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Human health risk assessment of potentially toxic elements in soil and air particulate matter of automobile hub environments in Kumasi, Ghana

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ABSTRACT

Rapid urbanization and uncontrolled industrial activities in developing countries have raised concerns about potentially toxic metal contamination of the environment. This study assessed the levels of potentially toxic elements in soil and airborne particulate matter in the Suame and Asafo areas in the Kumasi metropolis, characterized by a high concentration of auto mechanic workshops and residential settlements. X-ray fluorescence analysis and inductively coupled plasma-mass spectrometry were used to determine the metal concentrations in the samples. The results showed high concentrations of potentially toxic elements in the soil and air samples, indicating contamination from automotive activities. Metals such as Co, Ni, Pb, and Zn were found to be present at concentrations (13.42–6101.58 mg/kg and 14.15–11.74 mg/kg for Suame and Asafo respectively) that pose potential health risks to exposed populations. Mathematical models such as pollution indices were used to assess the extent of contamination and determine the potential sources of the metals - the automotive repairs. The findings highlight the urgent need for environmental management and remediation strategies to mitigate the health risks of exposure to potentially toxic elements in the Kumasi metropolis automotive hub.

1. Introduction

Urban areas in most developing nations, including Ghana, are densely populated and host various human pursuits. These areas usually have no clear boundaries between industrial, residential, and commercial activities. The root cause of this phenomenon can be attributed primarily to inadequate industrial urban planning and zoning practices, as well as a lack of stringent enforcement of laws governing human activities [1]. Industrial activities significantly impact countries' economic and urban development [2] by providing people with social amenities, healthcare facilities and jobs. However, the uncontrolled acceleration of industrial activities releases potentially toxic elements into the environment, endangering human health and the ecosystem [3]. The contamination of the environment by potentially harmful elements arising from human activities has become a significant global concern. These elements accumulate in urban soil and waterways, posing a grave threat to urban agriculture and water supplies [4,5].

Soils frequently serve as reservoirs for potentially toxic elements due to non-biodegradable element bioaccumulation, and topsoils may also serve as sources for re-introducing these elements into the environment, either through water or air currents caused by erosion or windy conditions [6]. Exposure to airborne particulate matter is a major emerging issue in working environments and along roadsides with heavy traffic due to its potential to precipitate various health issues [7,8]. The presence of potentially toxic elements such as Cu, Ni, Pb, and Zn in airborne particulates may contribute to some degree of health effects such as triggers of carcinogenesis, teratogenesis and mutagenesis [9]. Because of particulate matter-related health problems in the sensitive population, most cities have focused on routine particulate matter monitoring [10,11]. The harmful effects of air particulates on health are frequently attributed to their particle size, as indicated by PM_{10} or $PM_{2.5}$, or their chemical composition. The chemical composition of fine particulate matter can reveal the hazards of this air pollutant to human health which is very important concerning the number of people at risk and the

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continuous nature of exposure [7,8].

Informal economic activities, such as auto mechanic workshops, have increased in most developing countries' urban areas, contaminating soil and other environmental matrices with toxic elements [5]. Heavy metal contamination has been reported in surface soils near auto mechanic workshops in Ghana [12–14]. Notably, artisanal activities in these areas generate a significant amount of untreated waste [12], which is carelessly released into the environment, polluting it with potentially toxic elements.

Several activities are carried out at auto mechanic workshops, including engine repairs and body spraying. These activities involve releasing potentially toxic elements in oils, greases, gasoline, and other substances into the soil and atmosphere. This study aims to assess the levels of potentially toxic elements in soil and air particulates in the Suame and Asafo suburbs of the Kumasi metropolis, which are well-known automobile hubs in Ghana. Additionally, it serves as a residential settlement area for the populace. The ecological and human health risks associated with exposure to contaminants in these mixed activity areas were modelled based on the concentrations of the metals found.

This study provides valuable insights for policymakers, urban planners, and environmental agencies in developing countries to address the environmental challenges associated with industrial activities in urban areas. Adopting sustainable practices and implementing effective measures to control the release of contaminants into the environment from auto mechanic workshops are critical to protecting human health and preserving the ecosystem.

2. Material and methods

Kumasi metropolis lies between latitudes 6.35°N and 6.40°S and longitude 1.30°W and 1.35°E with an area coverage of about 299 km^2. Kumasi is primarily a commercial/trade centre, with trade and commerce employing approximately 71% of the population, followed by industry and agriculture, which employ 24% and 5%, respectively [15]. Suame Magazine is a light industrial facility in the municipality of Kumasi with numerous metal engineering, manufacturing and vehicle repair shops. It is a major manual auto mechanic centre in the West African subregion [16,17]. Asafo is a prominent area in the Kumasi Metropolis known for its concentration of auto mechanic workshops, with a few residential areas scattered throughout. Auto mechanic workshops are noted for various activities, including engine servicing, body spraying, and changing filters and engine oils. These operations always result in the dumping of gasoline, grease, oil, battery electrolyte and other substances containing metals into the soil [18,19].

2.1. Soil sampling

Soil samples were systematically collected over 100 m x 100 m grid nets (Fig. 1) at a depth of 0–10 cm from Suame (n = 100) and Asafo (n = 31) areas at 100 m apart. About 0.5 kg of soil sample was collected at each sampling point and placed into well-labelled Ziplock bags. The sampling points were recorded with a hand-held geographic positioning system (GPS). A total of 145 composite samples, including 14 replicates, were collected from both sites during the dry season (February 2022). The control samples (n = 20) were gathered from the pristine areas of the KNUST Botanical Gardens (~15 km from Suame), with little human activity.

2.2. Air sampling

Particulate air matter, specifically total dust PM_{10}, was collected alongside soil samples from selected locations in two study sites. The samples were obtained using SKC Sidekick pumps (SKC Ltd. Dorset, United Kingdom) operating at a flow rate of 2 ± 0.1 L/min, positioned at the nose level, for 6 h [19]. The sampling procedure involved using air sampling cassettes (Millipore, Bedford, MA, USA) that were equipped with 5 mm pore size polyvinyl chloride membrane filters mounted in the workers' breathing zone at the sampling locations. The sampler functioned by drawing particles from the air onto the filter located in the cassette.

2.3. Sample preparation and instrumental analysis

The soil samples were air-dried in fume hoods at room temperature, sieved through a 250 μm sieve, and stored in Ziplock bags with labels. The metal contents of the sieved soil samples were determined using a

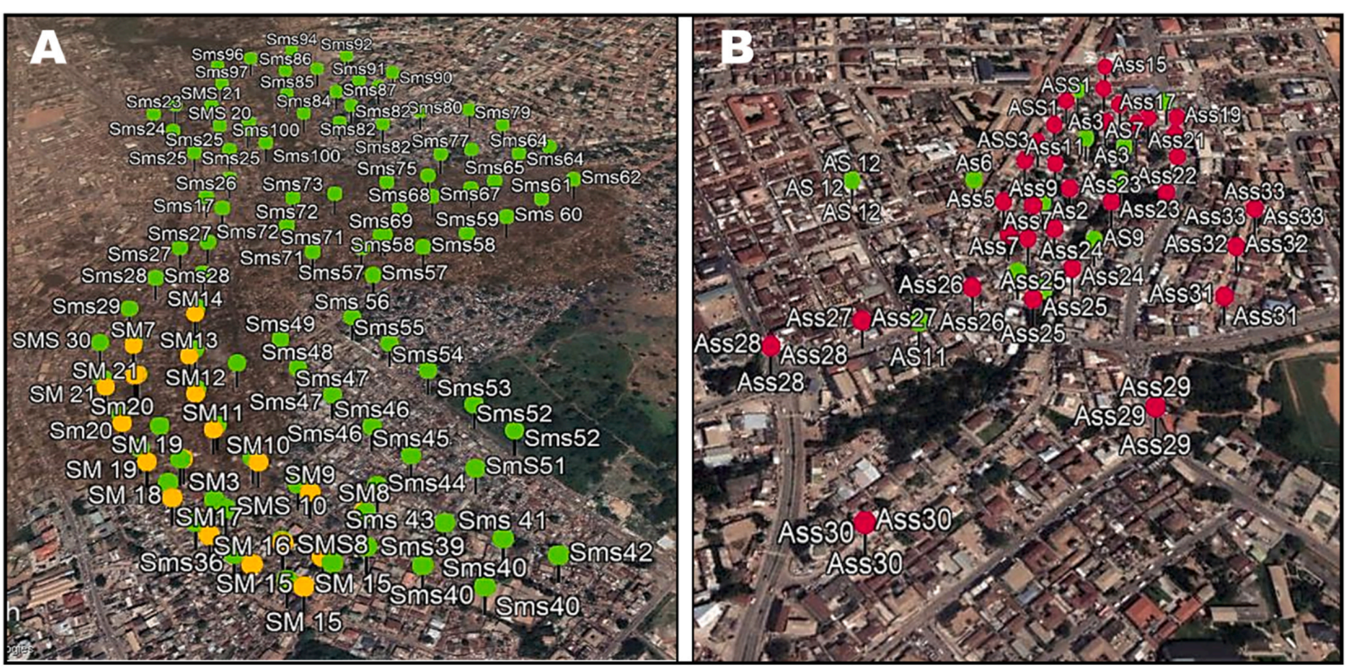

Fig. 1. Google Earth image of sampling points at Suame [A] and Asafo [B] study areas [Green colour indicating only soil was taken; Yellow and Red showing where both soil and air were sampled at Suame and Asafo, respectively].

Niton XL3t GOLDD+ X-ray fluorescence (XRF) analyzer and the United States Environmental Protection Agency Method 6200 [20]. Before analyzing the sieved soil samples, the XRF analyzer was checked for system errors, and a NIST 2711a certified standard reference material was run. Approximately 2 g of the sieved soil sample was taken and placed in a polyethene container, filling it up to about three-quarters of its capacity, and the sample was scanned in the XRF for 180 s. Each sample was run in triplicates, and the readings were averaged [21]. For the air samplers, the filters in the cassettes were individually removed and placed into the XRF sample shroud, where they were scanned for 180 s, and the readings were recorded as metal concentrations in the sample. A triplicate run using NIST 2711a certified reference material consistently produced recoveries within ± 10% of the certified value for each target analyte. Satisfactory reproducibility was demonstrated through the analysis of 10 replicates showing an average relative percent difference of ≤ 15% for all the metals. The XRF typically produces results for 24 elements; however, 11 toxicologically significant elements were used in this study. The limit of detection for the selected elements, based on three times the detector-estimated measurement error associated with the readings [22], are As (<2 mg/kg), Cd (<3 mg/kg), Co (<10 mg/kg), Cr (10 mg/kg), Cu (<6 mg/kg), Hg (<3 mg/kg), Mn (12 mg/kg), Ni (<10 mg/kg), Pb (2 mg/kg) and Zn (<3 mg/kg).

A multiparameter probe (Oakton Waterproof Multiparameter PCSTestr35, USA) was used to measure soil pH and electrical conductivity. The pH and EC analysis were carried out by combining 20 g of dry soil with 40 mL of distilled water (1:2 dry soil to distilled water ratio). The suspension of water and soil particles was allowed to settle for 10 min before determining the pH and EC of the supernatant liquid.

2.4. Statistical Analysis and Spatial Distribution

Descriptive statistics were conducted using the R statistical package version R-4.2.2 for Windows (R Foundation) and Minitab version 16.2.1 (Minitab Inc., USA). Using Golden Software Surfer Version 13 (Colorado, USA), the spatial distribution of metals in the air and soil were examined. The data were gridded using the minimum curvature algorithm [23], which uses tension splines to improve the smoothness and consistency of the generated grids [23] to gain insights into the spatial distribution of the metals.

The heat maps were created in ArcGIS ArcMap ver10.5 using the kernel density interpolation tools [24]. The resultant raster was classified into low, mid, high and very high concentrations.

The Principal Component Analysis (PCA) assessed the multivariate relationships and variances among the elements after the varimax rotated data [25]. Principal components having eigenvalues greater than 1.0 were considered. The PCA allows a considerable reduction in the number of variables and the detection of structure in the relationships of different variables.

2.5. Pollution estimation

The obtained levels of the potentially toxic elements were used to characterize the two study sites to ascertain the potential impact of the varied activities on the areas.

2.6. Geoaccumulation Index (Igeo)

The geo-accumulation index was used to calculate the metal contamination level within the study areas. Eq. 1 was used to calculate the metal index in the soil samples used in this study.

$$\text{Igeo} = \log_2\left(\frac{Cn}{1.5Bn}\right) \tag{1}$$

Where; Cn = measured metal concentration in soil, Bn = background values of metal concentrations. 1.5 = the background matrix correction factor due to the lithogenic effects. The Igeo data was evaluated using the following descriptive classes: ≤ 0 = unpolluted; 0–1 = unpolluted to moderately polluted; 1–2 = moderately polluted; 2–3 = moderately to highly polluted; 3–4 = highly polluted; 4–5 = highly to extremely high polluted; and 5–6 extremely high polluted [26].

2.7. Enrichment factor

The enrichment factor (EF) was utilized to determine the extent of anthropogenic heavy metal pollution and to distinguish between sources from human-caused activities and those that occur naturally [27]. The EF computations are as shown in Eq. 2, which is the ratio between the concentrations of the metal (M) and those of the normalizer (N),

$$\text{EF} = (\text{M/N})_{\text{sample}}/(\text{M/N})_{\text{baseline}} \tag{2}$$

The concentration of Fe was used as the reference for normalization [28]. An EF greater than one indicates enriched metal concentrations, likely anthropogenic, while EF less than 1 indicates natural sources [29].

2.8. Contamination factor

The contamination factor (CF) indicates the soil contamination level. It is computed using the measured concentrations of the potentially toxic elements and their corresponding values in background samples (Eq. 3).

$$\text{CF} = \frac{Mx}{Mr} \tag{3}$$

Mx and Mr are the mean concentrations of the metal contaminants in the soil samples and background reference material, respectively [30]. The designation of the CF classes are as follows: CF < 1 = low contamination; 1 – 3 = moderate contamination; 3 – 6 = considerable contamination, and > 6 = very high contamination [31].

2.9. Potential ecological risk index (PERI)

The potential ecological risk index (PERI) evaluates soil metal pollution using CF and environmental response (Trf), calculated using Eq. 5.

$$PERI = \sum_{i}^{n}(Trf \ x \ CF) \tag{4}$$

The toxic response factors for metals follow the following order: Zn = 1, Cr = 2,Co = Cu = Pb = 5, Ni = 6, As = 10, Cd = 30, and Hg = 40. The ecological risk level can be categorized as follows: PERI < 40 (low risk), 40 ≤ PERI < 80 (moderate risk), 80 ≤ PERI < 160 (considerable risk), 160 ≤ PERI < 320 (high risk), and PERI ≥ 320 (very high risk) [32].

2.10. Human health risk assessment

Human health risk assessment helps determine the risk of contaminant exposure in workplaces, protecting workers and others [28]. The effects of pollution or heavy metals on humans and the environment depend on their chemical characteristics, particle sizes, and exposure time. Heavy metal exposure can occur through direct ingestion, inhalation, and dermal absorption. The dose received through each path is calculated using Eqs. (5) - (7) [28]..

Dose intake by dermal contact (Dderm) is given as indicated in Eq. 5 (parameters are defined in Table 2):

$$\text{Dderm} = \text{C x} \frac{\text{SL x SA x ABS x EF x ED}}{\text{BW x AT}} \text{x} 10^{-6} \tag{5}$$

Dose intake by ingestion (Ding) is given as follows:

Table 1
Reference dose (RfD) for selected elements for the three exposure routes (Baptista et al., 2005).

Elements	As	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Zn
RfDinh	0.000086	-	-	0.0000285	-	0.000086	0.00143	-	-	-
RfDing	0.0003	0.0005	0.01	0.003	0.037	0.0030	0.024	0.00186	0.0036	0.3
RfDder	0.0003	0.0005	0.01	0.003	0.037	0.0030	0.024	0.00186	0.0036	0.3

Table 2
Exposure factors and the reference value of parameters used for the human health risk assessment of heavy metals/metalloids.

Factor	Definition	Unit	Value		Ref.
			Children	Adult	
C	the concentration of elements in the sample	mg/kg			this study
BW	body weight	kg	15	70	[33]
EF	exposure frequency	days/ year	350	250	[33]
ED	exposure duration	years	6	24	[33]
AT	average time	days	2190	8760	[33]
IngR	ingestion rate	mg/day	200	100	[33]
InhR	inhalation rate	m^3/day	10	10.4	[33]
PEF	particulate emission factor	m^3/day	1.3×10^9	1.3×10^9	[33]
SA	exposed surface area	cm^2/ day	5800	13110	[34]
AF	skin adherence factor	mg/ cm^2/ day	0.07	0.07	[34]
ABS	skin absorption factor	no unit	0.01	0.01	[34]

$$\text{Ding} = C \quad x \quad \frac{IngR \quad x \quad EF \quad x \quad ED}{BW \quad x \quad AT} x10^{-6} \tag{6}$$

Dose intake by inhalation (Dinh) of soil particles is given as:

$$\text{Dinh} = C \quad x \quad \frac{InhR \quad x \quad EF \quad x \quad ED}{PEF \quad x \quad BW \quad x \quad AT} \tag{7}$$

The organism is assumed to tolerate a tolerable daily intake or a reference dose with little to no risk of adverse health outcomes in risk assessments for non-carcinogenic toxicants [35]. For the determination of non-carcinogens or non-cancer risk of exposure, Eq. (8) [36] is used:

$$\text{HQ} = \frac{DI}{RfD} \tag{8}$$

Where HQ is the hazard quotient for a particular route of exposure, DI is the dose intake by a given route of exposure, and RfD is the reference dose for a particular element through a particular route.

The hazard index (HI) is calculated to determine the overall risk of exposure via ingestion, inhalation, and dermal contact using Eq. (9).

$$HI = HQ_{ing} + HQ_{inh} + HQ_{derm} \tag{9}$$

Where: HI is the hazard index, and HQ(ing, inh, and derm) represent the hazard quotients of the routes of exposure.

The hazard index is calculated as the sum of each metal's hazard quotients across all exposure pathways [37]. The hazard index is widely acknowledged as a valuable tool for assessing the health risks posed by contaminants [28]. An index below one indicates minimal or negligible non-cancerous impact or absence of adverse health risks. Conversely, a value above one raises concerns regarding potential health effects.

2. Results and discussion

3.1. Physicochemical parameters

The results of soil pH and electrical conductivity (EC) are shown in Table 3. The soil pH ranged from 8.88 to 11.00 for the Asafo study area with a mean of 9.89, and the soil pH for Suame ranged between 8.94 and 11.87 with a mean of 9.87. The soil samples from both sites exhibited alkaline soil characteristics, as indicated by a pH value greater than 7. The pH of the soils in the study is more alkaline than the national average of all soil types [38], the pH of the soils in the Kumasi Metropolis (which ranges between 4.69 and 8.66, with an average value of 7.97) [21], and a highly impacted waste electrical and electronic equipment dumpsite at Agbogbloshie, which ranges from 7.0 to 8.5 [39]. The high alkalinity could be due to the geological composition of the parent material from which the soil is formed [40], hampered leaching due to haphazard site planning, or oil and fluid leaks from the engines serviced at the sites. Leaking vehicle oils, transmission fluids, and other alkaline-containing fluids can gradually seep into the soil, potentially raising the pH in the area around the leak. High soil pH promotes metal retention and decreases metal solubility. The high soil alkalinity found at the study sites meant that the metals have been rendered insoluble and retained in the soil.

The electrical conductivity of the soil from Asafo ranged from 17.60 to 915.00 µS/cm with an average value of 124.60 µS/cm, and the electrical conductivity of soil from Suame ranged from 11.90 to 770.00 µS/cm with an average value of 146.30 µS/cm. Electrical conductivities

Table 3
Physicochemical parameters and concentrations of potentially toxic elements in soil.

		Physicochemical parameters		Metal concentrations (mg/kg)										
		pH	EC (µS/cm)	As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Ti	V	Zn
Asafo	Minimum	8.88	17.60	35.73	41.49	399.47	51.61	336.75	367.81	509.92	35.18	28.08	14.19	138.47
	Maximum	11.00	915.00	52.11	187.41	874.94	69.77	479.63	1174.63	658.33	120.73	295.76	19.00	775.41
	Median	9.88	83.40	42.38	53.17	480.33	55.84	393.10	451.30	601.11	43.86	56.63	15.38	156.06
	Mean	9.89	124.60	43.03	63.09	529.00	57.15	392.94	551.45	587.67	52.72	89.48	15.89	303.11
	Std. dev.	0.52	149.60	4.60	39.42	127.88	5.13	37.67	234.46	47.73	26.06	77.76	1.39	233.02
	Skewness	0.22	3.97	2.34	3.52	4.01	2.14	5.73	3.88	3.32	2.30	1.33	0.30	1.69
	Kurtosis	-0.11	19.34	7.21	15.03	17.28	5.41	34.36	15.50	12.09	5.72	2.06	-0.26	3.10
Suame	Minimum	8.94	11.90	39.52	29.07	511.66	51.22	336.85	409.27	322.85	43.79	49.91	13.42	264.28
	Maximum	11.87	770.00	195.39	59.50	1253.46	124.45	1260.65	2628.06	680.60	398.30	1179.71	42.26	6101.58
	Median	9.87	112.60	48.67	46.40	797.02	68.56	388.31	720.74	552.82	95.62	174.27	18.22	845.04
	Mean	9.92	146.30	65.51	46.14	828.65	74.06	469.80	1015.29	539.37	124.43	295.89	20.02	1354.01
	Std. dev.	0.50	132.60	41.51	7.23	226.58	19.82	210.93	728.24	92.54	100.36	326.02	7.48	1429.80
	Skewness	1.90	2.97	9.37	2.11	4.22	5.81	5.20	4.51	3.58	7.34	0.60	0.66	4.70
	Kurtosis	5.81	11.52	91.32	3.49	21.88	39.96	34.08	24.01	17.26	62.27	1.22	0.29	26.69

EC: Electrical conductivity

in the study areas were higher than in the Kumasi Metropolis, similar to pH [21]. Electrical conductivity is primarily affected by the presence of dissolved ions, particularly salts, which are responsible for soil solution conductivity. Electrical conductivity is usually high in soils that have been impacted by anthropogenic activities.

3.2. Potentially toxic metal concentrations in soil

Table 3 presents the descriptive statistics of concentrations of potentially toxic elements in soil samples collected from Asafo and Suame. The minimum concentrations observed at Asafo ranged from 14.19 mg V /kg to 509.92 mg Ni/kg, and the maximum concentrations observed ranged between 19.00 mg/kg to 1174.63 mg/kg for V and Mn, respectively. These findings indicate a wide range of concentrations for the different elements at Asafo, with Ni showing relatively higher mean and median values than the other elements. The mean concentrations of the elements varied from 20.02 mg/kg for V to 1354.01 mg/kg for Zn at the Suame hub. The median concentrations varied from 18.22 mg/kg for V to 845.04 mg/kg for Zn. Similarly, Zn exhibited higher mean and median concentrations at Suame.

These results highlight the variability in elemental concentrations in soil samples from both locations. The higher mean and median concentrations of Zn and Ni suggest potential anthropogenic inputs in these areas. Additionally, potentially toxic elements such as As, Cd, and Hg demonstrated relatively lower mean and median concentrations but exhibited higher maximum values, indicating localized contamination sources [41].

The concentrations of Cu, Cd and Pb in the two study areas were higher than that recorded in automobile mechanic workshops in Benin City, Nigeria [42] and Bogoso, Ghana [12]. However, the mean Pb concentration was lower than that reported from Sunyani, Ghana [43]. Again, this study reports higher Cu concentrations than what has been reported at an automobile workshop in Sunyani magazine, Ghana [43].

The country does not have its own guideline limits for metals in the soil. The WHO target values that indicate desirable maximum levels of metals in unpolluted soils are 0.8 mg Cd /kg, 50 mg Zn/kg, 36 mg Cu/kg, 100 mg Cr/kg, 85 mg Pb/kg, and 35 mg Ni/kg [44]. Except for Cr and Pb, which did not exceed the target values in the two sites, all other metals exceeded their respective target values, indicating metal contamination of the sites. Zinc exceeded its target value by 6-, and 27-fold in Asafo and Suame, respectively, while Cd exceeded by 79 and 58 folds respectively in the Asafo and Suame sites. Cadmium is one of the most hazardous heavy metals due to its considerable toxicity. Consequently, the elevated levels of cadmium within the environment raise significant concerns.

3.3. Spatial distribution of potentially toxic elements

Fig. 2A illustrates the spatial distribution of metals in the surface soils of Suame, with low concentrations of As observed in the North, East, and West areas. However, high to very high concentrations of As are found in the southern and central parts of Suame. The location showed very low concentrations of Cd, with the lowest levels occurring in the northern parts. In contrast, the northern parts rather showed very high concentrations of other metals, including Co, Ni, Pb, and Zn. While Cr is concentrated in the southeastern ports of the automobile mechanic hub, V and Ti are widely distributed at high concentrations across the entire area.

Fig. 2B displays the spatial distribution of toxic elements in the Asafo study area, with As concentrations ranging from low to high, with northern and western regions having the highest concentrations. Cd concentrations are primarily concentrated in the northwest. At the same time, Co levels vary, with high concentrations in the west, low in the east and south and high to very high concentrations in the central to the north. Asafo has similar distribution patterns for Pb, Zn, Mn, Ni, Ti, V, and V. The Pb and Zn levels are low in the west, south, and east, while central to northern regions have varying concentrations. Ni concentrations are high in the west, low in the south, and very high in the southeast. Ti concentrations vary in the north and central regions, while V concentrations are high in the south, east, and some of the north.

3.4. Potentially toxic metal concentrations in airborne particulates

The metal concentrations of the selected metals in the airborne particulates for Asafo and Suame are tabulated in Table 4. In the Asafo study area, the median concentrations ranged from 42.38 to 601.11 mg/kg, while the mean concentrations varied from 43.03 to 587.67 mg/kg. Compared to Suame Magazine, the median concentrations ranged from 46.40 to 845.04 mg/kg for Cd and Zn, respectively, while the mean concentrations ranged from 46.14 to 1354.01 mg/kg for the analyzed elements. Except for Cd and Ni that recorded lower concentrations in particulates in Suame than Asafo, all the other elements (As, Co, Cr, Cu, Mn, Pb, Ti, V and Zn) had mean concentrations higher than their values recorded in Asafo. Generally, the concentrations of metals did not statistically differ between the two areas (Mann-Whitney U = 95, $p = 0.9086$). The concentrations of 3 metals (Cr, Cu and Zn) in this study

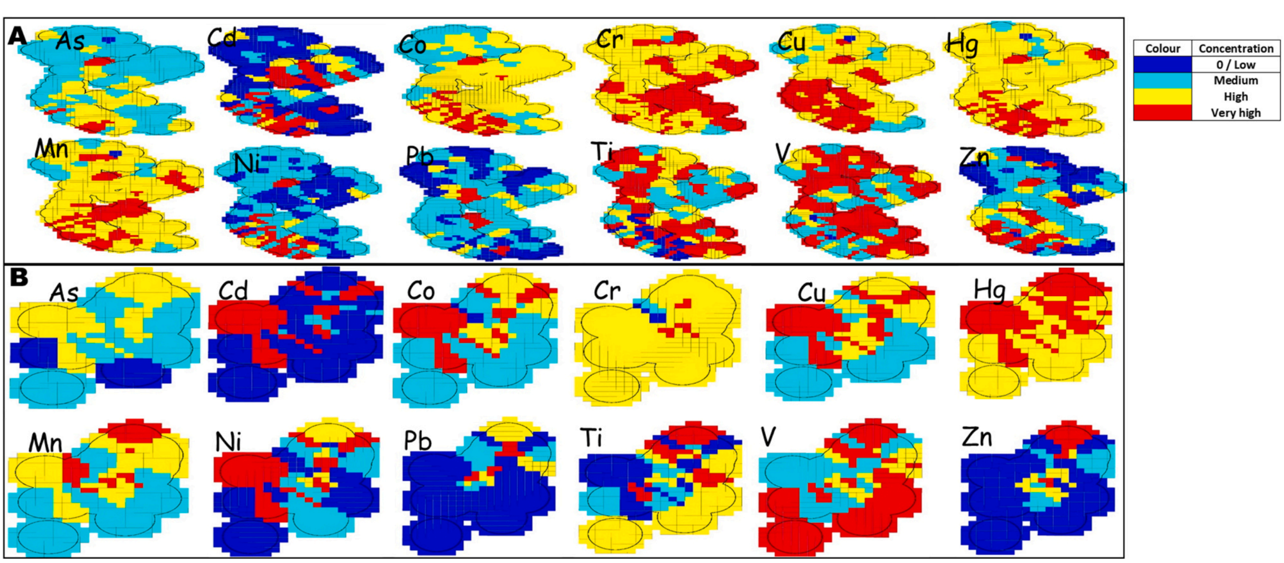

Fig. 2. Spatial Distribution Analysis of Metal Concentrations in Suame [A] and Asafo [B] Surface Soils.

Table 4
Descriptive Statistics of potentially toxic elements concentrations (mg/kg) in air particulates from Asafo and Suame.

		As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Ti	V	Zn
Asafo	Minimum	35.73	41.49	399.47	51.61	336.75	367.81	509.92	35.18	28.08	14.19	138.47
	Maximum	52.11	187.41	874.94	69.77	479.63	1174.63	658.33	120.73	295.76	19.00	775.41
	Median	42.38	53.17	480.33	55.84	393.10	451.30	601.11	43.86	56.63	15.38	156.06
	Mean	43.03	63.09	529.00	57.15	392.94	551.45	587.67	52.72	89.48	15.89	303.11
	Std. Dev	4.60	39.42	127.88	5.13	37.67	234.46	47.73	26.06	77.76	1.39	233.02
Suame	Minimum	39.52	29.07	511.66	51.22	336.85	409.27	322.85	43.79	49.91	13.42	264.28
	Maximum	195.39	59.50	1253.46	124.45	1260.65	2628.06	680.60	398.30	1179.71	42.26	6101.58
	Median	48.67	46.40	797.02	68.56	388.31	720.74	552.82	95.62	174.27	18.22	845.04
	Mean	65.51	46.14	828.65	74.06	469.80	1015.29	539.37	124.43	295.89	20.02	1354.01
	Std. Dev.	41.51	7.23	226.58	19.82	210.93	728.24	92.54	100.36	326.02	7.48	1429.80

were higher than that reported in the Manjung district of Malaysia [45], the Megalopolis city in Greece [46], and Frankfurt and Main in Germany [47].

Airborne particulates contribute significantly to air pollution in industrial hubs and heavy traffic areas. These toxic metals, including Cd, Cr, Cu, Pb, and Ni, can cause health issues like carcinogenesis, teratogenesis, and mutagenesis. The study found higher levels of Cd, Cu, Mn, Zn, and Pb in airborne particulates than in Accra, Ghana [48], posing risks to vulnerable groups like pregnant women and children.

Between the two sites, there were significant differences in soil and air samples (Kruskall-Wallis $H = 12.64$, $p = 0.005454$). A Mann-Whitney pairwise test was used to investigate this further, and it identified the sample differences. The concentrations of potentially harmful metals in the soil from the study areas differ significantly, but those in the air do not..

3.5. Principal component analysis

The principal component analysis identified a component with an eigenvalue of 10.05, which accounted for 83.8% of the total variability, as the source of the metals in the Suame air particulates. The component is heavily weighted by Cd, Ni, and Hg (with large negative loadings) and Co, Cr, Mn, Pb, Ti, V and Zn (with large positive loadings). Various auto mechanic repair activities, metal smelting, and refining processes likely cause the release of potentially toxic elements into the atmosphere.

The principal component analysis, however, revealed two sources of heavy metals in the airborne particulates in Asafo, with the first principal component (Hg, Ni, Cd, and Cu) accounting for 53.4% of the total variance while the second (As, Co, Pb, Ti, Zn, V, Mn, and As) accounting for 29.5% of the total variability.

Table 6 presents a principal component analysis of surface soils in various study areas, revealing three main sources of potentially toxic elements in Asafo soil. Principal component 1 (made up of As, Cd, Co, Cr, Mn, Ni, and Zn) has an eigenvalue of 6.593, accounting for 45.9% of total loadings, while components 2 (Cu, Hg, Pb) and 3 (Ti and V) have eigenvalues of 2.043 and 1.275, respectively. These elements are attributed to various activities at automobile workshops.

Asafo surface soil had four components from the principal component analysis, with Component 1 (loaded with As, Co, Mn, and Ni) having an eigenvalue of 4.715 (29.3% of total metal loadings), Component 2 (loaded with Ti, V, and Zn) with an eigenvalue of 2.255 (18.6% variance), Component 3 (loaded with Cr) with an eigenvalue of 1.245 (15.5% variance), and PC4 (loaded with Cu, Hg, and Pb) with an eigenvalue of 1.146 (14.6% variance).

Table 5
Component characteristics of air particulates in Suame and Asafo study areas.

Location	Component	Eigenvalue	Rotated solution		
			Sum of sq. loadings	Proportion of variation	Cumulative
Suame	Component 1	10.05	10.05	0.838	0.838
Asafo	Component 1	7.448	6.409	0.534	0.534
	Component 2	2.462	3.541	0.295	0.829

Table 6
Component characteristics of surface soil in Suame and Asafo study areas.

Location	Components	Eigenvalue	Rotated solution		
			Sum of sq. loadings	Proportion of variation	Cumulative
	Component 1	6.593	5.504	0.459	0.459
	Component 2	2.043	2.204	0.184	0.642
Suame	Component 3	1.275	2.203	0.184	0.826
Asafo	Component 1	4.715	3.521	0.293	0.293
	Component 2	2.255	2.230	0.186	0.479
	Component 3	1.245	1.859	0.155	0.634
	Component 4	1.146	1.750	0.146	0.780

3.6. Pollution characterisation of the study site

The study areas were characterized using different pollution indices, as estimated in Table 7. Igeo classified the surface soils of Asafo and Suame as unpolluted to moderately polluted for all potentially toxic elements except Cd. Contamination factor rankings characterized Asafo surface soil as uncontaminated with Hg, Mn, Ni, Ti and V; moderately contaminated with As, Cr, Cu and Co but very highly contaminated with Cd, Pb and Zn. Suame surface soils, on the other hand, were characterized as uncontaminated with Hg, Mn, Ni, Ti and V; moderately contaminated with As, Cr and Cu and highly contaminated with Cd, Co, Pb and Zn.

In terms of enrichment factor, the surface soils of the Asafo automobile hub were enriched with all of the potentially toxic elements studied except Hg, Mn, Ni, and Ti, which was similar to the surface soils of the Suame study area, which were enriched with all of the potentially toxic elements studied except Hg, Mn, Ni, and V. Thus, the study areas could be said to be highly enriched with potentially toxic elements, and the surface soils in the areas could be said to be heavily influenced by the activities that occur in the automobile hubs.

According to the ecological risk assessment, the Asafo study area is generally a low-risk ecological area for all of the analyzed potentially toxic elements, except for Cd, which poses a very high ecological risk to humans (PER = 659). Similarly, Cd had a PER value of 882.7 in the Suame study area, indicating a high ecological risk to humans in the Suame automobile environment.

3.7. Pollution estimation

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3.8. Risk assessment

Fig. 3 illustrates the hazard index (HI) for children and adults in the study area. The hazard quotients (HQ) and indexes for potentially toxic elements for children and adults were evaluated under three exposure pathways to potentially toxic elements from the soil. Any values higher than unity indicate an elevated risk and possible adverse health [49]. Children are exposed to higher risks than adults because children recorded higher hazard indices than adults. Approximately, 29% of the samples from the Asafo study area around the vicinity of auto-mechanic facilities/workshops registered HI < 1, making them unlikely to pose any adverse health risks resulting from metals. Children exposed to the soil will likely experience adverse health effects from the 71% of the samples that recorded HI > 1. However, only one of the 31 samples (HI = 1.039) can negatively impact or pose adverse health effects. Sixty-nine per cent of soil samples from Suame had As levels registering HQ > 1, indicating they are likely to pose risks and harmful adverse health effects on children. In contrast, only 4% of the samples were likely to have harmful adverse health effects on adults.

Cd in Asafo samples in this study is likely to pose adverse health effects to children as 100% of the samples in this investigation had HI > 1, with a minimum HI of 3.37 and a maximum HI of 4.84, the amount of cadmium present is likely to be harmful to children's health. Approximately 16% of the samples are likely to cause adverse health effects resulting from Cd to adults, but there is an increased risk for all samples to cause adverse effects over time to adults since the minimum HI of 0.75 is closer to 1 and Cd coupled with its persistent and bioaccumulative nature, may accumulate over time and have adverse health effects on adults. However, there is an increasing risk that all samples will adversely affect adults over time. With samples from Suame expected to have adverse effects, 100% and 31% will likely pose adverse effects resulting from Cd to children and adults due to Cd, respectively. The highest Co levels show no sign of adverse health effects to adults and children because the maximum HI are less than one (adults = 0.04 and children = 0.19).

One sample out of 31 had a Cr level with HQ < 1. The remaining 30 samples had HI > 1 and reached 32. This indicates a higher likelihood of adverse health effects for children within the vicinities of these auto-mechanic workshops. About 6% of the samples are not likely to pose adverse health effects from Cr to adults working or living in these areas. Cu and Zn levels in this study do not pose any adverse health effects as they all recorded HI < 1. These metals are essential because humans need them in trace amounts for the normal functioning of the human body.

Mn levels show that 13% of the samples will likely pose adverse health effects to children but not adults. Pb levels indicate the likelihood of adverse health effects to children from 100% of the samples and adults from 6%. Ni behaved like Cu and Zn in this study as it is not likely to pose any adverse health effects as HI < 1. The cumulative effects of the HI, which is indicated by the Total hazard quotient (THQ), show a higher likelihood of non-carcinogenic adverse health effects posed to children (THQ = 7.34–62.10) and adults (THQ = 1.07–10.97).

The potentially toxic elements, including As, Cd, Cr, and Pb, contributed mainly to the overall risk, while Mn contributed in a few instances. The order of the extent of contribution to the overall risk (THQ) is Cr > Pb > Cd > As > Mn for children and Cr > Cd > Pb > As > Mn for adults. The order of contribution of pathways to the overall risk is dermal > ingestion > inhalation for Cd and Cr in both adults and children, as well as As and Pb in adults. For Mn in adults and children, as well as As and Pb in children, the order is ingestion > dermal > inhalation. Children who live on-site or are brought there by parents are at higher risk because of their hand-to-mouth activities [50] and lower body mass [51].

4. Conclusion

This study comprehensively assesses potentially toxic elements in soil and airborne particulate matter in two automotive hubs in Kumasi, Ghana. The results indicate that soil in the study areas is contaminated with potentially toxic elements, exceeding background levels. The pollution assessment models, including geoaccumulation index, enrichment, and contamination factors, reveal moderate to highly polluted soil conditions near auto mechanic workshops. Furthermore, the pollution load index calculations confirm the overall pollution status, categorizing the sampled areas as moderately to strongly polluted.

Airborne particulate matter, specifically PM_{10}, was also found to contain elevated levels of potentially toxic elements, further emphasizing the risks associated with exposure to these pollutants. The elemental composition of fine particulate matter plays a crucial role in determining health hazards, particularly due to the toxicity of the metals and the continuous nature of exposure. The findings highlight the significant contamination of the environment by potentially harmful elements resulting from various human activities, particularly in the areas surrounding auto mechanic workshops. The presence of metals such as Cu, Ni, Pb, and Zn in soil and air particulates poses potential risks to human health, including the development of carcinogenic, teratogenic, and mutagenic effects.

The study highlights the urgent need for environmental management and control measures to mitigate the risks posed by potentially toxic elements in soil and airborne particulate matter. Implementing stricter regulations and enforcing existing laws governing industrial activities, particularly in densely populated urban areas, is crucial. Additionally, measures should be taken to promote proper waste management practices in auto mechanic workshops to prevent the careless release of untreated waste containing potentially toxic elements into the environment. Furthermore, the study emphasizes the importance of public awareness and education regarding the risks associated with exposure to potentially toxic elements. Efforts should be made to educate workers and residents in the affected areas on properly handling and disposing of hazardous substances and personal protective measures.

Table 7
Mean Pollution Indices of Asafo and Suame study sites.

		As	Cd	Cr	Co	Cu	Hg	Mn	Ni	Pb	Ti	V	Zn
	Igeo	-0.82	3.86	-0.81	1.86	0.47	-2.89	-1.98	-1.31	2.86	-10.12	-0.81	1.67
Asafo	CF	1.08	21.97	1.00	5.79	3.19	0.40	0.32	0.74	20.87	0.0014	0.80	6.37
	EF	1.15	30.14	1.12	6.97	3.34	0.47	0.49	0.80	23.36	0.002	1.09	6.59
	PER	10.83	659.20	2.00	28.95	15.98	15.99	0.52	3.71	104.4	0.0014	1.60	6.37
	Igeo	-0.77	4.16	0.03	2.07	1.06	-4.21	-1.45	-1.57	2.45	-0.75	-0.82	1.81
Suame	CF	1.87	29.12	1.78	6.69	5.41	0.12	0.69	0.68	13.68	0.93	0.89	7.45
	EF	1.09	31.83	1.73	6.52	4.50	0.11	0.59	0.62	11.98	1.02	0.93	6.58
	PER	18.77	882.70	3.57	33.48	27.06	4.91	0.69	3.41	68.40	0.93	1.79	7.45

Igeo = Index of geoaccumulation; CF = Contamination Factor; EF = Enrichment factor; PER = Potential Ecological Risk factor

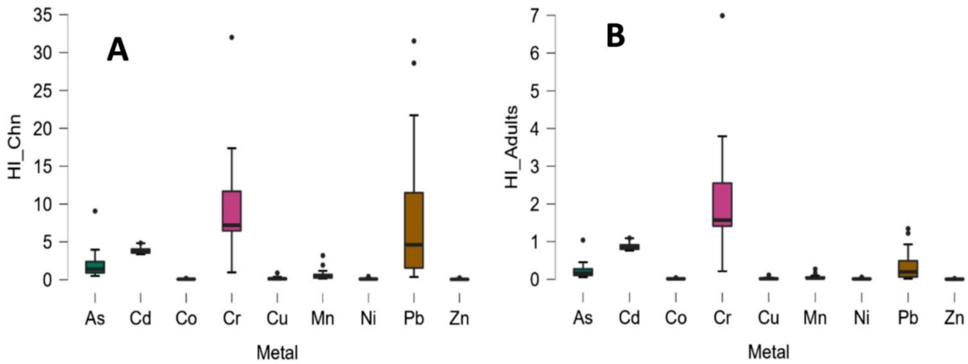

Fig. 3. Hazard Indices for Children and Adults.

Availability of data and materials

All data generated or analyzed during this study are included in this published article. The raw datasets are available from the corresponding author upon request.

Ethics approval and consent to participate

Not applicable; no human or animal subjects were directly used in the study for which approval ought to be sought.

Consent for publication

All authors have proofread the manuscript and approved the submission.

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CRediT authorship contribution statement

Godfred Darko, **Matt Dodd**, and **Lawrence Sheringham Borquaye** were in charge of research Conceptualization, Methodology, oversight, and leadership. **Francisca Nti Konadu**, **Opoku Gyamfi**, **Eugene Ansah**, **Seth Obiri-Yeboah**, and **Godfred Darko** collected and analyzed the samples, while **Victor Agyei** and **Emmanuel Dartey** curated the data. **Francisca Nti Konadu** wrote the first draft, which was edited and approved by all of the authors.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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