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Research article

Assessment of elemental chemistry, spatial distribution, and potential risks of road-deposited dusts in Sharjah, United Arab Emirates

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ABSTRACT

Road dust is a major source of pollution in the environment, carrying different pollutants, including heavy metals and metalloids, from one location to another. This study assesses the concentrations of eight heavy metals and one metalloid (Zn, Pb, Mn, Fe, Cr, Cu, Cd, Ni, and As) in dust samples collected from sixty-eight streets of Sharjah, United Arab Emirates using ICP-OES, as well as investigates their effects on both the environment and humans. Mean concentrations of the elements in μg/g across the sites were 392 ± 46 (Zn), 68.28 ± 11.3 (Pb), 1437 ± 67 (Mn), 39,481 ± 4611 (Fe), 460 ± 31 (Cr), 150 ± 44 (Cu), 1.25 ± 0.65 (Cd), 856 ± 72 (Ni), and 0.97 ± 0.28 (As). The C_{deg} and ERI calculated from the study were 54.79 and 573, respectively, suggesting varying pollution levels. The highest contributions were from Ni, Cd, Zn, Cu, Cr, and Pb, especially in areas with heavy traffic. The non-carcinogenic risk assessments were generally low for the three routes of exposure, except HQ_{oral} that was slightly higher for children. Similarly, none of the elements exhibited any carcinogenic risk except chromium. Overall, the cancer risk is considered low. In view of the limited studies from UAE in relation to the metal content of road-deposited dusts, the current study serves as novel knowledge, especially in the context of geographical areas with a higher occurrence of sandstorms and the presence of particulate matter. The study also adds to the global understanding of the contribution of street dust to environmental pollution and its implications for human health.

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1. Introduction

Road dust has been considered a very important means for assessing the quality of an urban environment [1,2]. It is defined as solid particles with sizes below 1.0 mm, which are found accumulated on any hard surface such as roadways or asphalt in an urban environment [3]. It is also a receptor of particles from the atmosphere and other environmental sources [4], and so has become a major source of pollution. Road dust is carried from one location to another, re-suspended in the air in some cases or carried into the nearby waterbodies by means of sewage or stormwater runoff [5,6]. Pollutants of automobile origin, such as vehicular emission, fluid leakage, wear of component parts, and metallic corrosion, are considered major sources of heavy metals in urban or roadside dust [7,8]. Other main sources include domestic and industrial emissions, wear and tear of building materials, polluted soil, mining activities, and illegal disposal of industrial waste. Heavy metals could also emanate from natural sources such as erosion, soil particle deposition from the atmosphere, and weathering [9,10].

Heavy metals and metalloids are often found in higher concentrations in urban dust compared to soils or dust from other local areas, owing to several anthropogenic activities taking place in cities [11]. Concentrations of these metallic elements in the dust could also be influenced by the concentration of their organic matter, as well as their texture, mineralogy, and the environment in which they are deposited [12]. It is noteworthy that heavy metals are non-degradable and bio-accumulative in adipose tissues; they also persist for a very long time in the environment and are always in cyclic movement within ecosystems [13]. Heavy metals adversely affect internal organs and systems, including the central nervous system. They also exhibit carcinogenic, mutagenic, and teratogenic effects in some cases; hence, they are considered to be of risk to human health [9,14,15].

Heavy metals have been implicated in the cause of certain respiratory, neurodegenerative, and cardiovascular diseases [8,16]. Notable among the heavy metals commonly found in urban road dust are cadmium, copper, lead, and zinc [17,18]. The effects of heavy metals in roadside dust are not limited to humans alone; several animals of the aquatic and terrestrial habitats are also greatly affected [2,19]. People living or trading in the urban centers are often more exposed to these metallic contaminants, and hence, are at higher risk compared to those in remote areas [20,21].

Elevated concentrations of heavy metals in urban street dusts have been recorded globally. For instance, Shi et al. [22] reported high concentrations of Pb, Cd, Cu, Ni, Zn, and Cr in the street dusts of Xianyang City, China compared to background soil concentrations. In the road-deposited dusts of the Dhanbad and Bokaro regions of India, Singh [12] found that Si was the most dominant element, constituting an overall average of 34.3% of the whole samples investigated. The next most abundant metals were Fe, Ti, and Mn, followed by Zn, Cr, Pb, Cu, Ni, and Co. Similar reports were also documented from Zurich, Switzerland [23], Tehran, Iran [24], Delta region, Egypt [25], and Toronto, Canada [26]. Numerous studies focusing on street dust as a major source of pollutants in urban environments are widely available; however, such studies are restricted to developed countries, capitals, or densely populated cities, while information from developing countries and other geographical locations, including the United Arab Emirates, is limited.

The United Arab Emirates (UAE) is the second largest economy in the Middle East (after Saudi Arabia), and Sharjah is the third largest emirate in the UAE, with significant business and industrial relevance [27]. Dust has been recognized as a major source of environmental pollution in the country, owing to its fast rate of urban development, economic and industrial growth, and its desert landscape and arid climate. Road dust may be a source of air pollutants, including heavy metals and polycyclic aromatic hydrocarbons (PAHs), mostly from traffic emissions [28–30].

Previous studies from Gulf Cooperation Council (GCC), including Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates, reported average PM_{10} and $PM_{2.5}$ concentrations of 75 $\mu g/m^3$ and 28 $\mu g/m^3$, respectively, in samples collected from roads, ports, airports, and industrial and residential areas. Collected PM_{10} samples were also analyzed for some key heavy metals (Cd, Ni, As, and Pb). The highest PM_{10} values were recorded in road dust samples compared to other areas being studied, and the metal concentrations were found comparable to those of other geographical locations such as Hungary [31]. Similarly, Al-Taani et al. [32] assessed the level of air pollution via the daily concentrations of CO, SO_2, NO_2, O_3, PM_{10}, $PM_{2.5}$, Total Suspended Particulate, and Total Volatile Organic Compounds from 2015 to 2016 in an industrial area located between Ajman and Sharjah's border in the United Arab Emirates. All investigated parameters were found within the acceptable standard limits, except $PM_{2.5}$. In another 2021 study by Nazzal et al. [30], selected heavy metals (Cu, Pb, Cr, Cd, Zn and Ni) were evaluated in road dust samples collected from 15 varying sampling sites from each of the urban areas of Sharjah and Ajman emirates. Sampling locations encompassed residential, commercial, industrial, airport, and university areas. Findings from the study ranked the concentrations of the metals in the following order: Zn > Ni > Cr > Cu > Pb > Cd, with only Zn, Ni, and Cr exceeding their allowable limits in some industrial areas [30].

However, none of the studies assessed the potential ecological risks due to heavy metals, and none of them conducted any source apportionment study. It is therefore necessary to conduct a comprehensive study that will address the hotspots of the heavy metals in the dust, as well as their possible ecological and health risks. Hence, this study was aimed at assessing the elemental chemistry of road-deposited dust in terms of heavy metals and one metalloid (Cr, Mn, Fe, Ni, Cu, Zn, Cd, Pb, and As) in the road dust collected from various locations throughout Sharjah. In addition, the study aimed to investigate their distribution, source apportionment using multivariate statistical analysis, including principal component analysis, Pearson correlation and cluster analysis, as well as the abundance of nutritional components such as Nitrogen (N), Phosphorus (P), and Total Organic Carbon (TOC) in road-deposited dusts in relation to the nearby vegetation.

2. Materials and methods

2.1. Study area

Sharjah is one of the seven emirates in the United Arab Emirates (UAE), and the third largest, both by population and land mass, covering an area of 2590 km^2. It has a population of about 1.4 million and is regarded as the cultural capital and heritage center of the Arab World, for preserving and promoting Arab culture and showcasing their well-known art galleries and museums. Being a port city, Sharjah is also well located in a place that connects to many international trade routes, with ports on both the Indian Ocean and the Arabian Gulf; thus, it is a center of intercontinental business. Economically, it contributes to at least 7.4% of the gross domestic product of the UAE. However, its renowned center is densely populated and exhibits a high volume of traffic, factors which may have a burden on the environmental quality [33,34].

2.2. Collection and preparation of samples

Sixty-eight street dust samples (roughly 500 g in each location) were collected from different locations in Sharjah, UAE in 2021. Sample collection was conducted in two rounds; the first sampling was conducted between January and February (collection time varying from 08:41 to 17:19), while the second one was spread throughout September to December 2021 (time of collection starting from 09:41 to 17:19). The two sampling campaigns were during the winter and autumn seasons of the country, respectively. The sampling areas were predominantly industrial (20), residential (20), and commercial (20), and two each of the sampling sites were from airport, desert, agricultural, and university environments. Moreover, the traffic pattern in those areas of sample collection ranged between heavy (35), moderate (22), and light (11), with about twenty-three of them having traffic lights within 100 m distance. All the soils around the locations where samples were taken were notably sandy. Each sampling point with coordinates and characteristics are presented in Fig. 1 and Table S1 accordingly.

An area of approximately 2 m^2 alongside each of the selected roads was carefully swept with a plastic broom into a very clean

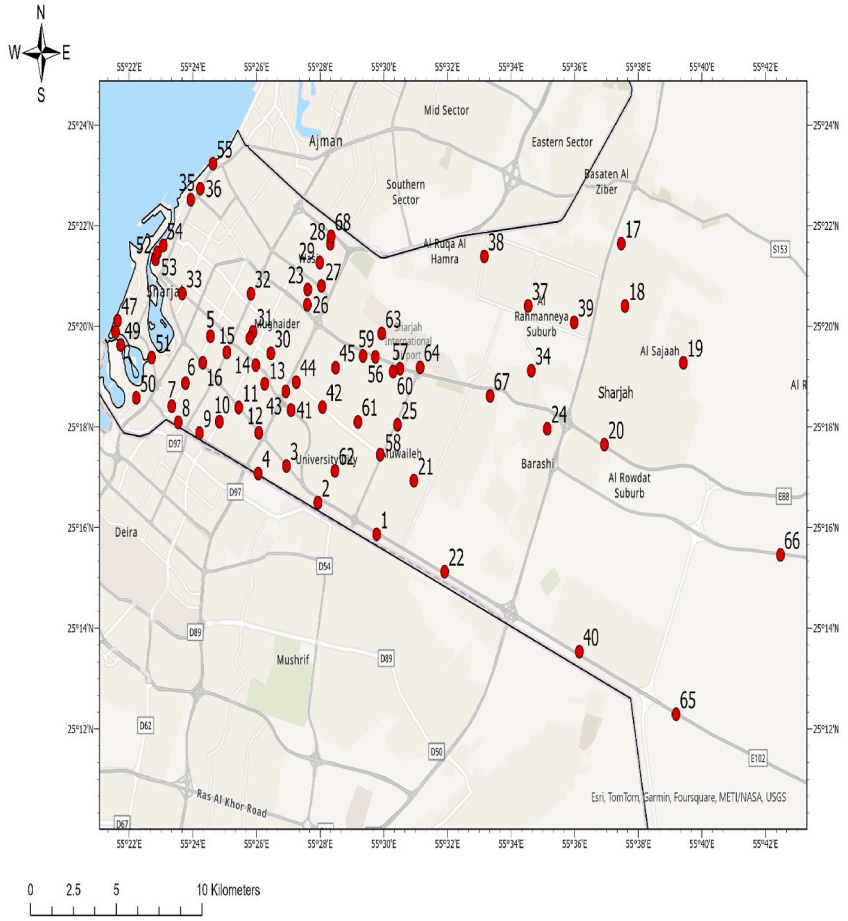

Fig. 1. Map showing the sampling locations in Sharjah, United Arab Emirates.

dustpan according to the USEPA AP-42, Appendix C.1 & C.2 methods [35,36] and poured into a clean polyethylene bag for transport to the laboratory. This was done in triplicate at each collection point [14,37]. The samples were oven-dried (GenLab, UK) at 40 °C for 48 h, then sieved with a 1-mm non-metallic mesh to remove foreign substances such as leaves, stones, fragments of bricks, cigarette remains, and other large particles. The dust fraction with a diameter below 63 μm was subsequently obtained by passing the sample through a 220 mesh, followed by homogenization using an agate mortar. The fine particles were transferred into plastic conical tubes and sealed tightly for subsequent analyses [37,38].

2.3. Sample digestion, analysis, and quality control

An aliquot of 0.5 g of the finest particles of the road-deposited dusts was digested with 6 ml of 70% HNO_3 and 3 ml of 37% HCl in microwave-heated polytetrafluoroethylene (PTFE) containers in accordance with the following program: 700 W, 10 min holding time and 1000 W, 10 min holding time (duration of the program: 50 min, max. T = 200 °C, max. P = 30 bar) by means of an Anton Paar Multiwave Go Plus microwave digestion system (Austria). The resulting solution was diluted up to 50 ml using Type 1 water, and then an aliquot of 10 ml was filtered through 25 mm syringe filters made of cellulose acetate membrane (0.45 μm pore size) into 15 ml centrifuge tubes. Heavy metals and the metalloid (Cr, Mn, Fe, Ni, Cu, Zn, Cd, As, and Pb) of interest in the digested samples were then determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) (iCAP 7400, ICP-OES Duo, ThermoFisher Scientific, USA) [37,39,40]. The radial/axial wavelengths (nanometers) used for measuring the selected metals/metalloid were Cr (283.563/119); Mn (257.610/131); Fe (259.940/130); Ni (221.647/452); Cu (324.754/104); Zn (213.856/458); Cd (226.502/449); As (189.042/478); and Pb (220.353/453).

Six concentrations of calibration standards (0.05, 0.5, 1, 3, 7, and 10 mg/L) were spiked into pure samples of sand sequentially to determine the recovery percentages of the analytes using the same analytical methods and instruments. Each of the blank, spiked standard solutions and triplicate samples were analyzed in duplicate for precision and accuracy. The recoveries of the spiked standards were generally in the range of 99.86% (As) and 100.10% (Pb). Relative standard deviations obtained (0.03–9.88%) were also in the acceptable range for such an environmental investigation [14,41].

For the elemental analysis of samples, aliquots (100 mg) of dried and sieved dust samples were compressed into dedicated sample boats and introduced into the elemental analyzer (Elementar, New Zealand) for subsequent combustion and analysis of carbon, nitrogen, hydrogen, and sulphur (CNHS).

2.4. Statistical analyses and source apportioning

SPSS (version 21, SPSS Inc., USA) for Windows was used for statistical analyses. Potential sources of the heavy metals in the street dust samples, as well as the inter-relationship among the metal contaminants, were statistically determined using One-way ANOVA, Spearman's correlation, hierarchical cluster, spatial distribution maps (using ArcGIS 10.8.1), and principal component analyses. The ANOVA test was used to identify the connection between the concentration of metals found in the dusts and the geographical sites from where they were collected [37,42]. Kendall's tau_b and Spearman's rho (r_s) non-parametric correlations were used to assess the level of relationships that exist among pairs of the metals owing to the nonlinearity of the data set. In this study, a data matrix consisting of sixty-eight sites and seven metals (excluding As and Cd, which were deleted from the data set because they were below detection limits in most of the sites) was used for both the principal component analysis (PCA) and Cluster analysis. The hierarchical cluster analysis was employed to appraise the similarities of the sources of these metals in the collected dust samples. The analysis was conducted using a between-groups linkage algorithm combined with the squared Euclidean distances. Selection of the optimal number of clusters was achieved by means of the elbow method, in which the shorter branches are considered to demonstrate more similarities [19]. Moreover, PCA was used for the extraction of a smaller number of principal components, PCs (independent factors), which are easier to interpret for the analysis of possible relationships among the observed variables. PCA was accomplished using varimax rotation with Kaiser's normalization with eigenvalues >1 to identify the likely origin of the metals in dust samples. By extracting the eigenvalues and eigenvectors from the correlation matrix, the number of significant factors and the percent of variance explained by each of them were calculated. Thus, PCA was used to identify sources, apportioning them to natural and anthropogenic sources as necessary [37,38,40]. A p value < 0.05 was set as the significance level in these analyses. Microsoft Excel 2016 was also used for descriptive statistics where necessary [14,42].

2.5. Pollution variations among the study sites

2.5.1. Contamination Factor (CF) and contamination degree (C_{deg})

An elemental concentration above the natural or background value is an indicator of human-induced pollution in the environment [43]. Contamination Factor (CF) is a term used to assess the level of pollution due to heavy metals in roadside dust. In this study, CF was estimated as the ratio of each metallic concentration in the sample investigated (C_s) to the natural (background) value for the same metal in the upper earth crust (C_b) as depicted in Equation (1) [14,44,45].

$$CF = C_s / C_b \quad \text{Eq. 1}$$

CF values are usually interpreted in this order: below 1 (low), between 1 & 3 (moderate), between 3 & 6 (considerable), and ≥6 (very high) [14,38,41,42]. Similarly, contamination degree (C_{deg}) was calculated as the sum of the CFs for all the heavy metals

determined (Equation (2)) [42].

$$C_{deg} = \Sigma CF \quad \text{Eq. 2}$$

For the C_{deg}, any value that is up to or above 24 calls for concern and suggests the need for an urgent remediation to safeguard public health. However, values below 6 imply low contamination, while those between 6 and 12 suggest a moderate degree of pollution, and those varying from 12 to 24 indicate considerable contamination [42].

2.6. Assessment of ecological risks

2.6.1. Potential ecological risk, E_i, and ecological risk index (PER or ERI)

The potential ecological risk index (ERI) developed by Häkanson [46] is a tool for the evaluation of potential risk due to the pollution caused by heavy metals in an environmental matrix (e.g. street dust). ERI (also referred to as PER) is often expressed as the sum of the potential ecological risk, E_i, for all the heavy metals under consideration as shown in Equation (3). To determine E_i for each metal of interest, its toxic response factor, T_r, is multiplied with the CF for the metal (Equation (4)). The T_r values for Cr, Mn, Ni, Cu, Zn, Cd, As, and Pb are 2, 1, 5, 5, 1, 30, 10, and 5, respectively. No T_r value was found for Fe [14,40,41]. Values of E_i, which indicate different levels of ecological risks posed by the heavy metals in the dust samples, fall into different categories, which are: below 15 (low risk), between 15 and 30 (moderate risk), between 30 and 60 (considerable risk), between 60 and 120 (high risk), and ≥120 (very high risk) [14,37,41,42,46,47].

$$ERI = \Sigma E_i \quad \text{Eq. 3}$$

$$E_i = T_r \times CF \quad \text{Eq. 4}$$

The ERI values can fall into any of the four groups in this order: below 150 (low risk), between 150 and 300 (moderate risk), between 300 and 600 (considerable risk), and ≥600 (very high risk) [14,37,41,42,46].

2.7. Assessment of health risks to humans

Carcinogenic and non-carcinogenic risks to humans after exposure to heavy metals are typically calculated using risk assessment models established by the United States Environmental Protection Agency (USEPA) [6,41,42,48–51]. The estimation could be done by considering three major routes of exposure: inhalation (inh), skin contact or absorption (dermal), and oral ingestion (oral), for both children and adults [52]. The first step involves determination of the possible dose (or dosage) an individual could be exposed to on a daily basis. This can be referred to as average daily dose (ADD) in mg/kg/day for non-carcinogenic risk assessment and lifetime average daily dose (LADD) in mg/kg/day for the carcinogenic risk calculation [14].

Equations (5)–(8) present the formulae for calculating both the ADD and LADD following the three means of exposure as mentioned earlier. It is worthy of note that LADD was only computed for Pb, Ni, As, Cd, and Cr with available slope factors. Moreover, since inhalation is the predominant route of exposure to heavy metals in street dust, carcinogenic risk was only computed via that route [41,53].

All the parameters used in the equations are described in Table 1.

Table 1
Parameters and units for human health risk assessment [14,49,54,55].

Parameter		Unit	Adults	Children	Element	RfD_{Inh}	RfD_{Oral}	RfD_{Derm}	SF_{Inh}
Abbreviation	Full Meaning								
R_{Inh}	Rate of Intake (Inhalation)	m^3/day	20	7.6	Zn	3.00×10^{-1}	5.24×10^{-4}	0.3	–
R_{Oral}	Rate of Intake (Oral)	mg/day	100	200	Pb	3.50×10^{-3}	5.24×10^{-4}	3.52×10^{-3}	0.042
EF	Exposure Factor or Frequency	days/year	350	350	Ni	2.00×10^{-2}	5.40×10^{-3}	2.06×10^{-2}	0.84
ED	Exposure Duration or Period	years	24	6	Mn	1.40×10^{-1}	–	–	–
SL	Skin Level	mg/cm^2/day	0.07	0.2	Fe	7.00×10^{-1}	–	–	–
SA	Skin Area Exposed	cm^2	5700	2800	Cr	3.00×10^{-3}	6.00×10^{-5}	2.86×10^{-5}	42
ABS	Absorption Factor for Skin	–	0.001	0.001	Cu	4.00×10^{-2}	1.20×10^{-2}	4.00×10^{-3}	–
PEF	Particulate Emission Factor	m^3/kg	1.36×10^9	1.36×10^9	As	3.00×10^{-4}	1.23×10^{-4}	1.23×10^{-4}	15
BW	Body Weight	kg	70	15	Cd	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-3}	6.3

$$ADD_{Oral} = \frac{C \times R_{Oral} \times ED \times EF \times 10^{-6}}{BW \times AT} \quad \text{Eq. 5}$$

$$ADD_{Inh} = \frac{C \times R_{Inh} \times ED \times EF}{AT \times BW \times PEF} \quad \text{Eq. 6}$$

$$ADD_{Derm} = \frac{C \times SL \times ED \times SA \times EF \times ABS \times 10^{-6}}{AT \times BW} \quad \text{Eq. 7}$$

$$LADD_{Inh} = \frac{EF \times C}{PEF \times AT}\left(\frac{R_{Inh-Child} \times ED_{Child}}{BW_{Child}} + \frac{R_{Inh-Adult} \times ED_{Adult}}{BW_{Adult}}\right) \quad \text{Eq. 8}$$

In equations (5)–(8), C stands for the measured concentration (mg kg^{-1}) of each heavy metal in this study, and AT represents the average time of contact, which is ED × 365 days for non-carcinogenic risk, and 70 × 365 = 25,550 days for the carcinogenic risk [56]. The non-carcinogenic risk, termed hazard quotient (HQ), was thereafter calculated as the ratio of ADD to the reference dosage (RfD) for each metal of interest with regards to each route of exposure as presented in Equation (9). Moreover, the hazard index was estimated as the sum of all HQs for metals determined along the chosen path of exposure (Equation (10)). These were done separately for adults and children, using the parameters provided in Table 1 [41].

$$HQ = \frac{ADD}{RfD} \quad \text{Eq. 9}$$

$$HI = \Sigma HQ \quad \text{Eq. 10}$$

It is therefore necessary to point out that HQ and/or HI values below 1 suggest there would be no potential non-cancerous health risk to any individual that is exposed to the selected metal at a particular concentration in a particular environment over a specified period of time. However, values above 1 indicate possible serious health effects other than cancer [42,49].

Cancer or carcinogenic risk (CR), on the other hand, is often determined as a product of LADD and the slope factor for each metal under investigation. CR demonstrates the possibility of an individual developing cancer after exposure to some heavy metals during their lifetime. This was calculated using Equation (11). Cancer risk index (CRI), being the sum of CRs for all the metals investigated, is also determined to assess the cumulative effects of all the metals in a specified environment (Equation (12)) [41]. The RfD and SF values for each metal, where available, are presented in Table 1.

$$CR = LADD_{Inh} \times SF \quad \text{Eq. 11}$$

$$CRI = \Sigma CR \quad \text{Eq. 12}$$

A CR and/or CRI value below 10^{-6} suggests no cancer risk, while values between 10^{-6} and 10^{-4} are considered to fall within the allowable range. However, a CR or RI above 10^{-4} is an indication of serious risk of lifetime cancer. In this study, CR and CRI were only estimated for the following metals with established values for SF as shown in Table 1: Ni, Cr, and Cd [42,56–58].

3. Results and discussion

3.1. Concentrations of heavy metals in the street dust samples

Concentrations of the heavy metals and metalloid determined in the street dust collected from Sharjah, United Arab Emirates are

Table 2
Heavy metal concentrations in the street dust collected from Sharjah, UAE.

Element	Mean (μg/g dry dust)	Median (μg/g dry dust)	Mode (μg/g dry dust)	Range (μg/g dry dust)	Total (μg/g dry dust)	Upper Crust Value (μg/g dry dust)	CF	E_i
Zn	392 ± 46	207	13.29[a]	13.29–3791	26,633	67[b]	5.85	5.85
Pb	68.28 ± 11.3	27.53	BDL	BDL - 1100	4643	17[b]	4.02	20.08
Ni	856 ± 72	611	21.16[a]	21.16–5200	58,176	47[b]	18.2	91.01
Mn	1437 ± 67	1389	96.98[a]	96.98–3611	97,704	1,000[c]	1.44	1.44
Fe	39,481 ± 4611	30,088	732[a]	732–455,222	2,684,692	46,500[c]	0.85	–
Cr	460 ± 31	363	8.34[a]	8.34–1626	31,302	92[b]	5.00	10.01
Cu	150 ± 44	50.93	BDL	BDL - 5783	10,202	28[b]	5.36	26.8
As	0.97 ± 0.28	BDL	BDL	BDL - 20	66.09	4.8[b]	0.20	2.03
Cd	1.25 ± 0.65	BDL	BDL	BDL - 64	84.9	0.09[b]	13.87	416
Total	**42,846± 5979**	-	-	-	**2,913,503**	-	-	-

BDL: Below detection limit; CF: Contamination Factor; E_i: Potential Ecological Risk.
[a] Multiple modes exist, smallest value is shown.
[b] Rudnick and Gao [44].
[c] Yaroshevsky [45].

shown in Table 2. The concentrations obtained were compared with the values earlier reported in literature for the upper crust [44,45]. For Zn, Pb, Ni, Mn, Fe, Cr, Cu, As, and Cd, the recorded mean concentrations were 392 ± 46 μg/g, 68.28 ± 11.3 μg/g, 856 ± 72 μg/g, 1437 ± 67 μg/g, 39,481 ± 4611 μg/g, 460 ± 31 μg/g, 150 ± 44 μg/g, 0.97 ± 0.28 μg/g, and 1.25 ± 0.65 μg/g, respectively, on a dry sample basis. Apart from Fe and As, the mean concentrations of the other seven metallic elements were above their respective background values in the upper crust; a finding similar to that reported by Saeedi et al. [40] and Soltani et al. [37]. This suggests a possible anthropogenic contribution. The order of increasing concentrations among the nine metals/metalloid is given as: Fe > Mn > Ni > Cr > Zn > Cu > Pb > Cd > As. This finding is similar to previous reports from other parts of the world, where either Fe, Mn, Zn, Pb, or Cu were found to be predominant in urban roadside dusts [14,41,42,59,60].

Moreover, Fig. 2 revealed that the sampling points with the highest mean and total concentrations of heavy metals in the study area were sites 33 and 42, respectively. The first site recorded a mean concentration of 42,752 μg/g, while the latter had 18,065 μg/g. For site 33, Fe (98.36%), Mn (0.73%), and Zn (0.58%) contributed significantly to the total values recorded. Similarly, Fe (99.18%), Mn (0.34%), and Ni (0.25%) were the most dominant metals at site 42. Both sites 33 and 42 are three-lane highways and are characterized by a heavy flow of traffic daily.

Even though there are no universal procedures for the collection of street dust samples and their subsequent analyses, it is usual practice to compare the results obtained from each determination to the reports from other locations around the world [37,40].

The results obtained in this study are comparable with many previously reported studies. For instance, the mean concentrations of Cu, Pb, and Mn in the present work are within the same range as those reported from eight districts of Beijing [61] and four major streets in eastern and southern Tehran [40]. The recorded Zn concentration is also comparable to the reports of [40,62,63] for dust samples collected from Oslo in Norway, the mega-city Nanjing in China, and the IUST Campus in Iran. In the same vein, the Cd concentration is similar to those documented for street dusts in Oslo [62], Nanjing [63], and Madrid city, Spain [14]. The concentrations of Zn, Cu, Pb, and Cd in this study are much lower than values documented for urban roadside dusts in many other regions of the world, including Madrid, Tehran, Pakistan (Karachi and Shikarpur cities), and districts of Beijing, China. However, concentrations of Ni and Cr in the current study were found higher than values reported from the cities mentioned before [14,37,40,41,61–63]. Similarly, the Fe and Mn concentrations in the street dusts of the IUST Campus in Iran, Ottawa in Canada, and the national capital city of Delhi, India [42] were below values obtained in this study, even though the Fe concentration in the dusts from the city of Tehran was much higher. Soltani et al. [37] also reported a higher value of As than the mean concentration in the present work from Isfahan metropolis, Iran. A report from Delhi, India shows that the mean concentration of Pb measured in the National Capital Territory was 164.2 ± 53.2 μg/g dry dust, much higher than was reported in this study. Meanwhile, other elements determined in their evaluation (i.e. Zn, Cu, Ni, Cr, Mn, Fe) were much lower than the values in this study.

The high concentrations of Ni, Cr, and Mn in this study, above their natural/background concentrations in the upper crust, suggest possible anthropogenic contributions from the combustion of petroleum products, vehicular emissions, and/or other vehicular-related sources [37,40]. It is therefore noteworthy that the composition and concentrations of heavy metals in roadside dusts vary from city to city, and country to country, depending on the volume of activities (industrial, business, and/or commercial) taking place in each location, types/nature of technologies in use, as well as the patterns of wind and weather situations in such an environment [37].

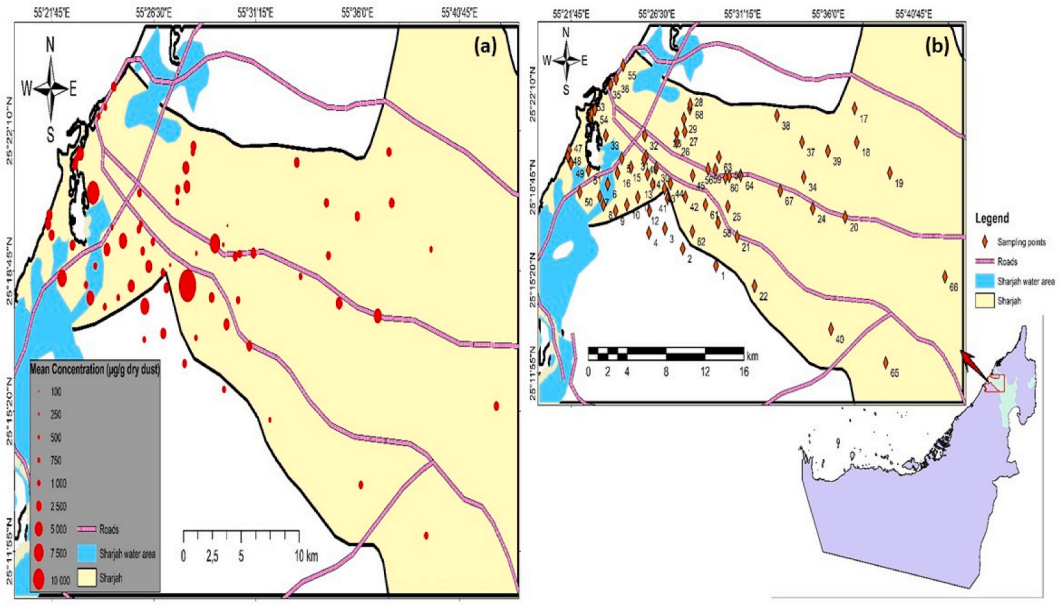

Fig. 2. Spatial distribution maps showing the mean concentrations of heavy metals in the investigated street dust samples.

Table 3
Non-parametric correlations of the elements and CHNS in the street dust samples collected from Sharjah, UAE.

		Zn	Pb	Ni	Mn	Fe	Cr	Cu	As	Cd	N	C	H	S
Kendall's tau_b	Zn	1.000												
	Pb	0.665**	1.000											
	Ni	0.479**	0.399**	1.000										
	Mn	0.459**	0.362**	0.561**	1.000									
	Fe	0.494**	0.393**	0.597**	0.749**	1.000								
	Cr	0.522**	0.411**	0.744**	0.703**	0.740**	1.000							
	Cu	0.716**	0.590**	0.495**	0.435**	0.470**	0.527**	1.000						
	As	0.104	0.127	0.065	0.060	0.103	0.079	0.139*	1.000					
	Cd	0.220**	0.185**	0.139*	0.222**	0.246**	0.206**	0.111	−0.087	1.000				
	N	−0.218**	−0.145*	−0.286**	−0.215**	−0.218**	−0.283**	−0.249**	−0.087	−0.035	1.000			
	C	−0.045	−0.023	−0.234**	−0.189**	−0.205**	−0.226**	−0.095	−0.016	−0.045	0.147*	1.000		
	H	0.375**	0.345**	0.327**	0.096	0.177**	0.250**	0.384**	0.075	0.203**	−0.148*	−0.101	1.000	
	S	0.338**	0.279**	0.193**	0.144*	0.176**	0.196**	0.382**	0.115	0.101	−0.342**	0.032	0.308**	1.000
Spearman's rho	Zn	1.000												
	Pb	0.842**	1.000											
	Ni	0.658**	0.561**	1.000										
	Mn	0.632**	0.506**	0.748**	1.000									
	Fe	0.671**	0.548**	0.762**	0.896**	1.000								
	Cr	0.704**	0.574**	0.904**	0.882**	0.883**	1.000							
	Cu	0.858**	0.743**	0.670**	0.602**	0.635**	0.699**	1.000						
	As	0.131	0.157	0.080	0.067	0.122	0.095	0.177*	1.000					
	Cd	0.271**	0.227**	0.173*	0.277**	0.301**	0.256**	0.137	−0.091	1.000				
	N	−0.320**	−0.207*	−0.408**	−0.311**	−0.311**	−0.407**	−0.360**	−0.110	−0.043	1.000			
	C	−0.068	−0.031	−0.336**	−0.268**	−0.293**	−0.317**	−0.133	−0.021	−0.055	0.216*	1.000		
	H	0.519**	0.478**	0.453**	0.140	0.252**	0.355**	0.531**	0.091	0.252**	−0.207*	−0.136	1.000	
	S	0.488**	0.411**	0.283**	0.208*	0.257**	0.287**	0.542**	0.144	0.125	−0.497**	0.052	0.441**	1.000

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

3.2. Statistical analyses and source apportioning

The spatial distribution maps in Fig. 2 show that the following sites (42, 33, 59, 50, 12, 15, 8, 20, 54, 16) had the highest concentrations of metals in this study compared to the others. Kendall's tau_b and Spearman's rho correlation coefficients were determined for the selected metals/metalloid and CHNS (carbon, hydrogen, nitrogen, and sulphur) under investigation in this study using SPSS in order to determine the type of relationships that exist amongst the elements found in the street dusts of Sharjah. Table 3 reveals strong positive relationships among all the metals/metalloid being investigated (mostly at $p < 0.01$), except Arsenic. This suggests the possibility of similar sources for all of them. Correlation is a good statistical tool for determining the fate and origin of different chemical contaminants in the environment [19,37]. All the elements analyzed in the present work were significantly different from each other across the locations of study ($p < 0.01$), except Cu, As, Cr, and Mn (Table S2). Moreover, only Pb correlated strongly ($r = 0.257$ at $p < 0.01$) with the number of lanes on the streets investigated in Sharjah; this suggests that an increase in the number of lanes could increase the amount of Pb in the street dusts (Table S3). Zn, Pb, and Cu had an inverse relationship with the streetlights in those locations, while other metals did not show any form of connection with those lights at all. Similarly, Zn ($r = 0.219$), Ni ($r = 0.188$), Mn ($r = 0.201$), and Fe ($r = 0.194$) showed a correlation with the vegetation around the sampling sites ($p < 0.05$). This was also seen with Cr ($r = 0.241$) and Cu ($r = 0.355$), but with higher statistical significance ($p < 0.01$), suggesting possible accumulation.

The correlations of Zn, Pb, Ni, Mn, Fe, Cr, Cu, and Cd with one another suggest they might all emanate from the same or a similar source. Arsenic correlates moderately with Cu only ($r = 0.139$; $p < 0.05$), but not with any other elements, whereas Cu correlates strongly with all, implying it must have come from multiple origins (possibly anthropogenic and geological/natural) [40]. All the elements with concentrations above their background values in the upper earth crust suggest a possible anthropogenic contribution. So, this corroborates the reason why As (arsenic) has no form of relationship with the others except Cu. The analysis of variance (ANOVA) indicated there are significant differences in the values obtained for five of the nine metals/metalloid determined in this study across the selected sampling points, except for Mn, Cu, Cr, and As (Table S2). This confirms that the compositions and concentrations of these contaminants are subject to the happenings in each location. The post hocs revealed that the following locations are significantly different from the rest: Zn (33, 54), Pb (50), Ni (5, 8, 36, 40, 41, 43, 46, 48), Cd (33), and Fe (33). Cu and Cr also exhibit substantial variation in some locations: Cu (site 12) and Cr (sites 5 and 18). The study sites varied between industrial (5, 8, 11, 18), residential (33, 36, 40), and commercial (41, 43, 46, 48, 50, 54); all have consistent heavy traffic, with the exception of sites 40 and 48, which have moderate traffic.

Arsenic and Cadmium were deleted from the data before conducting PCA and Cluster analyses, since they were mostly below detection limits. Following the cluster analysis, the remaining seven elements were distributed into three different clusters with Cluster 1 containing Zn, Pb, Ni, Mn, and Cr, while Clusters 2 and 3 had Fe and Cu, respectively (Table S4 & Fig. 3). For the Principal Component Analysis (PCA), the Kaiser-Meyer-Olkin value was 0.767 and the Bartlett sphericity test result was less than 0.001, suggesting that the PCA model would be an appropriate way of determining the principal components (PCs) of the heavy metal sources in the street dust samples under study [64] (Table S5). Using the extraction method, only one component (PC 1) was extracted with an eigenvalue of 3.958, accounting for 56.54% of the total variance and thus it cannot be rotated (Table S6). Other components (PC2, PC3, PC4, PC5, PC6 & PC7) had eigenvalues <1, and so were not extracted. The pattern matrix also supported the cluster analysis results in that Zn, Pb, Ni, Mn, and Cr had regressions above 0.7 (strong positive loading) for sample size of approximately 70 [65], while Fe (0.612) is close (moderate loading), and Cu (0.465) is below 0.5 (weak loading) as shown in Table S4. These results point to three possible sources of the metal/metalloid contaminants determined in the road dust samples, with the first five possibly coming from the same source or similar pathways of transportation and vehicular emissions, considering their high loading strengths and the correlation of Pb with the number of street lanes [66].

This report to a large extent corroborates the Kendall's tau_b and Spearman's rho non-parametric correlations of the elements in this study as earlier discussed, with As showing no correlation with other elements other than Cu. Besides, their mean concentrations, which were below their background values in the earth crust, indicate different source(s) aside from traffic emissions. The correlation

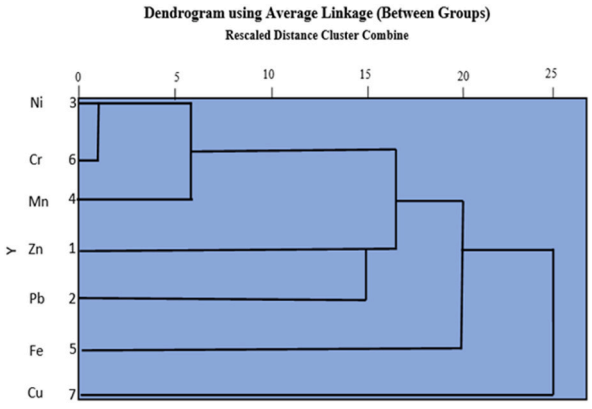

Fig. 3. Dendrogram of the hierarchical cluster analysis of the concentrations of heavy metals in road dusts under study.

of Fe and Cu with other metals and their individual appearances in separate clusters (2 and 3), as well as their moderate (0.612) and weak (0.465) loadings in PCA, suggest the possibility of two sources. From all indications, Zn, Pb, Ni, Mn, and Cr are products of traffic activities in the streets of Sharjah as reported earlier by other researchers [37,40,67]. However, Fe and Cu could have some natural and industrial (such as smelting and mining) contributions as they are among the most abundant. In addition, almost a third of the streets investigated in this study are located in the industrial areas of Sharjah. Besides, the United Arab Emirates is well known for active industrial/mining activities, being a major producer of iron and steel, industrial minerals and metals, as well as other products such as refined petroleum, cement, gypsum, nitrogen fertilizers, sulphur and lime, and direct-reduced iron, among many others in the region [68,69]. Arsenic may have solely emanated from such industrial activities and not from traffic emissions, given its negative correlations with most of the metals. Other possible sources are depositions from the atmosphere and agrochemicals [70].

Previous studies have shown that Pb is commonly added to gasoline as an anti-knock, hence it is a by-product of the combustion of leaded fuel [71]. Another prominent source of Pb in the road dust is engine lubricant, which functions as an anti-wear additive. Pb and Zn could originate from the abrasion of engines, brake pads, and tires, in the same way as Zn, Cr, Cu, Mn, and Ni. Fe may be from rusting and wearing off from various vehicle components made of iron, including brake linings and exhaust [42]. Cu is used in vehicle radiators due to its heat conductivity and non-corrosive properties [72,73]. Cd is conventionally used as plating in brake pads to prevent corrosion; it is also a component of vehicle lubricating oil, a product of tire abrasion, and a by-product of fuel combustion [71,74]. Hence, it could be inferred that the hotspots for heavy metals in the roadside dust of Sharjah are the following sites: 33, 50, 12, and 54, which are located in the residential, commercial, industrial, and residential areas, respectively (all with heavy traffic), going by the interpretation of the spatial distribution maps and ANOVA (post hoc). The highest proportion of the mean value of all metals recorded at site 42 was due to iron (Fe), unlike the other sites. This confirms the mixed origins for these contaminants in the study area.

Table 4 shows the abundance of nutritional components in the collected street dust samples. The order of decrease in the percentages of elements determined is given as follows: N > C > H > S, with mean values of 10.38 ± 2.04%, 6.56 ± 0.10%, 0.33 ± 0.02%, and 0.11 ± 0.01%, respectively. Table 3 shows that nitrogen correlates negatively with almost all the metals except C, As, and Cd; its positive relationship with the trio of carbon, arsenic, and cadmium implies they are from similar sources, other than vehicular emissions [75]. Hence, N in the road dusts collected might originate from industrial/mining activities, especially the production of nitrogen fertilizers, or even atmospheric deposition [68,69]. This is supported by the negative correlation of C with other elements such as Ni, Mn, Fe, and Cr. In the same way, high concentrations of elemental carbon in the dust samples could be related to biomass burning, or possibly re-suspended carbon [76]. It has been reported that elemental carbon contributes immensely to global warming, next to carbon dioxide [77]. However, the positive correlation of H and S with all other metals/metalloid except As and Cd indicates that they are possibly from traffic emissions.

3.3. Pollution degrees, ecological and health risk assessments

3.3.1. Pollution degrees

CF and C_{deg} were determined in order to get a full perspective of the pollution due to heavy metals in the road deposited dusts under study [14]. The results of the analyses are presented in Figure S1, as well as in Tables 2 and 5. The values of CF determined using the mean concentrations of all the elements across the sites ranged between low (0.20) for As and very high (18.2) for Ni (Table 2). Of all the elements considered with CF, Ni and Cd exhibited very high contamination in this category. The levels of pollution with regards to Fe and As were low; Mn was moderate, while contamination with respect to Zn, Pb, Cr, Cu was considerably high. The CF values across the 68 points of sampling collection in this study follow this decreasing order: Ni > Cd > Zn > Cu > Cr > Pb > Mn > Fe > As (see Table S7). Nickel, cadmium, lead, chromium, arsenic, copper, and zinc are among the metals toxic to humans as identified by the USEPA Part 503 rule [78,79]. Ni forms soluble complexes that could be charged negatively or neutral when co-existing in the environment with some organic complexing agents; in this way, the Ni complexes may become more mobile and consequently contaminate aquatic resources in the surrounding environment [14]. Cadmium is carcinogenic especially by the inhalation route and accumulates principally in the kidney and liver, among other soft tissues in the human body. It is also known to be very persistent in the body for up to ten to thirty-five years [80,81]. CF is regarded a good indicator of pollution due to traffic density; hence, its application in this study is justified [14].

Contamination degree (C_{deg}) is the sum of the CF values for all the nine elements being considered in each location of study. This was used to assess the level of contamination across the sampling sites and ranged between 5.66 (site 66) and 616 (site 33). Figure S1 reveals that only sites 65 and 66 have C_{deg} values below 6 (low contamination), while 48, 60, and 68 were moderately contaminated. Moreover, sites 25, 32, 34, 36, 37, 39, 40, 41, 42, 43, 47, 53, 56, 57, 62, 63, 64, and 67 had C_{deg} values between 12 and 24 (considerably high contamination), while the remaining 45 locations exhibited very high contamination. The ten most contaminated sites were 33 > 61 > 12 > 54 > 5 > 30 > 3 > 50 > 11 > 8, with 80% of them located in areas with heavy traffic; in fact, most of them

Table 4
Abundance of nutritional components in the street dusts of Sharjah.

Element	Mean (% dry dust)	Median (% dry dust)	Mode (% dry dust)	Range (% dry dust)	Total (% dry dust)
N	10.38 ± 2.04	0.58	0.53	0.29–120	706
C	6.56 ± 0.10	6.46	6.81	4.36–10.13	446
H	0.33 ± 0.02	0.26	0.25	0.02–1.11	22.46
S	0.11 ± 0.01	0.09	0.01	0.01–0.61	7.47

Table 5
Pollution degree and ecological risk assessment parameters of heavy metals in road dust samples under study.

Parameters	Mean Value	Minimum Value	Maximum Value
C_{deg}	54.79 ± 7.18	5.66	616
ERI	573 ± 190	17.9	16510
CF	6.09 ± 0.8	0.63	68.38
E_i	63.71 ± 21.1	1.99	1834

are three-lane roads. This is in agreement with the findings of Delgado-Iniesta et al. [14] and others [42,46]. The mean C_{deg} for all metals of interest in this study across all the sampling location is 54.79.

3.3.2. Ecological risk assessment

In order to evaluate the possible ecological risks posed by heavy metals in the road-deposited dusts under investigation, the potential ecological risk for an individual element (Ei) and the sum for all the elements (ERI) were determined (Tables 5 and S7 and Figure S1) [14]. The values of E_i (potential ecological risk) with respect to the heavy metals/metalloid under study varied from 1.44 (Mn) to 416 (Cd), thus, ranging from low to very high risk (Table 2). Zn, Mn, Cr, and As demonstrated low risk; Pb and Cu, however, presented a moderate level of ecological risk. In the same way, Ni was found to pose a high risk, while Cd was very high. E_i was not computed for Fe, since no T_r was found for the element. Across the sampling locations, mean concentrations of all the metals were used to determine E_i as shown in Figure S1, as well as Tables 6 and S7. The order of decreasing values among the elements under study was: Cd > Ni > Cu > Pb > Cr > Zn > As > Mn. Furthermore, the sum of all the E_i for the nine elements were estimated for each sampling point and the results were presented as ERI (Ecological Risk Index) (Table S7 and Figure S1) [82]. ERI thus shows the cumulative impacts of all the heavy metals being studied in the entire sampling area. Forty-three of the sites were low in ERI, thirteen were moderate, six were having considerable risk, while the remaining six were very high. The ERI values amongst the 68 sampling locations varied from 17.9 (site 65) to 16510 (site 33), with twelve of them having higher ecological risks, ranked in decreasing order as follows: 33 > 61 > 30 > 54 > 12 > 5 > 59 > 50 > 3 > 18 > 11 > 8. This order revealed most of the roads with heavy traffic density (especially in the commercial and industrial areas) as the most polluted [14,40]. The ERI calculated with the mean concentrations of all metals investigated in this study across the 68 sampling points is 573, which falls between 300 and 600; thus, it indicates that the streets pose considerable ecological risks with respect to this parameter of assessment. In a similar way as reported by Saeedi et al. [40], most of the residential/commercial/desert/agricultural locations with light or moderate traffic patterns were found to have low ecological risk. Some of these sites have vegetation or trees around, which to some extent protect them from the direct influx of emissions and particles related to traffic. Examples of these are sites 65, 66, 60, 48, 68, 36, 40, 57, 56, 47, 41, and 42, amongst others. However, it is noteworthy that streets around the university, such as site 61, which has a lighter traffic pattern and vegetation in the surroundings, is among the most contaminated. This suggests that traffic may not be the only primary source of these metals, in agreement with earlier results by Saeedi et al. [40]. Precipitation may be one possible source; this may be further investigated by the analysis of surface soil in such locations. Another possible source may be the use of recycled wastewater for landscape irrigation in such locations.

3.3.3. Human health risk assessment

3.3.3.1. Non-carcinogenic risks. Table 6 presents the results of the human health risk assessments with respect to the nine metals/metalloid in this study. From the Table, it is evident that HQ_{oral} varied from 1.71×10^{-3} (Cd) to 2.10×10^{-1} (Cr) for adults, and from 1.60×10^{-2} (Cd) to 1.96 (Cr) for children, with an HI of 4.00×10^{-1} and 3.73 for adults and children, respectively. Similarly, the HQ_{derm} ranged from 4.32×10^{-5} (As) to 4.19×10^{-2} (Cr) for adults, and from 2.83×10^{-4} (As) to 2.75×10^{-1} (Cr) for children, with an HI of 4.80×10^{-2} and 3.14×10^{-1} for adults and children, respectively. Similarly, the HQ_{inh} varied from 2.52×10^{-7} (Cd) to 3.24×10^{-3} (Cr) for adults, and from 4.46×10^{-7} (Cd) to 5.75×10^{-3} (Cr) for children, with an HI of 3.26×10^{-3} and 5.79×10^{-3} for adults

Table 6
Human health risk assessment of heavy metals in the street dust samples under study.

Element	Adults			Children			
	HQ_{oral}	HQ_{derm}	CR_{inh}	HQ_{oral}	HQ_{derm}	HQ_{inh}	
Zn	1.79×10^{-3}	4.09×10^{-3}	2.63×10^{-7}	1.67×10^{-2}	2.68×10^{-2}	4.66×10^{-7}	–
Pb	2.67×10^{-2}	7.12×10^{-4}	3.91×10^{-6}	2.49×10^{-1}	4.67×10^{-3}	6.93×10^{-6}	2.86×10^{-10}
Ni	5.86×10^{-2}	8.66×10^{-4}	8.37×10^{-6}	5.47×10^{-1}	5.67×10^{-3}	1.48×10^{-5}	7.16×10^{-8}
Mn	1.41×10^{-2}	–	–	1.31×10^{-1}	–	–	–
Fe	7.73×10^{-2}	–	–	7.21×10^{-1}	–	–	–
Cr	2.10×10^{-1}	4.19×10^{-2}	3.24×10^{-3}	1.96	2.75×10^{-1}	5.75×10^{-3}	1.93×10^{-6}
Cu	5.14×10^{-3}	6.83×10^{-5}	7.56×10^{-6}	4.80×10^{-2}	4.48×10^{-4}	1.34×10^{-5}	–
As	4.44×10^{-3}	4.32×10^{-5}	1.59×10^{-6}	4.14×10^{-2}	2.83×10^{-4}	2.82×10^{-6}	1.45×10^{-9}
Cd	1.71×10^{-3}	2.73×10^{-4}	2.52×10^{-7}	1.60×10^{-2}	1.79×10^{-3}	4.46×10^{-7}	7.84×10^{-10}
HI/CRI	**4.00×10^{-1}**	**4.80×10^{-2}**	**3.26×10^{-3}**	**3.73E**	**3.14×10^{-1}**	**5.79×10^{-3}**	**2.00×10^{-6}**

HI: Hazard Index; HQ: Hazard Quotient; CR: Cancer Risk; CRI: Cancer Risk Index; derm: Dermal; inh: Inhalation.

and children, respectively. Thus, the ranking of the elements as the HQ_{oral} value decreases was as follows: Cr > Fe > Ni > Pb > Mn > Cu > As > Zn > Cd, showing that chromium had the highest value, while cadmium had the lowest.

The decreasing order of HQ_{derm} among the metals of interest was as follows: Cr > Zn > Ni > Pb > Cd > Cu > As. HQ_{derm} was not estimated for Mn and Fe because no RfD was found for them. For the same reason, the HQ_{inh} was determined for all except Mn and Fe. HQ_{inh} decreased among the nine elements studied in this order: Cr > Ni > Cu > Pb > As > Zn > Cd. Generally, it could be seen that the assessment of potential non-carcinogenic health risks via the three possible routes of exposure followed this order: $HQ_{oral} > HQ_{derm} > HQ_{inh}$; this indicates that non-carcinogenic risks are higher via ingestion than other routes, with inhalation having the lowest risk. This is a similar order reported by Roy et al. [42]. Moreover, the risk assessment results show there is no likelihood of any risk to humans if exposed to the metals in this study, either separately or collectively by means of dermal contact or inhalation for both age categories. In this same way, the HQ_{oral} and HI_{oral} for adults were both less than one, and hence, suggest no possible risk.

However, the HQ_{oral} for Cr and HI_{oral} for children were both greater than the benchmark value of 1.0, thus, implying the possibility of a non-carcinogenic risk to children, especially via exposure to chromium. For children, the HQ_{oral} and HI_{oral} values of 1.96 and 3.73 for Cr and combined heavy metals, respectively, both indicate medium levels of non-carcinogenic health risks to children after exposure [83,84]. The oral ingestion pathway is therefore the main possible route of exposure that is dangerous to human health, especially to children. This is also in line with the reports of Roy et al. [42] and Delgado-Iniesta et al. [14] in their analyses of street dusts of Delhi, India and Madrid, Spain, respectively. Besides, Cr and Ni appear to be the two leading metals with the highest levels of non-carcinogenic health risks to humans via the three routes of exposure in agreement with the report of Moryani et al. [41]. In previous studies, children have been found to be more susceptible to health risks due to heavy metals in road dusts than adults [85,86], and this may be linked to their smaller body weight [42].

High concentrations of heavy metals in road dusts are likely to generate weak immune systems in humans; hence, they cannot be overlooked. Toxic metals such as Ni can even adversely affect DNA function, kidneys, respiratory systems, and the bones of the body [41]. The major sources of Cr, Cu, Pb, and Zn have been linked with the abrasion of tires, building paints, brakes, and vehicle engines [7,38]. Hence, efforts should be made to prevent these hazardous dusts from finding their way into residential houses through shoes and windows. Regular house cleaning is therefore recommended in those areas with heavy traffic [14]. Furthermore, risk due to Cr was found high in other studies documented in Beijing, China and Delhi, India in agreement with the present work [41,87].

3.3.3.2. Carcinogenic risks in humans. CR_{inh} as presented in Table 6 was estimated collectively for the two age categories, and the results ranged from 2.86×10^{-10} for Pb to 1.93×10^{-6} for Cr; with the CRI being 2.00×10^{-6}. The decreasing order of the elements in terms of the CR_{inh} values is given thus: Cr > Ni > As > Cd > Pb. This order is similar to that reported by Delgado-Iniesta et al. [14]. No CR_{inh} was calculated for Zn, Mn, Fe, and Cu because no slope factor was found for them. Overall, Cr and Ni still appear to be the leading metals with the highest carcinogenic risks; however, the cancer risk for each of them was below 10^{-6}, except for Cr (1.93×10^{-6}). Nevertheless, the cancer risk level is low, since the CR and CRI values were both between 10^{-6} and 10^{-5}, as reported earlier by Li et al. [88], Rahman et al. [6], Moryani et al. [41], and Agoro et al. [79]. Notwithstanding, Cr is known to be very toxic and carcinogenic; so, efforts must be made to reduce its release into the environment. A high CR value was also reported for chromium in a previous study conducted in Beijing [7], and both age categories were affected, contrary to the reports generated from the present study, where only children were affected [41].

3.4. Limitations of the study

Investigating heavy metal pollution in the road dusts of Sharjah is very significant, considering the impacts on humans and the environment. However, this study is not exhaustive, and there are a few limitations that could be improved in future studies. Although toxicity of the elements can be fully understood by speciation, the available ICP-OES instrument used for the analysis can only determine them at their elemental levels. Moreover, only two sampling campaigns were conducted in this study; seasonal variation in the concentrations of the pollutants can be better understood if the study is conducted throughout the four seasons of the year. Not all the available pollution indices were used for assessment in this work because some of the metallic contaminants were not found at all in some sites.

4. Conclusions

The current study elucidates the contribution of road-deposited dusts to heavy metal pollution in Sharjah as well as informs potential associated risks through multiple exposure pathways. Fe was found to be the principal metal in the street dusts of Sharjah, UAE, followed by Mn, Ni, and Cr, in that order. Seven of the nine elements measured in this study were above their background values in the upper earth crust, except Fe and As. The assessment indices used for determining the degree of pollution and ecological risk levels in the dust samples collected established that the collected dust samples were contaminated with varying concentrations of Ni, Cd, Zn, Cu, Cr, and Pb. Heavy traffic was a major contributing factor to heavy metal contamination in street dusts, especially in commercial and industrial areas, as indicated by the correlation, cluster, and principal component analyses. The main sources of Fe and Cu are possibly from traffic emissions as well as industrial/natural origins, considering the industrial activities in the area and the results of the correlation, cluster analysis, and PCA conducted. Arsenic is likely to have also emanated from industrial origins, atmospheric depositions, or the agrochemicals used in the environment, given its negative correlations with most of the metals. The health risk assessments to humans indicate that oral ingestion is the only pathway with a tendency to generate non-carcinogenic risks in children,

possibly because of their smaller body weights. For the cancer risk assessments, Cr is the only metal with a CR above the benchmark of 10^{-6}; however, the cancer risk level is low. Further efforts by relevant authorities and contributing sources to reduce the concentrations of these contaminants to the barest minimum in the street dusts of the Sharjah remain highly recommended to safeguard public health.

Data availability statement

Data are included in the article, supplementary material, or referenced in the article.

CRediT authorship contribution statement

Lucy Semerjian: Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization, Resources, Writing – original draft. **Abiodun O. Adeniji:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Abdallah Shanableh:** Writing – review & editing, Resources, Conceptualization. **Mohammad H. Semreen:** Writing – review & editing, Resources, Methodology. **Muath Mousa:** Methodology, Investigation. **Khaled Abass:** Writing – review & editing, Formal analysis. **Anthony Okoh:** Writing – review & editing, Conceptualization.

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.

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Appendix A. Supplementary data

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References

[1] T. Godish, Air Quality, fourth ed., A CRC Press Company, Lewis Publishers, 2005.
[2] E. Liu, T. Yan, G. Birch, Y. Zhu, Pollution and health risk of potentially toxic metals in urban road dust in Nanjing, a mega-city of China, Sci. Total Environ. 476–477 (2014) 522–531.
[3] X. Xu, X. Lu, X. Han, N. Zhao, Ecological and health risk assessment of metal in resuspended particles of urban street dust from an industrial city in China, Curr. Sci. 108 (2015) 72–79.
[4] A. Aguilera, J.L. Cortés, C. Delgado, Y. Aguilar, D. Aguilar, R. Cejudo, P. Quintana, A. Goguitchaichvili, F. Bautista, Heavy metal contamination (Cu, Pb, Zn, Fe, and Mn) in urban dust and its possible ecological and human health risk in Mexican cities, Front. Environ. Sci. 10 (2022) 854460, https://doi.org/10.3389/fenvs.2022.854460.
[5] B. Keshavarzi, S. Abbasi, F. Moore, S. Mehravar, A. Sorooshian, N. Soltani, et al., Contamination level, source identification and risk assessment of potentially toxic elements (PTEs) and polycyclic aromatic hydrocarbons (PAHs) in street dust of an important commercial center in Iran, Environ. Manag. 62 (4) (2018) 803–818, https://doi.org/10.1007/s00267-018-1079-5.
[6] M.S. Rahman, M.D.H. Khan, Y.N. Jolly, J. Kabir, S. Akter, A. Salam, Assessing risk to human health for heavy metal contamination through street dust in the Southeast Asian Megacity: Dhaka, Bangladesh, Sci. Total Environ. 660 (April) (2019) 1610–1622, https://doi.org/10.1016/j.scitotenv.2018.12.425.
[7] C. Men, R. Liu, F. Xu, Q. Wang, L. Guo, Z. Shen, Pollution characteristics, risk assessment, and source apportionment of heavy metals in road dust in Beijing, China, Sci. Total Environ. 612 (2018) 138–147.
[8] S. Dytłow, B. Go′rka-Kostrubiec, Concentration of heavy metals in street dust: an implication of using different geochemical background data in estimating the level of heavy metal pollution, Environ. Geochem. Health 43 (2021) 521–535, https://doi.org/10.1007/s10653-020-00726-9, 2021.
[9] Y. Shao, G. Yang, M. Luo, D. Xu, H. Tazoe, M. Yamada, L. Ma, Multiple evaluation of typical heavy metals pollution in surface soil and road dust from Beijing and Hebei province, China, Bull. Environ. Contam. Toxicol. (2022), https://doi.org/10.1007/s00128-022-03537-z.
[10] S. Hou, N. Zheng, L. Tang, X. Ji, Y. Li, X. Hua, Pollution characteristics, sources, and health risk assessment of human exposure to Cu, Zn, Cd and Pb pollution in urban street dust across China between 2009 and 2018, Environ. Int. 128 (2019) 430–437, https://doi.org/10.1016/j.envint.2019.04.046.
[11] I.C. Yadav, N.L. Devi, V.K. Singh, J. Li, G. Zhang, Spatial distribution, source analysis, and health risk assessment of heavy metals contamination in house dust and surface soil from four major cities of Nepal, Chemosphere 218 (2019) 1100–1113, https://doi.org/10.1016/j.chemosphere.2018.11.202.
[12] A.K. Singh, Elemental chemistry and geochemical partitioning of heavy metals in road dust from Dhanbad and Bokaro regions, India, Environ. Earth Sci. 62 (2011) 1447–1459.
[13] F. Ahmadipour, N. Bahramifar, S.M. Ghasempouri, Fractionation and mobility of cadmium and lead in soils of Amol area in Iran, using the modified BCR sequential extraction method, Chem. Speciat. Bioavailab. 26 (2014) 31–36.
[14] M.J. Delgado-Iniesta, P. Marín-Sanleandro, E. Díaz-Pereira, F. Bautista, M. Romero-Muñoz, A. Sánchez-Navarro, Estimation of ecological and human health risks posed by heavy metals in street dust of Madrid city (Spain), Int. J. Environ. Res. Public 19 (2022) 5263, https://doi.org/10.3390/ijerph19095263.

[15] M. Valko, C.J. Rhodes, J. Moncol, M. Izakovic, M. Mazur, Free radicals, metals and antioxidants in oxidative stress-induced cancer, Chem. Biol. Interact. 160 (2006) 1–40.
[16] H. Khademi, M. Gabarr′on, A. Abbaspour, S. Martinez–Martínez, A. Faz, J.A. Acosta, Environmental impact assessment of industrial activities on heavy metals distribution in street dust and soil, Chemosphere 217 (2019) 695–705, https://doi.org/10.1016/j.chemosphere.2018.11.045.
[17] I. Yoshinori, M.N.M. Shouta, M. Kaampwe, C. Kennedy, T. Hiroki, M. Naoharu, I. Mayumi, Heavy metal contamination of soil and sediment in Zambia, Afr. J. Environ. Sci. Technol. 4 (11) (2010) 729–739.
[18] J. Aslam, S. Ahmad Khan, S. Haque Khan, Heavy metals contamination in roadside soil near different traffic signals in Dubai, United Arab Emirates, J. Saudi Chem. Soc. 17 (2013) 315–319.
[19] X. Lu, L. Wang, L.Y. Li, K. Lei, L. Huang, D. Kang, Multivariate statistical analysis of heavy metals in street dust of Baoji, NW China, J. Hazard Mater. 173 (2010) 744–749.
[20] D.E. Sabath, L.R. Osorio, Medio ambiente y riñón: nefrotoxicidad por metales pesados, Nefrologia 32 (2012) 279–286.
[21] WHO, World Health Organization, Review of Evidence on Health Aspects of Air Pollution-REVIHAAP; First Results, WHO Regional Office for Europe, Copenhagen, Denmark, 2013.
[22] X. Shi, L. Chen, J. Wang, Multivariate analysis of heavy metal pollution in street dusts of Xianyang city, NW China, Environ. Earth Sci. 69 (2013) 1973–1979.
[23] F. Amato, M. Pandolfi, T. Moreno, M. Furger, J. Pey, A. Alastuey, N. Bukowiecki, A.S.H. Prevot, U. Baltensperger, X. Querol, Sources and variability of inhalable road dust particles in three European cities, Atmos. Environ. 45 (2011) 6777–6787.
[24] M. Xue, Y. Yang, J. Ruan, Z. Xu, Assessment of noise and heavy metals (Cr, Cu, Cd, Pb) in the ambience of the production line for recycling waste printed circuit boards, Environ. Sci. Technol. 46 (2012) 494–499.
[25] M.A. Khairy, A.O. Barakat, A.R. Mostafa, T.L. Wade, Multielement determination by flame atomic absorption of road dust samples in delta region, Egypt, Microchem. J. 97 (2011) 234–242.
[26] Y. Nazzal, M.A. Rosen, A.M. Al-Rawabdeh, Assessment of metal pollution in urban road dusts from selected highways of the greater Toronto area in Canada, Environ. Monit. Assess. 185 (2013) 1847–1858.
[27] R. Mzannar, UAE Air Pollution; Sources, Causes, and All You Need to Know, UAE Pedia Network, 2023. Published 7 months ago on 11 June, 2023, https://uaepedia.net/uae-air-pollution/. (Accessed 18 January 2024).
[28] A. Barbulescu, Y. Nazzal, Statistical analysis of dust storms in the united Arab Emirate, Atmos. Res. 231 (2020) 104669.
[29] A. Bărbulescu, S.C. erban, S. Caramihai, Assessing the soil pollution using a genetic algorithm, Rom. J. Phys. 66 (2021) 806.
[30] Y. Nazzal, N.B. Orm, A. Barbulescu, F. Howari, M. Sharma, A.E. Badawi, A.A. Al-Taani, J. Iqbal, F.E. Ktaibi, C.M. Xavier, et al., Study of atmospheric pollution and health risk assessment: a case study for the Sharjah and Ajman Emirates (UAE), Atmosphere 12 (2021) 1442, https://doi.org/10.3390/atmos12111442.
[31] T. Merétei, P.Z. Bite, C. Báthory, Z. Bolla, Particulate matter and heavy metal air pollution in the Middle East region, Mater. Sci. Eng. 42 (1) (2017) 86–93.
[32] A.A. Al-Taani, F.M. Howari, Y. Nazzal, A. Yousef, Seasonal impact to air qualities in industrial areas of the Arabian Gulf region, Environ. Eng. Res. 23 (2) (2018) 143–149, https://doi.org/10.4491/eer.2017.153, 2018.
[33] A.S. Kubat, Y.İ. Güney, Ö. Özer, Historic city centers under threat: the case of Sharjah, UAE, ITU A|Z, 2014-2 11 (2) (2014) 131–151.
[34] I.I. Abu-Abdoun, Z.A. Al-Balawna, Heavy metals contents in neem tree (Azadirachta indica) parts and surroundings, Acta Scientific Med. Sci. 3 (8) (2019) 126–130.
[35] USEPA, United States Environmental Protection Agency, AP-42, Appendix C.1. Procedures for Sampling Surface/Bulk Dust Loading, fifth ed., US Environmental Protection Agency, Washington, DC, USA, 2003.
[36] USEPA, United States Environmental Protection Agency, AP-42, Appendix C.2. Procedures for Laboratory Analysis of Surface/Bulk Dust Loading Samples, fifth ed., US Environmental Protection Agency, Washington, DC, USA, 2003.
[37] N. Soltani, B. Keshavarzi, F. Moore, T. Tavakol, A.R. Lahijanzadeh, N. Jaafarzadeh, M. Kermani, Ecological and human health hazards of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in road dust of Isfahan metropolis, Iran, Sci. Total Environ. 505 (2015) 712–723, https://doi.org/10.1016/j.scitotenv.2014.09.097.
[38] A. Aguilera, F. Bautista, M. Gutiérrez-Ruiz, A.E. Ceniceros-Gómez, R. Cejudo, A. Goguitchaichvili, Heavy metal pollution of street dust in the largest city of Mexico, sources and health risk assessment, Environ. Monit. Assess. 193 (2021) 193, https://doi.org/10.1007/s10661-021-08993-4, 2021.
[39] USEPA, United States Environmental Protection Agency, Test Methods for Evaluating Solid Waste Physical/chemical Methods, SW-846, http://www.epa.gov/wastes/hazard/testmethods/Sw846/pdfs/3050b.pdf, 1996.
[40] M. Saeedi, L.Y. Li, M. Salmanzadeh, Heavy metals and polycyclic aromatic hydrocarbons: pollution and ecological risk assessment in street dust of Tehran, J. Hazard Mater. 227– 228 (2012) 9–17, https://doi.org/10.1016/j.jhazmat.2012.04.047.
[41] H.T. Moryani, S. Kong, J. Du, J. Bao, Health risk assessment of heavy metals accumulated on PM2.5 fractioned road dust from two cities of Pakistan, Int. J. Environ. Res. Publ. Health 17 (2020) 7124, https://doi.org/10.3390/ijerph17197124, 2020.
[42] S. Roy, S.K. Gupta, J. Prakash, G. Habib, K. Baudh, M. Nasr, Ecological and human health risk assessment of heavy metal contamination in road dust in the National Capital Territory (NCT) of Delhi, India, Environ. Sci. Pollut. Control Ser. 26 (2019) 30413–30425, https://doi.org/10.1007/s11356-019-06216-5.
[43] A. Kabata-Pendias, H. Pendias, Trace Elements in Soils and Plants, third ed., CRC Press, New York, NY, USA, 2001.
[44] R.L. Rudnick, S. Gao, Composition of the continental crust, in: R.L. Rudnick (Ed.), The Crust, Elsevier, 2003, pp. 1–64.
[45] A.A. Yaroshevsky, Abundances of chemical elements in the earth's crust, Geochem. Int. 44 (1) (2006) 48–55, https://doi.org/10.1134/S001670290601006X, 2006.
[46] L. Hakanson, An ecological risk index for aquatic pollution control. A sedimentological approach, Water Res. 14 (1980) 975–1001.
[47] Z.Q. Xu, S.J. Ni, X.G. Tuo, Calculation of heavy metals toxicity coefficient in the evaluation of potential ecological risk index, Environ. Sci. Technol. 31 (2008) 112–115.
[48] USEPA, United States Environmental Protection Agency, Exposure Factors Handbook EPA/600/P-95/002F, 1997.
[49] USEPA, United States Environmental Protection Agency, Risk Assessment Guidance for Superfund (RAGS) Volume III - Part A: Process for Conducting Probabilistic Risk Assessment, Appendix B, vol. III, U.S. Environmental Protection Agency, 2001. EPA 540-R-02–002, http://www.epa.gov/sites/production/files/2015-09/documents/rags3adt_complete.pdf.
[50] R. Khan, M. Strand, Road Dust and its effect on human health: a literature review, Epidemiol. Health 40 (2018) e2018013, 2018.
[51] S. Tian, T. Liang, L. Kexin, Fine road dust contamination in a mining area presents a likely air pollution hotspot and threat to human health, Environ. Int. 128 (2019) 201–209.
[52] E. De Miguel, I. Irribaren, E. Chacón, A. Ordoñez, S. Charlesworth, Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain), Chemosphere 66 (2007) 505–513.
[53] A. Hernández-Pellón, W. Nischkauer, A. Limbeck, I. Fernández-Olmo, Metal(loid) bioaccessibility and inhalation risk assessment: a comparison between an urban and an industrial area, Environ. Res. 165 (2018) 140–149.
[54] R. Van den Berg, Human Exposure to Soil Contamination: A Qualitative and Quantitative Analysis towards Proposals for Human Toxicological Intervention Values; RIVM Repport. 725201011, National Institute for Public Health and the Environment, Bilthoven, The Netherlands, 1994.
[55] W. Zgłobicki, M. Telecka, Heavy metals in urban street dust: health risk assessment (Lublin city, E Poland), Appl. Sci. 11 (2021) 4092, https://doi.org/10.3390/app11094092.
[56] H. Wei, Z. Le, L. Shuxian, W. Dan, L. Xiaojun, J. Lan, M. Xiping, Health risk assessment of heavy metals and polycyclic aromatic hydrocarbons in soil at coke oven gas plants, Environ. Eng. Manage. J. 14 (2015) 487–496.
[57] A.O. Adeniji, O.O. Okoh, A.I. Okoh, Distribution pattern and health risk assessment of polycyclic aromatic hydrocarbons in the water and sediment of Algoa Bay, South Africa, Environ. Geochem. Health 41 (3) (2019) 1303–1320, https://doi.org/10.1007/s10653-018-0213-x.
[58] A.O. Adeniji, O.O. Okoh, A.I. Okoh, Levels of polycyclic aromatic hydrocarbons in the water and sediment of Buffalo River Estuary, South Africa and their health risk assessment, Arch. Environ. Contam. Toxicol. 76 (4) (2019) 657–669, https://doi.org/10.1007/s00244-019-00617-w.

[59] C. Pagotto, N. Remy, M. Legret, P. Le Cloirec, Heavy metal pollution of road dust and roadside soil near a major rural highway, Environ. Technol. 22 (2001) 307–319.
[60] M.P. Sanleandro, A. Sánchez Navarro, E. Díaz-Pereira, F. Bautista Zúñiga, M. Romero Muñoz, M.J. Delgado Iniesta, Assessment of heavy metals and color as indicators of contamination in street dust of a city in SE Spain: influence of traffic intensity and sampling location, Sustainability 10 (2018) 4105.
[61] J. Chen, W. Wang, H. Liu, L. Ren, Determination of road dust loading and chemical characteristics using resuspension, Environ. Monit. Assess. 184 (2012) 1693–1709.
[62] E. De Miguel, J.F. Llamas, E. Chacon, T. Berg, S. Larssen, O. Royset, M. Vadest, Origin and patterns of distribution of trace elements in street dust: unleaded petrol and urban lead, Atmos. Environ. 31 (1997) 2733–2740.
[63] X. Hu, Y. Zhang, J. Luo, T. Wang, H. Lian, Z. Ding, Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China, Environ. Pollut. 159 (2011) 1215–1221.
[64] S. Liu, X. Zhang, C. Zhan, J. Zhang, J. Xu, A. Wang, H. Zhang, J. Xu, J. Guo, X. Liu, et al., Evaluating heavy metals contamination in campus dust inWuhan, the university cluster in Central China: distribution and potential human health risk analysis, Environ. Earth Sci. 81 (2022) 210.
[65] J.F. Hair Jr., R.E. Anderson, R.L. Tatham, W.C. Black, Multivariate Data Analysis, fifth ed., Prentice Hall, Upper Saddle River, NJ, 1998.
[66] Q. Zhang, X. Zhang, Quantitative source apportionment and ecological risk assessment of heavy metals in soil of a grain base in Henan Province, China, using PCA, PMF modeling, and geostatistical techniques, Environ. Monit. Assess. 193 (2021) 655.
[67] H. Chen, D. Wu, Q. Wang, L. Fang, Y. Wang, C. Zhan, J. Zhang, S. Zhang, J. Cao, S. Qi, S. Liu, The predominant sources of heavy metals in different types of fugitive dust determined by principal component analysis (PCA) and positive matrix factorization (PMF) modeling in Southeast Hubei: a typical mining and metallurgy area in Central China, Int. J. Environ. Res. Publ. Health 19 (2022) 13227, https://doi.org/10.3390/ijerph192013227, 2022.
[68] B. Dong, R. Zhang, Y. Gan, L. Cai, A. Freidenreich, K. Wang, T. Guo, H. Wang, Multiple methods for the identification of heavy metal sources in cropland soils from a resource-based region, Sci. Total Environ. 651 (2019) 3127–3138.
[69] USGS (U.S. Geological Survey), 2019 minerals yearbook - United Arab Emirates [advance release], Available at: https://pubs.usgs.gov/myb/vol3/2019/myb3-2019-united-arab-emirates.pdf, 2023. (Accessed 16 December 2023).
[70] J. Zhang, H. Li, Y. Zhou, D. Lei, Y. Jing, Bioavailability and soilto-crop transfer of heavy metals in farmland soils: a case study in the Pearl River Delta, South China, Environ. Pollut. 235 (2018) 710–719.
[71] Y. Bai, Y. Zhang, X. Liu, Y. Wang, The spatial distribution and source apportionment of heavy metals in soil of Shizuishan, China, Environ. Earth Sci. 82 (2023) 494.
[72] X. Chen, X. Lu, Contamination characteristics and source apportionment of heavy metals in topsoil from an area in Xi'an city, China, Ecotoxicol. Environ. Saf. 151 (2018) 153–160.
[73] L. Sun, D. Guo, K. Liu, H. Meng, Levels, sources, and spatial distribution of heavy metals in soils from a typical coal industrial city of tangshan, China, Catena 175 (2019) 101–109.
[74] J. Duan, J. Tan, Atmospheric heavy metals and Arsenic in China: situation, sources and control policies, Atmos. Environ. 74 (2) (2013) 93–101.
[75] D.L. Tomlinson, J.G. Wilson, C.R. Harris, D.W. Jeffrey, Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index, Helgol. Meeresunters. 33 (1980) 566–575.
[76] A.A. Koelmans, M.T.O. Jonker, G. Cornelissen, T.D. Bucheli, P.C.M. van Noort, O. Gustafsson, Black carbon: the reverse of its dark side, Chemosphere 63 (2006) 365–377.
[77] Y.M. Han, J.J. Cao, J.C. Chow, J.G. Watson, Z.S. An, S.X. Liu, Elemental carbon in urban soils and road dusts in Xi'an, China and its implication for air pollution, Atmos. Environ. 43 (2009) 2464–2470, https://doi.org/10.1016/j.atmosenv.2009.01.040.
[78] USEPA, United States Environmental Protection Agency, A Guide to the Biosolids Risk Assessments for the EPA Part 503 Rule, vol. 1995, U.S. Environmental Protection Agency Office of Wastewater Management, Washington, DC, USA, 1995.
[79] M.A. Agoro, A.O. Adeniji, M.A. Adefisoye, A.I. Okoh, O.O. Okoh, Quantitative analysis of heavy metals in the wastewaters and sludge from three treatment facilities in Eastern Cape Province, South Africa and associated health risks, Water 12 (2020) 2746, https://doi.org/10.3390/w12102746.
[80] B.J. Alloway, Sources of heavy metals and metalloids in soils, in: Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability, Springer, Dordrecht, The Netherlands, 2013, pp. 11–50.
[81] WHO, World Health Organization, Guidelines for Drinking Water Quality: Fourth Edition Incorporating the First Addendum vol. 631, WHO, Cham, Switzerland, 2017. ISBN 978-92-4-154995-0.
[82] T.T. Duong, B.K. Lee, Determining contamination level of heavy metals in road dust from busy traffic areas with different characteristics, J. Environ. Manag. 92 (3) (2011) 554–562.
[83] B. Duan, W. Zhang, H. Zheng, C. Wu, Q. Zhang, Y. Bu, Comparison of health risk assessments of heavy metals and as in sewage sludge from wastewater treatment plants (WWTPs) for adults and children in the urban district of Taiyuan, China, Int. J. Environ. Res. Publ. Health 14 (2017) 1194.
[84] Y. Titilawo, A. Adeniji, M. Adeniyi, A. Okoh, Determination of levels of some metal contaminants in the freshwater environments of Osun State, Southwest Nigeria: a risk assessment approach to predict health threat, Chemosphere 211 (2018) 834–843, https://doi.org/10.1016/j.chemosphere.2018.07.203.
[85] X. Qing, Z. Yutong, L. Shenggao, Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China, Ecotoxicol. Environ. Saf. 120 (2015) 377–385.
[86] F. Li, J. Zhang, J. Huang, D. Huang, J. Yang, Y. Song, G. Zeng, Heavy metals in road dust from Xiandao District, Changsha City, China: characteristics, health risk assessment, and integrated source identification, Environ. Sci. Pollut. Res. 23 (13) (2016) 13100–13113.
[87] Y. Du, B. Gao, H. Zhou, X. Ju, H. Hao, S. Yin, Health risk assessment of heavy metals in road dusts in urban parks of Beijing, China, Procedia Environ. Sci. 18 (2013) 299–309.
[88] F. Li, Z. Qiu, J. Zhang, C. Liu, Y. Cai, M. Xiao, Spatial distribution and fuzzy health risk assessment of trace elements in surface water from Honghu Lake, Int. J. Environ. Res. Publ. Health 14 (2017) 1011.