	4.27×10^{-8}	3.14×10^{-8}	7.78×10^{-9}	–	8.77×10^{-9}	3.1×10^{-8}
Bridget et al. (2023)	Tertiary	4.95×10^{-9}	8.08×10^{-10}	–	–	4.34×10^{-10}	–	–	1.12×10^{-8}

Table 14. Hazard quotient and hazard index for children in Nigeria.

		Children								
		Hazard Quotient								
Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn	Hazard index
Ipeaiyeda & Dawodu (2008)	Basement	7.31×10^{-8}	1.32×10^{-5}	3.42×10^{-9}	1.65×10^{-5}	3.17×10^{-5}	2.98×10^{-5}	3.68×10^{-8}	3.29×10^{-10}	7.65×10^{-5}
Adewole and Uchegbu (2010)	Basement	2.07×10^{-5}	–	–	0.000319	1.8×10^{-5}	–	–	–	0.000358
Adelekan and Abegunde (2011)	Basement	9.14×10^{-6}	1.56×10^{-3}	3.36×10^{-7}	–	3.45×10^{-5}	0.001384	6.34×10^{-7}	6.34×10^{-8}	0.002993
Adewoyin et al. (2013)	Basement	9.02×10^{-5}	1.23×10^{-4}	4.44×10^{-7}	–	3.45×10^{-5}	–	1.28×10^{-7}	–	0.000248
Ololade (2014)	Basement	5.53×10^{-6}	–	4.11×10^{-7}	–	1.2×10^{-5}	–		1.72×10^{-7}	1.81×10^{-5}
Isibor (2016)	Basement	–	–		5.67×10^{-5}	9.17×10^{-6}	–	1.51×10^{-8}	2.26×10^{-8}	6.59×10^{-5}
Peter et al. (2017)	Basement	2.02×10^{-7}	–		4.66×10^{-6}	5.99×10^{-6}	–	6.28×10^{-8}	5.63×10^{-9}	1.09×10^{-5}
Eluyera & Tukura (2020)	Basement	0.048	–	7.03×10^{-6}	–	0.000409	0.00408	5.01×10^{-7}	4.99×10^{-7}	0.052005
Komolafe et al. (2020)	Basement	1.76×10^{-7}	–	–	0.001881	–	–		2.3×10^{-8}	0.001881
Vincent et al. (2022)	Basement	1.04×10^{-5}	5.49×10^{-5}	–	–	–	–	1.5×10^{-7}	7.17×10^{-10}	6.54×10^{-5}
Durumin-Iya et al. (2023)	Basement	9.69×10^{-6}	3.03×10^{-4}	–	–	0.000785	–	–	–	0.001098
Abii (2012)	Cretaceous	1.58×10^{-6}	–	8.98×10^{-8}	–	–	–	3.61×10^{-8}	4.8×10^{-8}	1.75×10^{-6}
Ojiako & Oknkwo (2013)	Cretaceous	1.32×10^{-7}	2.59×10^{-6}	3.33×10^{-8}	1.01×10^{-5}	1.06×10^{-5}	4.36×10^{-5}	5.99×10^{-9}	4.79×10^{-9}	6.71×10^{-5}
Pam et al. (2013a)	Cretaceous	9.31×10^{-8}	6.04×10^{-6}	1.01×10^{-8}	0.000467	2.19×10^{-6}	0.000358	3.1×10^{-9}	1.38E x 10^{-8}	0.000833
Pam et al. (2013b)	Cretaceous	2.8E x 10^{-8}	1.36×10^{-6}	2.63×10^{-10}	2.56×10^{-5}	2.82×10^{-7}	4.19×10^{-6}	1.54×10^{-9}	6.58×10^{-10}	3.15×10^{-5}
Onah et al. (2019)	Cretaceous	5.6×10^{-7}	2.81×10^{-5}	1.04×10^{-8}	0.000974	9.87×10^{-6}	0.000438	3.56×10^{-8}	2.05×10^{-8}	0.00145
Ogunkolu et al. (2019)	Cretaceous	2.46×10^{-6}	2.98×10^{-4}	6.03×10^{-7}	–	0.00019	–	–	–	0.000491
Amaechi and Onwuka (2021)	Cretaceous	4.78×10^{-7}	–	3.08×10^{-7}	0.000997	4.83×10^{-5}	–	–	4.85×10^{-8}	0.001047
Yahaya et al. (2023)	Cretaceous	2.4×10^{-6}	1.60×10^{-3}	7.41×10^{-7}	0.001971	7.19×10^{-5}	0.000186	1.09×10^{-7}	2.16×10^{-8}	0.00383
Amos et al. (2023)	Cretaceous	–	–	5.79×10^{-9}	6.42×10^{-5}	–	0.000848	–	1.97×10^{-8}	0.000912
Nwachukwu et al. (2010)	Tertiary	6.79×10^{-6}	–	8.95×10^{-8}	–	0.001211	–	1.78×10^{-6}	–	0.00122
Osu and Okereke (2010)	Tertiary	9.12×10^{-6}	–	–	–	0.000198	–	–	–	0.000208
Nwachukwu et al. (2011)	Tertiary	1.04×10^{-6}	7.77×10^{-6}	1.25×10^{-8}	–	1.55×10^{-6}	–	9.58×10^{-9}	–	1.04×10^{-5}
Okoro et al. (2013)	Tertiary	1.23×10^{-5}		2.16×10^{-7}	–	2.12×10^{-5}	0.002268	1.44×10^{-7}	5.02×10^{-8}	0.002302
Idugboe et al. (2014)	Tertiary	1.69×10^{-4}	1.77×10^{-5}	3.43×10^{-6}	–	0.000455	–	–	–	0.000805
Osakwe (2014)	Tertiary	1.16×10^{-5}	–	3.38×10^{-6}	0.078993	0.000705	0.0213	6.85×10^{-7}	9.68×10^{-7}	0.101119
Akporido et al. (2015)	Tertiary	5.87×10^{-5}	3.7×10^{-4}	5.64×10^{-6}	9.69×10^{-5}	0.001169	0.018358	3.39×10^{-7}	–	0.020059
Lawal et al. (2015)	Tertiary	1.95×10^{-6}	0.000196	2.8×10^{-6}	–	0.000333	–	1.42×10^{-7}	1.8×10^{-7}	0.000532
Chokor and Ekanem (2016)	Tertiary	4.64×10^{-6}	–	–	–	0.000505	–	6.5×10^{-9}	–	0.000509
Menkiti et al. (2017)	Tertiary	1.48×10^{-5}	0.00128	5.23×10^{-7}	0.004734	0.000209	–	8.7×10^{-7}	–	0.00624
Anegbe et al. (2018)	Tertiary	1.24×10^{-4}	0.00169	7.57×10^{-7}	–	1.87×10^{-5}	0.028532	4.61×10^{-7}	3.6×10^{-7}	0.030365
Ibrahim et al. (2019)	Tertiary	3.01×10^{-7}	1.73×10^{-5}	–	–	9.17×10^{-6}	–	1.18×10^{-8}	–	2.67×10^{-5}
Azorji et al. (2021)	Tertiary	1.35×10^{-7}	3.33×10^{-6}	1.11×10^{-7}	0.000106	1.73×10^{-5}	–	1.59×10^{-8}	1.83×10^{-7}	0.000127
Osayande et al. (2022)	Tertiary	6.21×10^{-8}	–	1.46×10^{-8}	2.58×10^{-6}	3.67×10^{-5}	–	1.2×10^{-9}	1.22×10^{-8}	3.93×10^{-5}
Enete et al. (2022)	Tertiary	1.59×10^{-6}	0.00075	2.48×10^{-6}	0.000333	0.001815	–	9.94×10^{-7}	2.41×10^{-7}	0.002903
Bridget et al. (2023)	Tertiary	3.28×10^{-6}	6.59×10^{-5}	–	–	0.000101	–	–	8.72×10^{-8}	0.00017

Table 15. Hazard quotient and hazard index for adults in Nigeria.

		Adults								
		Hazard Quotient								
Author & year	Terrian	Pb	Cr	Cu	Fe	Cd	Mn	Ni	Zn	Hazard index
Ipeaiyeda & Dawodu (2008)	Basement	3.13×10^{-8}	5.65×10^{-6}	1.47×10^{-9}	7.07×10^{-7}	1.36×10^{-5}	1.28×10^{-5}	1.58×10^{-8}	1.41×10^{-10}	3.28×10^{-5}
Adewole and Uchegbu (2010)	Basement	8.85×10^{-6}	–	–	0.000137	7.71×10^{-6}	–	–	–	0.000153
Adelekan and Abegunde (2011)	Basement	3.92×10^{-6}	0.00067	1.44×10^{-7}	–	1.48×10^{-5}	0.000593	2.72×10^{-7}	2.72×10^{-8}	0.001283
Adewoyin et al. (2013)	Basement	3.86×10^{-5}	5.25×10^{-5}	1.9×10^{-7}	–	1.48×10^{-5}	–	5.49×10^{-8}	–	0.000106
Ololade (2014)	Basement	2.37×10^{-6}	–	1.76×10^{-7}	–	5.14×10^{-6}	–	–	7.35×10^{-8}	7.76×10^{-6}
Isibor (2016)	Basement	–	–	–	2.43×10^{-5}	3.93×10^{-6}	–	6.45×10^{-9}	9.7×10^{-9}	2.82×10^{-5}
Peter et al. (2017)	Basement	8.67×10^{-8}	–	–	2×10^{-6}	2.57×10^{-6}	–	2.69×10^{-8}	2.41×10^{-9}	4.68×10^{-6}
Eluyera & Tukura (2020)	Basement	0.02036	–	3.01×10^{-6}	–	0.000175	0.001749	2.15×10^{-7}	2.14×10^{-7}	0.022288
Komolafe et al. (2020)	Basement	7.55×10^{-8}	–	–	0.000806	–	–	–	9.85×10^{-9}	0.000806
Vincent et al. (2022)	Basement	4.48×10^{-6}	2.35×10^{-5}	–	–	–	–	6.43×10^{-8}	3.07×10^{-10}	2.8×10^{-5}
Durumin-Iya et al. (2023)	Basement	4.15×10^{-6}	0.00013	–	–	0.000336	–	–	–	0.00047
Abii (2012)	Cretaceous	6.77×10^{-7}	–	3.85×10^{-8}	–	–	–	1.55×10^{-8}	2.06×10^{-8}	7.52×10^{-7}
Ojiako & Oknkwo (2013)	Cretaceous	5.67×10^{-8}	1.11×10^{-6}	1.43×10^{-8}	4.33×10^{-6}	4.53×10^{-6}	1.87×10^{-5}	2.57×10^{-9}	2.05×10^{-9}	2.88×10^{-5}
Pam et al. (2013a)	Cretaceous	3.99×10^{-8}	2.59×10^{-6}	4.32×10^{-9}	0.0002	9.37×10^{-7}	0.000153	1.33×10^{-9}	5.9×10^{-9}	0.000357
Pam et al. (2013b)	Cretaceous	1.2×10^{-8}	5.81×10^{-7}	1.13×10^{-10}	1.1×10^{-5}	1.21×10^{-7}	1.8×10^{-6}	6.0×10^{-10}	2.82×10^{-10}	1.35×10^{-5}
Onah et al. (2019)	Cretaceous	2.4×10^{-7}	1.2×10^{-5}	4.47×10^{-9}	0.000417	4.23×10^{-6}	0.000188	1.53×10^{-8}	8.8×10^{-9}	0.000622
Ogunkolu et al. (2019)	Cretaceous	1.05×10^{-6}	0.000128	2.58×10^{-7}	–	8.14×10^{-5}	–	–	–	0.000211
Amaechi and Onwuka (2021)	Cretaceous	2.05×10^{-7}	–	1.32×10^{-7}	0.000427	2.07×10^{-5}	–	–	2.08×10^{-8}	0.000449
Yahaya et al. (2023)	Cretaceous	1.03×10^{-6}	0.000685	3.18×10^{-7}	0.000845	3.08×10^{-5}	7.97×10^{-5}	4.67×10^{-8}	9.28×10^{-9}	0.001641
Amos et al. (2023)	Cretaceous	–	–	2.48×10^{-9}	2.75×10^{-5}		0.000363		8.43×10^{-9}	0.000391
Nwachukwu et al. (2010)	Tertiary	2.91×10^{-6}	–	3.83×10^{-8}	–	0.000519	–	7.64×10^{-7}	–	0.000523
Osu and Okereke (2010)	Tertiary	3.91×10^{-6}	–	–	–	8.51×10^{-5}	–	–	–	8.9×10^{-5}
Nwachukwu et al. (2011)	Tertiary	4.47×10^{-7}	3.33×10^{-6}	5.37×10^{-9}	–	6.65×10^{-7}	–	4.11×10^{-9}	–	4.45×10^{-6}
Okoro et al. (2013)	Tertiary	5.28×10^{-6}	–	9.25×10^{-8}	–	9.07×10^{-6}	0.000972	6.19×10^{-8}	2.15×10^{-8}	0.000987
Idugboe et al. (2014)	Tertiary	7.25×10^{-5}	7.6×10^{-5}	1.47×10^{-6}	–	0.000195	–	–	–	0.000345
Osakwe (2014)	Tertiary	4.99×10^{-5}	–	1.45×10^{-6}	0.033854	0.000302	0.009129	2.93×10^{-7}	4.15×10^{-7}	0.043337
Akporido et al. (2015)	Tertiary	2.52×10^{-5}	0.000158	2.42×10^{-6}	4.15×10^{-5}	0.000501	0.007868	1.45×10^{-7}		0.008597
Lawal et al. (2015)	Tertiary	8.37×10^{-7}	8.39×10^{-5}	1.2×10^{-7}	–	0.000143	–	6.08×10^{-8}	7.71×10^{-8}	0.000228
Chokor and Ekanem (2016)	Tertiary	1.99×10^{-6}	–	–	–	0.000216	–	2.79×10^{-9}		0.000218
Menkiti et al. (2017)	Tertiary	6.34×10^{-6}	0.000549	2.24×10^{-7}	0.002029	8.96×10^{-5}	–	3.73×10^{-7}	–	0.002674
Anegbe et al. (2018)	Tertiary	5.29×10^{-5}	0.000724	3.24×10^{-7}	–	8.01×10^{-6}	0.012228	1.97×10^{-7}	1.54×10^{-7}	0.013014
Ibrahim et al. (2019)	Tertiary	1.29×10^{-7}	7.4×10^{-6}	–	–	3.93×10^{-6}	–	5.06×10^{-9}	–	1.15×10^{-5}
Azorji et al. (2021)	Tertiary	5.79×10^{-8}	1.43×10^{-6}	4.77×10^{-8}	4.56×10^{-5}	7.4×10^{-6}	–	6.82×10^{-9}	7.86×10^{-8}	5.46×10^{-5}
Osayande et al. (2022)	Tertiary	2.66×10^{-8}	–	6.24×10^{-9}	1.11×10^{-6}	1.57×10^{-5}	–	5.13×10^{-10}	5.24×10^{-9}	1.69×10^{-5}
Enete et al. (2022)	Tertiary	6.79×10^{-7}	0.000321	1.06×10^{-6}	0.000143	0.000778	–	4.26×10^{-7}	1.03×10^{-7}	0.001244
Bridget et al. (2023)	Tertiary	1.41×10^{-6}	2.83×10^{-5}	–	–	4.34×10^{-5}	–	–	3.74×10^{-8}	7.31×10^{-5}

Table 16. Chronic daily intake, carcinogenic risk and total carcinogenic risk values for children in Nigeria.

		Children						
		Chronic daily intake			Carcinogenic risk			
Author & year	Terrian	Pb	Cr	Ni	Pb	Cr	Ni	Total carcinogenic risk
Ipeaiyeda & Dawodu (2008)	Basement	4.52×10^{-6}	1.19×10^{-5}	5.10×10^{-6}	1.9×10^{-7}	0.000501	4.2803×10^{-6}	0.000505
Adewole and Uchegbu (2010)	Basement	–	0.002305	–	–	0.096827	–	0.096827
Adelekan and Abegunde (2011)	Basement	0.000444	–	–	1.86×10^{-5}	–	–	1.86×10^{-5}
Adewoyin et al. (2013)	Basement	0.000586	–	–	2.46×10^{-5}	–	–	2.46×10^{-5}
Ololade (2014)	Basement	0.000543	–	–	2.28×10^{-5}	–	–	2.28×10^{-5}
Isibor (2016)	Basement	–	0.00041	–	–	0.017209	–	0.017209
Peter et al. (2017)	Basement	–	3.37×10^{-5}	–	–	0.001415	–	0.001415
Eluyera & Tukura (2020)	Basement	0.009277	–	–	0.00039	–	–	0.00039
Komolafe et al. (2020)	Basement	–	0.013595	–	–	0.570972	–	0.570972
Vincent et al. (2022)	Basement	–	–	–	–	–	–	–
Durumin-Iya et al. (2023)	Basement	–	–	–	–	–	–	–
Abii (2012)	Cretaceous	0.000119	–	–	4.98×10^{-6}	–	–	4.98×10^{-6}
Ojiako & Oknkwo (2013)	Cretaceous	4.4×10^{-5}	7.31×10^{-5}	2.32×10^{-7}	1.85×10^{-6}	0.003069	1.9456×10^{-7}	0.003071
Pam et al. (2013a)	Cretaceous	1.33×10^{-5}	0.003373	–	5.59×10^{-7}	0.141673	–	0.141673
Pam et al. (2013b)	Cretaceous	3.47×10^{-7}	0.000185	–	1.46×10^{-8}	0.007782	–	0.007782
Onah et al. (2019)	Cretaceous	1.38×10^{-5}	0.007038	–	5.79×10^{-7}	0.295579	–	0.295579
Ogunkolu et al. (2019)	Cretaceous	0.000796	–	–	3.34×10^{-5}	–	–	3.34×10^{-5}
Amaechi and Onwuka (2021)	Cretaceous	0.000407	0.007208	–	1.71×10^{-5}	0.302748	–	0.302765
Yahaya et al. (2023)	Cretaceous	0.000979	0.014245	–	4.11×10^{-5}	0.598293	–	0.598334
Amos et al. (2023)	Cretaceous	7.64×10^{-6}	0.000464	–	3.21×10^{-7}	0.01948	–	0.019481
Nwachukwu et al. (2010)	Tertiary	0.000118	–	–	4.96×10^{-6}	–	–	4.96×10^{-6}
Osu and Okereke (2010)	Tertiary	–	–	–	–	–	–	–
Nwachukwu et al. (2011)	Tertiary	1.66×10^{-5}	–	–	6.96×10^{-7}	–	–	6.96×10^{-7}
Okoro et al. (2013)	Tertiary	0.000285	–	–	1.2×10^{-5}	–	–	1.2×10^{-5}
Idugboe et al. (2014)	Tertiary	0.004531	–	–	0.00019	–	–	0.00019
Osakwe (2014)	Tertiary	0.004459	0.57088	–	0.000187	23.97694	–	23.97713
Akporido et al. (2015)	Tertiary	0.007454	0.0007	–	0.000313	0.029398	–	0.029711
Lawal et al. (2015)	Tertiary	0.00037	–	–	1.55×10^{-5}	–	–	1.55×10^{-5}
Chokor and Ekanem (2016)	Tertiary	–	–	–	–	–	–	–
Menkiti et al. (2017)	Tertiary	0.000691	0.034212	–	2.9×10^{-5}	1.436914	–	1.436943
Anegbe et al. (2018)	Tertiary	0.001		–	4.2×10^{-5}	–	–	4.2×10^{-5}
Ibrahim et al. (2019)	Tertiary	–	–	–	–	–	–	–
Azorji et al. (2021)	Tertiary	0.000147	0.000768	2.07298×10^{-5}	6.17×10^{-6}	0.032263	1.7413×10^{-5}	0.032286
Osayande et al. (2022)	Tertiary	1.92×10^{-5}	1.86×10^{-5}	–	8.07×10^{-5}	0.000783	–	0.000784
Enete et al. (2022)	Tertiary	0.003277	0.002409	–	0.000138	0.101185	–	0.101323
Bridget et al. (2023)	Tertiary	–	–	–	–	–	–	–

Table 17. Chronic daily intake, carcinogenic risk and total carcinogenic risk values for adults in Nigeria.

		Adults						
		Chronic daily intake			Carcinogenic risk			
Author & year	Terrian	Pb	Cr	Ni	Pb	Cr	Ni	Total carcinogenic risk
Ipeaiyeda & Dawodu (2008)	Basement	2.02×10^{-11}	5.34×10^{-11}	2.28×10^{-11}	8.49×10^{-13}	2.24×10^{-9}	1.91×10^{-11}	2.26×10^{-9}
Adewole and Uchegbu (2010)	Basement	–	1.03×10^{-8}	–	–	4.33×10^{-7}	–	4.33×10^{-7}
Adelekan and Abegunde (2011)	Basement	1.99×10^{-9}	–	–	8.34×10^{-11}	–	–	8.34×10^{-11}
Adewoyin et al. (2013)	Basement	2.62×10^{-9}	–	–	1.1×10^{-10}	–	–	1.1×10^{-10}
Ololade (2014)	Basement	2.43×10^{-9}	–	–	1.02×10^{-10}	–	–	1.02×10^{-10}
Isibor (2016)	Basement		1.83×10^{-9}	–	–	7.7×10^{-8}	–	7.7×10^{-8}
Peter et al. (2017)	Basement		1.51×10^{-10}	–	–	6.33×10^{-9}	–	6.33×10^{-9}
Eluyera & Tukura (2020)	Basement	4.15×10^{-8}		–	1.74×10^{-9}		–	1.74×10^{-9}
Komolafe et al. (2020)	Basement	–	6.08×10^{-8}	–	–	2.55×10^{-6}	–	2.55×10^{-6}
Vincent et al. (2022)	Basement	–	–	–	–	–	–	–
Durumin-Iya et al. (2023)	Basement	–	–	–	–	–	–	–
Abii (2012)	Cretaceous	5.3×10^{-10}	–	–	2.23×10^{-11}	–	–	2.23×10^{-11}
Ojiako & Oknkwo (2013)	Cretaceous	1.97×10^{-10}	3.27×10^{-10}	1.04×10^{-12}	8.27×10^{-12}	1.37×10^{-8}	8.70×10^{-13}	1.37×10^{-8}
Pam et al. (2013a)	Cretaceous	5.96×10^{-11}	1.51×10^{-8}	–	2.5×10^{-12}	6.34×10^{-7}	–	6.34×10^{-7}
Pam et al. (2013b)	Cretaceous	1.55×10^{-12}	8.29×10^{-10}	–	6.53×10^{-14}	3.48×10^{-8}	–	3.48×10^{-8}
Onah et al. (2019)	Cretaceous	6.16×10^{-11}	3.15×10^{-8}	–	2.59×10^{-12}	1.32×10^{-6}	–	1.32×10^{-6}
Ogunkolu et al. (2019)	Cretaceous	3.56×10^{-9}		–	1.5×10^{-10}		–	1.5×10^{-10}
Amaechi and Onwuka (2021)	Cretaceous	1.82×10^{-9}	3.22×10^{-8}	–	7.65×10^{-11}	1.35×10^{-6}	–	1.35×10^{-6}
Yahaya et al. (2023)	Cretaceous	4.38×10^{-9}	6.37×10^{-8}	–	1.84×10^{-10}	2.68×10^{-6}	–	2.68×10^{-6}
Amos et al. (2023)	Cretaceous	3.42×10^{-11}	2.07×10^{-9}	–	1.44×10^{-12}	8.71×10^{-8}	–	8.71×10^{-8}
Nwachukwu et al. (2010)	Tertiary	5.28×10^{-10}	–	–	2.22×10^{-11}	–	–	2.22×10^{-11}
Osu and Okereke (2010)	Tertiary	–	–	–	–	–	–	–
Nwachukwu et al. (2011)	Tertiary	7.41×10^{-11}	–	–	3.11×10^{-12}	–	–	3.11×10^{-12}
Okoro et al. (2013)	Tertiary	1.27×10^{-9}	–	–	5.35×10^{-11}	–	–	5.35×10^{-11}
Idugboe et al. (2014)	Tertiary	2.03×10^{-8}	–	–	8.51×10^{-10}	–	–	8.51×10^{-10}
Osakwe (2014)	Tertiary	1.99×10^{-8}	2.55×10^{-6}	–	8.38×10^{-10}	1.07×10^{-5}	–	1.07×10^{-4}
Akporido et al. (2015)	Tertiary	3.33×10^{-8}	3.13×10^{-9}	–	1.4×10^{-9}	1.31×10^{-7}	–	1.33×10^{-7}
Lawal et al. (2015)	Tertiary	1.65×10^{-9}	–	–	6.95×10^{-11}	–	–	6.95×10^{-11}
Chokor and Ekanem (2016)	Tertiary	–	–	–	–	–	–	–
Menkiti et al. (2017)	Tertiary	3.09×10^{-9}	1.53×10^{-7}		1.3×10^{-10}	6.43×10^{-6}	–	6.43×10^{-6}
Anegbe et al. (2018)	Tertiary	4.47×10^{-9}	–	–	1.88×10^{-10}	–	–	1.88×10^{-10}
Ibrahim et al. (2019)	Tertiary	–	–	–	–	–	–	–
Azorji et al. (2021)	Tertiary	6.57×10^{-10}	3.44×10^{-9}	9.27×10^{-11}	2.76×10^{-11}	1.44×10^{-7}	7.79×10^{-11}	1.44×10^{-7}
Osayande et al. (2022)	Tertiary	8.6×10^{-11}	8.34×10^{-12}	–	3.61×10^{-12}	3.5×10^{-9}	–	3.51×10^{-9}
Enete et al. (2022)	Tertiary	1.47×10^{-8}	1.08×10^{-8}	–	6.16×10^{-10}	4.53×10^{-7}	–	4.53×10^{-7}
Bridget et al. (2023)	Tertiary	–	–	–	–	–	–	–

children. As expected, the CDI values were lower in adults compared to children (Tables 12, 13 , 16 and 17).

The HQ and total HI for children and adults range from 2.63×10^{-10} (Cu of Pam et al., 2013b) to 0.048 (Pb of Eluyera and Tukura 2020), 1.13×10^{-10} (Cu of Pam et al., 2013b) to 0.0204 (Pb of Eluyera and Tukura 2020), 5×10^{-6} (Abii 2012) to 0.052 (Eluyera and Tukura 2020) and 7.52×10^{-7} (Abii 2012) to 0.0433 (Osakwe 2014) respectively (Tables 14–15). The exposure of adults and children to multiple PTEs through inhalation at AMW sites gave values that were less than 1 which implies no significant non-cancer risks (Wei et al., 2015).

The children and adults carcinogenic risk (CR) and total carcinogenic risk (TCR) values range from 1.46×10^{-8} (Pb of Pam et al., 2013b) to 23.98 (Cr of Osakwe 2014); 6.53×10^{-14} (Pb of Pam et al., 2013b) to 1.07×10^{-5} (Cr of Osakwe 2014); 6.96×10^{-7} (Nwachukwu et al. 2011) to 23.98 (Osakwe 2014); and 3.11×10^{-12} (Nwachukwu et al. 2011) to 1.07×10^{-4} (Osakwe 2014) respectively (Tables 16 and 17). The calculated CR and TCR for children and adults exposed to PTEs through inhalation are within the acceptable range of values (1×10^{-6} to 1×10^{-4}) suggested by the United States Environmental Protection Agency (USEPA, 1996), Li et al. (2016) and Zhou et al. (2022). This makes their effects insignificant (no risk or negative).

5. Conclusion

The concentrations of PTEs (Pb, Cr, Cu, CD, Fe, Mn, Ni and Zn) in soils at AMW sites of the thirty-six reviewed articles were used to calculate the pollution indices, human health risk and statistical relationship between PTEs and geological environments. The degree of Igeo contamination in basement, cretaceous, and tertiary environments follows the decreasing order of Cr > Ni > Mn > Fe > Pb > Cu > Zn > Cd; Cr > Cu > Fe > Pb > Zn > Ni > Mn > Cd; and Fe > Ni > Cr > Mn > Cd > Pb > Cu > Zn respectively. Similarly, the degree of ERF contamination in basement, cretaceous, and tertiary environments follow the decreasing order of Cd > Pb > Ni > Cr > Cu > Mn > Fe > Zn; Cd > Cu > Cr > Pb > Ni > Zn > Fe > Mn; and Cd > Fe > Ni > Pb > Cu > Cr > Mn > Zn respectively. The potential ecological risk factor (RI) showed that AMW soils have low to considerable risk (cretaceous environments), low to moderate risk (basement environments) and low to high risk (tertiary environment) respectively. The human health risk assessment revealed that the calculated HI, CR and TCR values were within the acceptable limits, which imply that children and adults are not at risk of developing non-cancer and cancer diseases. Pairwise relationships among PTEs revealed strong correlation for Cu-Mn (−0.6086, −0.5395 and 0.7398) and Fe-Mn (0.9998, 0.8416 and 0.6989) across the three geological terrains.

Analysis of variance revealed that PTEs values were higher than the alpha level of 0.05, which implies that the null hypothesis was accepted for all. This implies that the level of soil pollution is almost the same across different geological environments with very little variation.

The scope of this study is limited by the availability of data in three out of five geological environments in Nigeria. Future reviews should consider incorporating groundwater contamination data and longer periods of study to provide a more comprehensive assessment of the PTEs contamination in AMW soils and groundwater and for the remaining two environments to get data. In addition, future research should also assign weighted values to various automotive activities that may contribute to elevated concentrations of PTEs in soils in order to accurately determine the potential environmental and health hazards. This review is vital for future policy making and planning to mitigate these risks.

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Dr. Ale has the right to review a trending topic.

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