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Abstract: Dust is a significant pollution source in the United Arab Emirates (UAE) that impacts population health. Therefore, the present study aims to determine the concentration of heavy metals (Cd, Pb, Cr, Cu, Ni, and Zn) in the air in the Sharjah and Ajman emirates' urban areas and assesses the health risk. Three indicators were used for this purpose: the average daily dose (ADD), the hazard quotient (HQ), and the health index (HI). Data were collected during the period April–August 2020. Moreover, the observation sites were clustered based on the pollutants' concentration, given that the greater the heavy metal concentration is, the greater is the risk for the population health. The most abundant heavy metal found in the atmosphere was Zn, with a mean concentration of 160.30 mg/kg, the concentrations of other metals being in the following order: Ni > Cr > Cu > Pb > Cd. The mean concentrations of Cd, Pb, and Cr were within the range of background values, while those of Cu, Ni, and Zn were higher than the background values, indicating anthropogenic pollution. For adults, the mean ADD values of heavy metals decreased from Zn to Cd (Zn > Ni > Cr > Cu > Pb > Cd). The HQ (HI) suggested an acceptable (negligible) level of non-carcinogenic harmful health risk to residents' health. The sites were grouped in three clusters, one of them containing a single location, where the highest concentrations of heavy metals were found.

Keywords: heavy metals; pollution; concentration; indicators; health risk assessment

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1. Introduction

Heavy metals are the most common and hazardous chemicals in the environment due to their toxicity, persistence, and bioaccumulation [1,2]. Even at low concentrations, heavy metals (lead (Pb), chromium (Cr), nickel (Ni), arsenic (As), mercury (Hg), cadmium (Cd), cobalt (Co), zinc (Zn), and copper (Cu)) are known for their high toxicity [3]. These pollutants originate from anthropogenic and natural processes [4].

Anthropogenic processes that lead to the release of heavy metals and other pollutants include industrial, agricultural, mining, and metallurgical activities. Automobile exhaust, smelting, insecticides, and fossil burning are activities that contribute significantly to environmental pollution with heavy metals, e.g., lead, arsenic, copper, zinc, nickel, vanadium, mercury, selenium, and tin [4]. On the other hand, sources of natural emissions of these metals include sea-salt sprays, volcanic eruptions, forest fires, and wind-borne soil particles.

Rock-weathering is another source of heavy metals released into the atmosphere [5]. Several studies demonstrated that high levels of heavy metals result from natural emissions and vehicles' exhaust in the traffic [6,7].

A significant ecological and public health concern is associated with the environmental contamination and heavy metals' ultimate toxic effect [8–15]. Although many heavy metals are essential micronutrients necessary for various biochemical and physiological processes and functions [8], excessive exposure to these agents results in a wide range of adverse health effects and diseases [16]. Each metal has a distinctive toxicological profile and action mechanism. These toxicological effects depend on exposed individuals' age, gender, genetics, and nutritional status. Limiting access to arsenic, cadmium, chromium, lead, and mercury is a health priority given their systemic toxicity and carcinogenic effect on the population [17].

The rapid economic and industrial development in the United Arab Emirates (UAE) has markedly impacted the country's air quality, where gases and dust are being emitted into the air in exceedingly high concentrations, rendering air pollution a critical public health problem [18–21]. Recent studies have demonstrated that road dust is a significant source of air pollution with heavy metals [21–23] and is a leading factor affecting human health [21,24,25]. Indeed, in the UAE, results of ecological risk assessments showed that Cd and Hg in road dust constitute a high public health risk [12,18]. The primary sources of heavy metal in road dust are soil materials, vehicle exhaust emissions, atmospheric deposition, and industrial and commercial activities [26–28]. The vehicles' emissions—including a complex mixture of metals from tires, brakes, parts wear and tear, and suspended road dust—are perhaps the most important source of air pollution with heavy metals [21,26,29–32] in urban areas. Long-term inhalation, ingestion, and dermal contact of these factors are associated with a wide range of acute or chronic health adverse effects [24,26] by their accumulation in the vital organs, such as the brain, liver, bones, and kidneys [33,34].

Copper is a nutrient for humans, but exposure to high concentrations can produce diseases, as Taylor et al. [35] presented in their reviews on the literature about the effects of Cu on human health. Pb is regarded as a mutagen and probable carcinogen, producing renal tumors and disturbing the reproductive and nervous systems [36]. Exposure to increased concentration of Zn has toxic effects, rarely resulting in intoxication and interfering with Cu uptake [37]. The health effects produced by Ni can be cardiovascular diseases, contact dermatitis, respiratory diseases (respiratory tract cancer, lung fibrosis, and asthma) [38,39]. Inhalation and ingestion of contaminated food and water are the main ways of introducing Ni to the organism [40]. Cadmium is a toxic metal for the population and animals, deposited in the environment by agricultural and industrial pollution [41]. Its accumulation in the human body through inhalation and ingestion provokes different types of cancer. The primary way chromium (especially in the form of Cr(III) and Cr(VI)) enters the organism is through inhalation [42], affecting the respiratory tract by producing rhinitis, pharyngitis, bronchitis.

Therefore, the present study was performed to determine the levels of heavy metals in the road dust from urban areas in the Sharjah and Ajman emirates (UAE) and to evaluate these agents' impact on public health. Clustering the observation sites (based on the studied metals' concentrations in the atmospheric dust and health indicators) was performed to determine the most polluted zones and those with the highest risk for the population.

2. Materials and Methods

2.1. Study Area

Sharjah is the third emirate in the UAE, in terms of population number. Sharjah city, the capital of this emirate, is situated at 25°21′27″ N latitude and 55°23′27″ E longitude. Ajman is the fifth largest emirate in the UAE, and its capital, with the same name, is located at 25°24′49″ N latitude and 55°26′44″ E longitude (Figure 1).

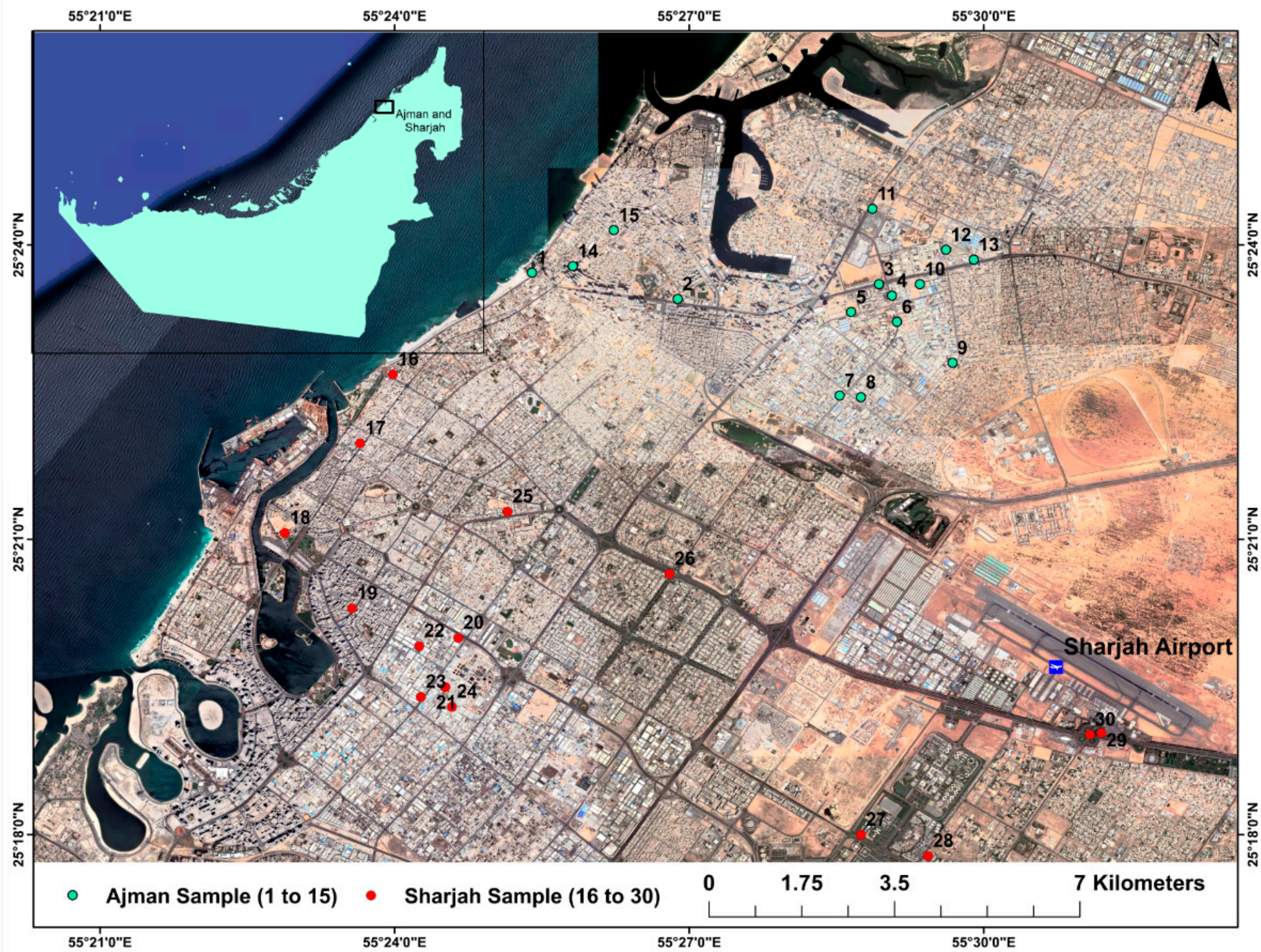

Figure 1. Study area location and sampling map.

The articles [21,25] present an extensive analysis of the climate in the region. Still, we summarize here some aspects related to the climate in the Sharjah and Ajman emirates. The study area belongs to a hot desert with warm winters and scorching and humid summers. Rainfall is generally light and erratic and occurs almost entirely from November to April. About two-thirds of annual precipitations fall in February and March [43].

The chart from Figure 2 presents the average temperatures and precipitation evolution. Figure 3 shows the cloudy, sunny, and precipitation days, precipitation amounts, maximum temperatures, and wind speed recorded at the Sharjah International Airport. Two sampling sites are situated nearby (29 and 30).

The wind rose for Sharjah International Airport (Figure 4) shows that most often throughout the year the wind blows from west to east or east to west, with speeds between 12 and 19 km/h.

Ajman has a similar climate as Sharjah.

Land use/Land cover (LULC) is the placement of activities and physical structures within a specific geographical area. It is a crucial metric for determining how human activities interact with the natural world [44]. The local, regional, and global environments are under tremendous stress due to changing land-use practices. The degradation of air quality is one of the most important environmental effects of urbanization.

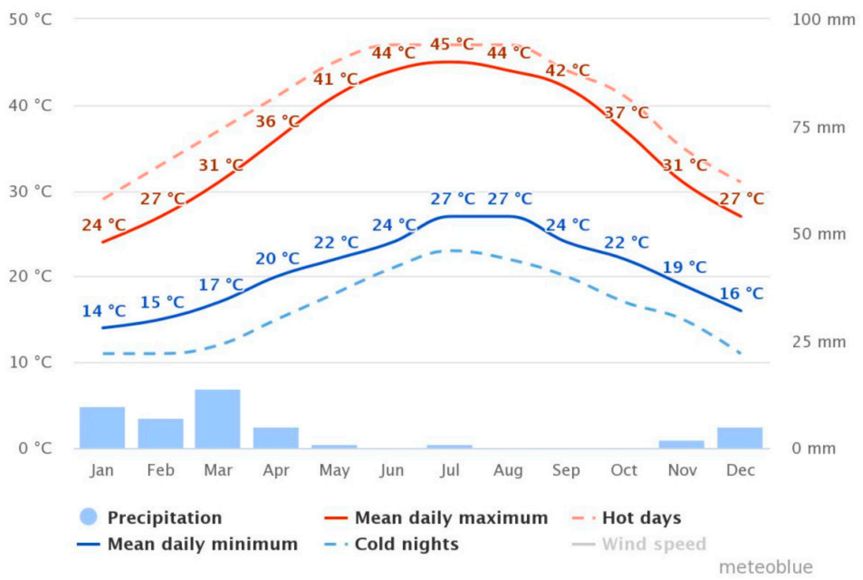

Figure 2. Average temperature and precipitation in Sharjah (International Airport).

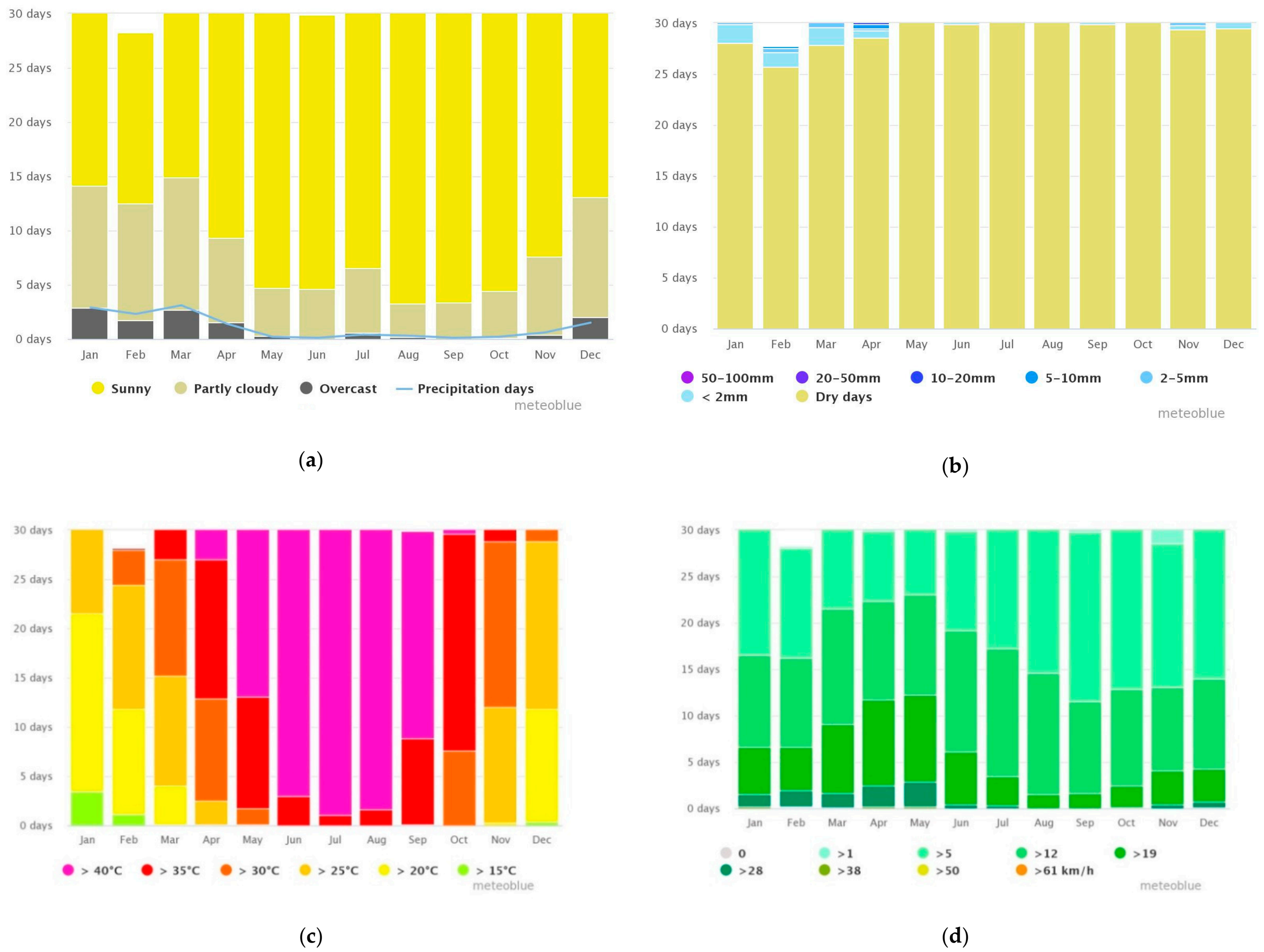

Figure 3. (**a**) Cloudy, sunny, and precipitation days; (**b**) precipitation amounts; (**c**) maximum temperatures; (**d**) wind speed.

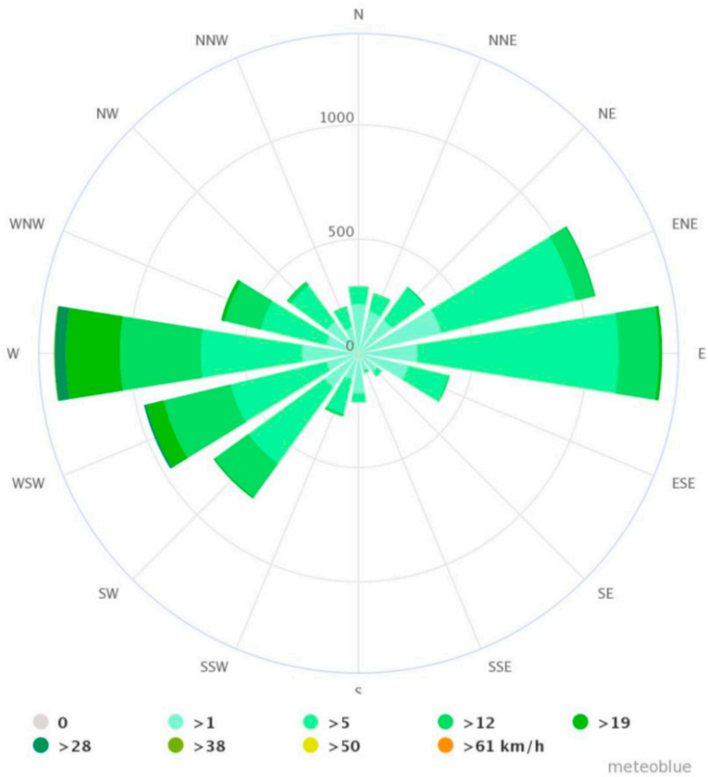

Figure 4. Wind rose for Sharjah International Airport.

Environmental and social factors, such as land use, community design, transportation networks, have been shown to have a significant impact on public health [45]. Many variables could cause particulate pollution, such as dust from construction, domestic garbage, and vehicle exhaust, but most pollution can be associated with land-use changes. Understanding the response mechanisms of urban particle pollution is crucial for pollution prevention and environmental protection [46].

To better understand the study area, we used recently released Landsat 8 satellite images for LULC mapping and monitoring in the region (Figure 5).

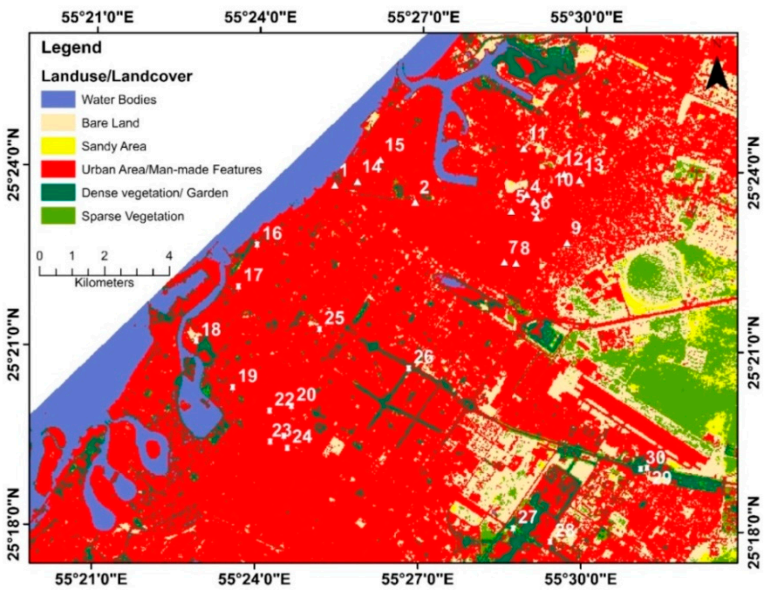

Figure 5. Landuse/Landcover (LULC) map of the study area.

Results of the land-cover analysis (Figures 5 and 6) show that 66% of the study area (187.61 km^2) mostly includes urban area/human-made features, which includes industrial sites, petrol pumps, hotels, tourist areas, residential and commercial buildings, airport, etc.

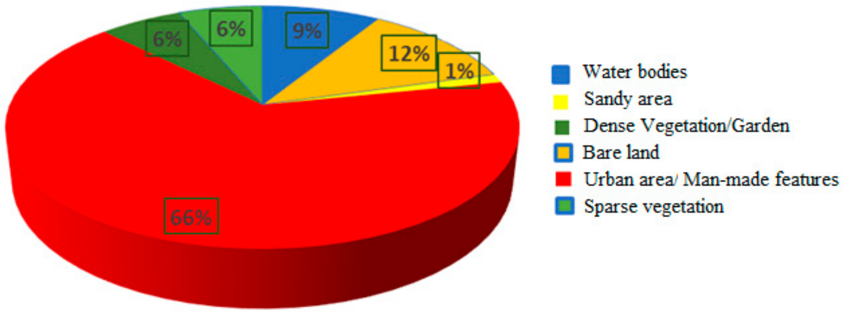

Figure 6. Pie chart showing the LULC percentage distribution of the studied region (from the LANDSAT 8).

Other land uses do not directly emit air pollutants but attract vehicular sources such as bus terminals, shopping centers, warehouses, etc.

The major categories of the land use and the associated surfaces in the study area are:

- Sparse vegetation: date palms, *Prosopis juliflora*, etc. (18.07 km^2);
- Water bodies: water in the terrestrial area and nearby sea (25.35 km^2);
- Dense vegetation/Garden: human-made garden areas and concentrated vegetation (17.77 km^2);
- Urban area/Human-made features: industrial areas, petrol pumps, hotels, tourist areas, residential and commercial buildings, airports, etc. (187.61 km^2);
- Sandy area (3.37 km^2)
- Bare land (33.52 km^2).

2.2. *Instruments and Methods*

2.2.1. Samples Collection

Dust samples were collected from thirty different Sharjah and Ajman emirates locations for five months (April–August 2020) using large dust traps placed at the height of 4 m above the ground level. Collected samples (150 at each site) were safely packed and moved to a desiccator before transporting to the laboratory. Samples were air-dried for 48 h to avoid moisture in a well-protected area. Then, each sample was sieved using a mechanical sieve shaker (Retsch, AS 200) with a 63µm filter to remove any large particles. A six-stage Anderson cascade impactor (Tecora, Italy) with an intake flow rate of 28.3 L/min was used to segregate dust particles.

Dust with a diameter lower than 10 µm was collected on the glass disks in the cascade impactor. The size ranges were 10 µm, 9.0 µm, 7.0 µm, 5.8 µm, 4.7 µm, and 3.3 µm. A cellulose nitrate filter with 100 mm diameter and 3 µm pore size was used as a backup filter.

2.2.2. Reagents, Standards, and Laboratory Ware

All experiments were performed using analytical reagent (AR) grade chemicals. The reference standard, check standard, and reagents were purchased from Sigma Aldrich. A 1:1 acid mixture was prepared using conc. nitric acid (69% v/v) and hydrochloric acid (37% v/v). Ultra-pure water with chemical resistivity of 18.2 MΩ.cm was obtained from a Merck Millipore (Massachusetts, USA) water purification system in the lab. For the sample oxidation, 30% hydrogen peroxide was used. Class-A grade glassware was utilized throughout the analysis. All glassware and plasticware were washed 5–6 times with ultrapure water followed by 10% nitric acid to remove contaminations and then air-dried. The Mars-6 system (CEM, North Carolina, USA) was employed to digest the samples. ICP-OES analysis was performed using a Perkin Elmer (Ohio, USA) Avio 200 system.

2.2.3. Samples Analysis

Sample digestion was performed by following USEPA 3050B [47] procedure. A total of 0.2 g of each sample was accurately weighed and transferred to Teflon vessels for microwave-assisted digestion. Afterwards, 10 mL of 1:1 HCl: HNO_3 were added to the digestion vessel, mixed the slurry well, and digested it using the microwave digestion system at 95 °C for 5 min. The slurry was cooled and then added to 5 mL conc. HNO_3. It was then heated and refluxed at 95 °C for 5 min, cooled, followed by the careful addition of 10% H_2O_2 for oxidation. The solutions were carefully transferred to 100 mL volumetric flasks, made up to mark with water, and filtered using Whatman 41 filters. The filtered solutions were moved to the ICP-OES system and analyzed for heavy metals. Replicate analyses were carried out on each sample.

Strict quality control and quality assurance procedures were followed to prepare and analyze samples, laboratory blanks, check standards, and standard spiked samples. Laboratory blanks were prepared using the same reagents used for the digestion without adding dust samples. The laboratory blank values for each metal were much lower than those of metals' concentrations in the target samples. Method detection (*MDL*) was calculated using the equation:

$$MDL = Mean + 2\ 9 \times SD \quad (1)$$

where *Mean* is the average concentration and *SD* is the standard deviation of blanks [48]. The *MDL* values ranged between 0.02 µg/kg (Cd) and 25.2 µg/kg (K). The metals' recovery percentages (spiked and standard) were between 95% and 105%. The precision of repeated analysis was determined (for every metal) by computing the coefficient of variation, which was less than 3%.

2.3. Heath Risk Assessment

In this study, the impact of the pollution on the population exposed to dust metals has been assessed by computing the *ADD* (mg/kg/day) of pollutants via ingestion (ADD_{ing}), dermal contact (ADD_{derm}), and inhalation (ADD_{inh}). The utilized formulas are (2)–(4) [24,47].

$$ADD_{ing} = \frac{c \times R_{ing} \times CF \times EF \times ED}{BW \times AT}, \quad (2)$$

$$ADD_{derm} = \frac{c \times SA \times CF \times SL \times ABS \times EF \times ED}{BW \times AT}, \quad (3)$$

$$ADD_{inh} = \frac{c \times R_{inh} \times EF \times ED}{PEF \times BW \times AT}, \quad (4)$$

where the notations' meanings are given in Table 1.

Table 1. Exposure factors for dose models (adult).

Factor	Definition	Unit	Value	Reference
c	Concentration of the contaminant in dusts	mg/kg	-	This study
R_{ing}	Ingestion rate of soil	mg/day	100	[49]
AT	Average time	days	365 × ED	
BW	Average body weight	kg	55.9	Environmental site [50]
CF	Conversion factor	kg/mg	1×10^{-6}	
EF	Exposure frequency	days/year	35	
ED	Exposure duration	year	24	[50]

Table 1. *Cont.*

Factor	Definition	Unit	Value	Reference
SA	Surface area of the skin that contacts the dust	cm^2	5000	
R_{inh}	Inhalation rate	m^3/day	20	
SL	Skin adherence factor for dust	mg/cm^2	1	[50]
ABS	Dermal absorption factor (chemical specific)	-	0.001	
PEF	Particle emission factor	m^3/kg	1.32×10^9	

The model used in this study to calculate people's exposure to dust metals is based on those developed by the Environmental Protection Agency of the United States [24].

The reference dose (*RfD*) estimates the maximum acceptable risk on a population group (in this case, adults) through daily exposure during a lifetime. An unfavorable health effect during a lifetime can be signaled using the threshold of *RfD* value. No adverse health effect is concluded if the *ADD* value is lower than the reference dose. If the *ADD* value is higher than the *RfD*, the exposure pathway will likely cause harmful human health effects [24]. The reference dose (*RfD*) values of heavy metals for the ingestion, dermal contact, and inhalation are presented in Table 2 [50].

Table 2. Values of RfD for the six studied heavy metals [50].

Metal	Ingestion	Dermal	Inhalation
Cd	0.0010	0.00005	0.0030
Pb	0.0035	0.00053	0.0035
Cr	0.0050	0.00025	0.000029
Cu	0.0370	0.0011	0.0400
Ni	0.0200	0.0010	0.0210
Zn	0.300	0.0600	0.3200

After computing *ADD*, the hazard quotient (*HQ*), related to non-carcinogenic toxic risk, was calculated by dividing the daily dose by a specific reference dose (*RfD*).

$$HQ = \frac{ADD}{RfD} \tag{5}$$

The last index determined in this study is the hazard index (*HI*), representing the cumulative non-carcinogenic risk. It is estimated by summing up the hazard quotients for ingestion (HQ_{ing}), dermal (HQ_{derm}), and inhalation(HQ_{inh}):

$$HI = HQ_{ing} + HQ_{derm} + HQ_{inh} \tag{6}$$

2.4. Sites Classification

The last objective of this study was to classify the sites based on the metals concentrations in the samples and on the indexes computed in the previous section. To this aim, the k-means algorithm was utilized after choosing the optimal number of clusters by the elbow method [51,52]. A comparison of the clusters' contents was finally provided to determine the concordance between the pollution level and the health risk in the zones contained by the groups.

3. Results and Discussion

3.1. Analysis of the Heavy Metals' Concentrations

The average concentrations in the samples at the observation sites are presented in Table 3.

Table 3. Average concentration values of the metals in the samples.

Site no	Location	Latitude	Longitude	Pb (ppm)	Copper (ppm)	Zn (ppm)	Ni (ppm)	Cr (ppm)	Cd (ppm)
1	Sheraton hotel tourist area	25°23′43″	55°25′24″	6.06	34.84	89.80	142.34	61.49	0.02
2	Alnuaimiay tourist area	25°23′27″	55°26′53″	11.57	67.41	115.11	173.49	89.45	0.02
3	Ajman industrial areas and petrol stations	25°23′36″	55°28′56″	15.19	66.76	190.50	167.21	82.39	0.01
4		25°23′29″	55°29′04″	34.28	65.71	470.49	165.65	80.78	0.02
5		25°23′19″	55°28′39″	16.22	61.75	132.38	156.81	66.81	0.01
6		25°23′13″	55°29′07″	37.77	57.37	377.30	148.97	64.71	0.02
7		25°22′28″	55°28′32″	32.31	53.58	150.32	146.17	63.54	0.02
8		25°22′27″	55°28′45″	44.84	47.67	185.83	136.30	61.97	0.02
9		25°22′48″	55°29′41″	40.21	42.14	316.49	134.68	61.71	0.02
10		25°23′36″	55°29′21″	21.45	41.64	115.19	134.66	58.90	0.01
11	Ajman residential and commercial area	25°24′22″	55°28′52″	13.99	40.33	170.67	134.37	58.47	0.01
12		25°23′57″	55°29′37″	14.92	40.24	133.33	129.59	55.35	0.01
13	Adnoc Ajman	25°23′51″	55°29′54″	9.49	39.92	83.48	115.79	49.99	0.01
14	Ajman commercial area	25°23′47″	55°25′49″	16.47	37.53	101.15	114.93	49.84	0.01
15		25°24′09″	55°26′14″	11.06	35.41	106.18	108.56	49.67	0.01
16	Sharjah residential and commercial areas	25°22′41″	55°23′59″	4.54	35.16	121.45	98.72	47.61	0.01
17		25°21′59″	55°23′39″	18.49	32.99	229.41	97.02	45.50	0.01
18	Sharjah-bus station	25°21′4″	55°22′53″	20.46	31.11	152.75	96.55	44.94	0.01
19	Sharjah commerial area	25°20′18″	55°23′34″	11.06	29.22	124.60	93.76	44.85	0.01
20	Sharjah industrial area	25°19′06″	55°24′39″	52.74	28.73	192.01	90.92	41.25	0.01
21		25°19′30″	55°24′31″	24.01	27.90	127.34	89.87	39.87	0.01
22		25°19′55″	55°24′15″	20.59	27.32	105.58	84.01	38.11	0.01
23		25°19′24″	55°24′16″	15.89	25.26	106.31	83.19	37.69	0.01
24		25°19′18″	55°24′35″	4.08	25.25	55.95	79.86	35.29	0.01
25	Sharjah airport highway	25°21′17″	55°25′9″	16.15	24.53	126.11	79.42	34.81	0.01
26		25°20′39″	55°26′48″	7.05	20.69	66.94	78.66	34.19	0.01
27	Sharjah University	25°18′0″	55°28′45″	18.11	20.44	106.82	70.03	34.11	0.02
28		25°17′47″	55°29′26″	16.96	17.92	275.41	69.88	33.80	0.02
29	Sharjah airport	25°19′2″	55°31′12″	22.29	16.43	151.21	62.22	30.02	0.02
30		25°19′1″	55°31′5″	24.92	15.13	129.01	61.76	26.42	0.02

The most abundant metal measured was Zn, with a mean concentration of 160.304 mg/kg. The average concentrations of the other studied metals were, in decreasing order, Ni > Cr > Cu > Pb > Cd. The mean concentrations of Cd, Pb, and Cr were within the range of background values. The mean concentrations of Cu, Ni, and Zn were higher than the background values, indicating anthropogenic pollution.

Based on the experimental data, the maps reflecting the concentration of the metals are presented in Figure 7.

The minimum, mean, and maximum levels of heavy metals (Cd, Pb, Cr, Cu, Ni, and Zn) in the dust samples collected from the studied areas in Sharjah and Ajman are presented in Table 4.

Table 4. Extreme values of the heavy metals concentrations in the 30 samples.

Metal	Heavy Metals Concentrations in Samples (mg/kg)				Background Values of the World (mg/Kg)
	Mean	Min	Max	Std. Dev.	
Cd	0.013	0.005	0.018	0.003	0.35
Pb	20.105	4.075	52.737	12.000	35
Cr	50.783	26.416	89.445	16.100	70
Cu	37.011	15.125	67.411	15.200	30
Ni	111.513	61.762	173.486	35.600	50
Zn	160.304	55.953	470.493	92.100	90

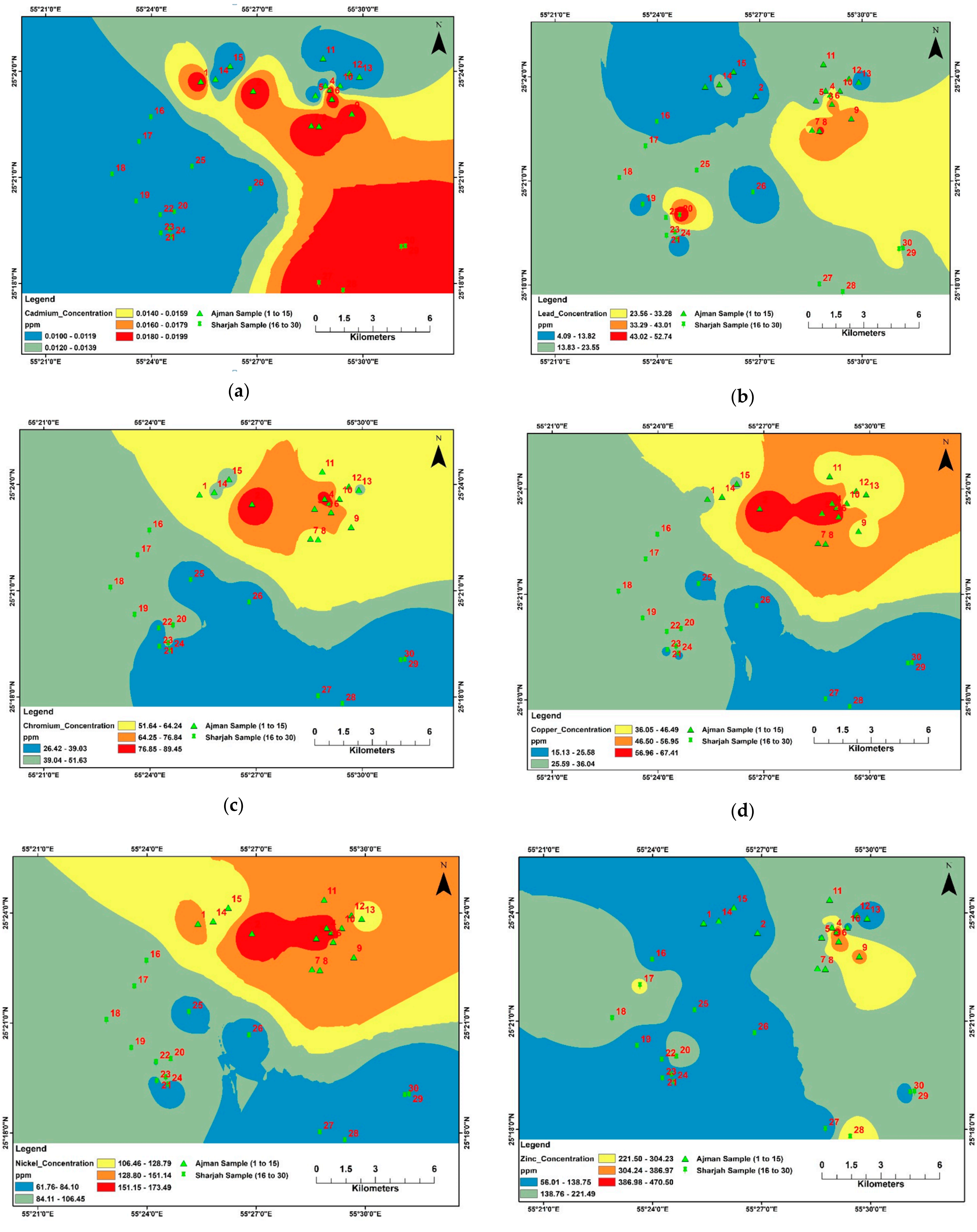

Figure 7. Maps showing the concentrations of (**a**) Cd, (**b**) Pb, (**c**) Cr, (**d**) Co, (**e**) Ni (**f**) Zn in the study area.

The composition of dust collected from industrial areas presents much higher concentrations of Zn and Ni than other metals. The highest concentration of Zn was found in samples 4, 6, and 9 (400.49, 377.30, and 316.49 mg/Kg, respectively), collected from the Ajman industrial area. The high zinc concentrations result from the steel processing activities, tire abrasion, and the corrosion of metallic parts of cars. The highest concentrations of Ni were contained by samples 7, 5, and 8 (173.49, 167.21, and 165.65 mg/Kg, respectively), collected from the Ajman industrial area. Nickel could originate from natural sources, but its presence in the air results from fuel combustion or metal plating activity.

The copper concentrations at sites 18, 28, 22, and 27 are the highest (67.41, 66.76, 65.71, and 61.75 mg/Kg). Site 18 is a bus station, and the presence of a high concentration of Cu can be attributed to traffic, tire abrasion, and the corrosion of metallic parts of cars. Site 22 is located in the Sharjah industrial area. Thus, Cu's presence can be attributed to industrial activities. The other two sites (27 and 28) are located at the University of Sharjah, where the heavy traffic can explain the high pollution.

The heavy metals concentrations in the collected dust samples from the study area were compared with those in selected cities in the world and the world reference values (Table 5). Based on the values of the pollutants' concentrations reported in different studies, the study zone occupies the first place for Cr pollution, the second one (after Hawaii) for Ni pollution, and the third for Zn pollution. These values indicate that the dust content is an issue in the area of Sharjah and Ajman.

Since each city has its specific combination of elemental compositions and the observed similarities may not reflect the actual natural and anthropogenic diversity among the different urban settings, it is necessary to establish a standard procedure to analyze the urban dust samples and draw conclusions based on the experiments [24,53].

Table 5. Heavy metals concentration in dust in different cities around the world, (mg/kg).

Location	Cr	Ni	Cu	Zn	Cd	Pb	Reference
Study area	89.44	173.48	67.91	470.49	0.018	52.73	This study
Beijing	69.33	25.97	72.13	219.20	0.64	202.82	[24]
Ottawa	43.30	15.20	65.84	112.50	0.37	39.05	[54]
Hawaii	273.0	177.0	167.0	434.0	-	106.0	[55]
Birmingham	-	41.1	466.9	534.0	1.62	48.0	[56]
Hong Kong	-	28.60	110.0	3840.0	-	120.0	[57]
Background values	70	50	30	90	0.35	35	[58]

The pollutants' concentrations recorded at different sites are not essentially influenced by wind transportation.

This conclusion results from comparing the wind rose and the metals concentrations in the samples collected at opposite sites, such as 25 and 28 or 27 and 30. We also remark that sites 29 and 30 are close to each other, but the concentrations of Zn differ. The same is valid for sites 25 and 26. This is due to the existence of small factories situated in the neighborhood of 25 and 29.

3.2. Health Risk Assessment

First, the non-carcinogenic effect on health was assessed by calculating the average daily doses (*ADD*) values, then the hazard quotient (*HQ*). The minimum, mean, and maximum levels of *ADD* and total *ADD* for adults via ingestion, dermal, and inhalation contact routes in the study area are listed in Table 6.

Table 6. Average daily dose (*ADD*) and total *ADD* for heavy metals through different pathways.

	Metal	Cd	Pb	Cr	Cu	Ni	Zn
ADD_{ing}	Mean	1.84×10^{-8}	2.75×10^{-5}	6.96×10^{-5}	5.07×10^{-5}	1.53×10^{-4}	2.20×10^{-4}
	Min.	6.85×10^{-9}	5.58×10^{-6}	3.62×10^{-5}	2.07×10^{-5}	8.46×10^{-5}	7.66×10^{-5}
	Max.	2.47×10^{-8}	7.22×10^{-5}	1.23×10^{-4}	9.23×10^{-5}	2.38×10^{-4}	6.45×10^{-4}
ADD_{derm}	Mean	4.47×10^{-11}	6.70×10^{-8}	1.69×10^{-7}	1.23×10^{-7}	3.72×10^{-7}	5.34×10^{-7}
	Min.	1.67×10^{-11}	1.36×10^{-8}	8.81×10^{-8}	5.04×10^{-8}	2.06×10^{-7}	1.87×10^{-7}
	Max.	6.00×10^{-11}	1.76×10^{-7}	2.98×10^{-7}	2.25×10^{-7}	5.78×10^{-7}	1.57×10^{-6}
ADD_{inh}	Mean	2.78×10^{-12}	4.17×10^{-9}	1.05×10^{-8}	7.68×10^{-9}	2.31×10^{-8}	3.33×10^{-8}
	Min	1.04×10^{-12}	8.46×10^{-10}	5.48×10^{-9}	3.14×10^{-9}	1.28×10^{-8}	1.16×10^{-8}
	Max.	3.74×10^{-12}	1.09×10^{-8}	1.86×10^{-8}	1.40×10^{-8}	3.60×10^{-8}	9.77×10^{-8}
Total ADD	Mean	1.84×10^{-8}	2.76×10^{-5}	6.97×10^{-5}	5.08×10^{-5}	1.53×10^{-4}	2.20×10^{-4}
	Min.	6.87×10^{-8}	5.60×10^{-6}	3.63×10^{-5}	2.08×10^{-5}	8.48×10^{-5}	7.68×10^{-5}
	Max.	2.47×10^{-8}	7.24×10^{-5}	1.23×10^{-4}	9.26×10^{-5}	2.38×10^{-4}	6.46×10^{-4}

The highest *ADD* values are those for Ni and Zn, corresponding to absorption by ingestion, while the lowest are those for Cd. The main pathway the pollutants enter the organism is ingestion. Indeed, ADD_{ing} is about 10^3 times higher than ADD_{derm} and 10^4 times higher than ADD_{inh}.

The ADD_{ing}, ADD_{derm}, and ADD_{inh} are lower than the *RfD* for the studied heavy metals, which preliminarily indicates no significant effect on the health.

The mean levels of total *ADD* (*ADD total*) (in mg/kg-day) are 1.84×10^{-8} for Cd, 2.76×10^{-5} for Pb, 6.97×10^{-5} for Cr, 5.08×10^{-5} for Cu, 1.53×10^{-4} for Ni, and 2.20×10^{-4} for Zn. The mean values of total *ADD* for adults are ordered decreasingly as follows: Zn > Ni> Cr >Cu > Pb > Cd.

The minimum, mean, and maximum levels of *HQ* and total *HQ* for adults through ingestion, dermal, and inhalation contact pathways are presented in Table 7.

Table 7. *HQ* for heavy metals through different pathways and *HI*.

	Metal	Cd	Pb	Cr	Cu	Ni	Zn
HQ_{ing}	Mean	1.84×10^{-5}	7.87×10^{-3}	1.39×10^{-2}	1.37×10^{-3}	7.64×10^{-3}	7.32×10^{-4}
	Min	6.85×10^{-6}	1.60×10^{-3}	7.24×10^{-3}	5.60×10^{-4}	4.23×10^{-3}	2.55×10^{-4}
	Max	2.47×10^{-5}	2.06×10^{-2}	2.45×10^{-2}	2.50×10^{-3}	1.19×10^{-2}	2.15×10^{-3}
HQ_{derm}	Mean	8.94×10^{-7}	1.28×10^{-4}	6.77×10^{-4}	1.13×10^{-4}	3.72×10^{-4}	8.91×10^{-6}
	Min	3.33×10^{-7}	2.59×10^{-5}	3.52×10^{-4}	4.63×10^{-5}	2.06×10^{-4}	3.11×10^{-6}
	Max	1.20×10^{-6}	3.35×10^{-4}	1.19×10^{-3}	2.06×10^{-4}	5.78×10^{-4}	2.61×10^{-5}
HQ_{inh}	Mean	2.78×10^{-9}	1.19×10^{-6}	3.69×10^{-4}	1.91×10^{-7}	1.12×10^{-6}	1.04×10^{-7}
	Min	1.04×10^{-9}	2.40×10^{-7}	1.92×10^{-4}	7.81×10^{-8}	6.22×10^{-7}	3.63×10^{-8}
	Max	3.74×10^{-9}	3.11×10^{-6}	6.49×10^{-4}	3.48×10^{-7}	1.75×10^{-6}	3.05×10^{-7}
Total HQ	Mean	1.93×10^{-5}	8.00×10^{-3}	1.50×10^{-2}	1.48×10^{-3}	8.01×10^{-3}	7.41×10^{-4}
	Min	7.18×10^{-6}	1.62×10^{-3}	7.78×10^{-3}	6.06×10^{-4}	4.44×10^{-3}	2.59×10^{-4}
	Max	2.59×10^{-5}	2.10×10^{-2}	2.63×10^{-2}	2.70×10^{-3}	1.25×10^{-2}	2.18×10^{-3}

$HQ \leq 1$ indicates no adverse health effects, while $HQ > 1$ indicates likely negative health effects [59]. All the studied heavy metals had total HQs below 1 (Table 7). Accordingly, the health risk estimation of Cd, Pb, Cr, Cu, Ni, and Zn suggests a low level of non-carcinogenic harmful health risk in all samples taken from the Ajman and Sharjah studied areas. The average hazard index *HI* is 3.32×10^{-2}. It shows a negligible non-carcinogenic risk to residents' health.

3.3. Site Clustering

Clustering has been performed for grouping the observation sites' function of the pollution impact on the population health, based on the health indexes.

The series containing the pollutants concentrations recorded at each site were normalized, and the silhouette and elbow methods (Figure 8) were used to determine the optimal number of clusters. Based on them, *k* was found to be 2 and 4.

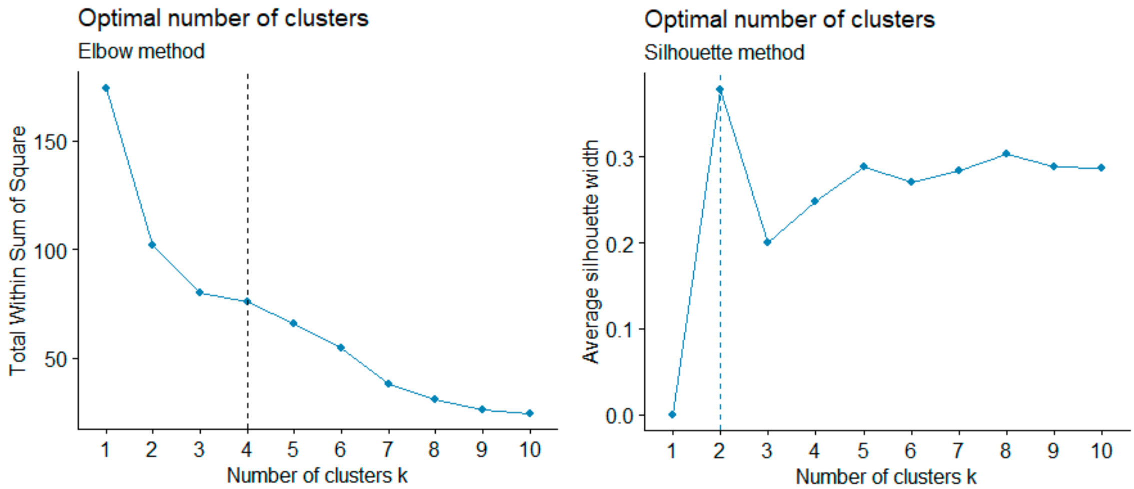

Figure 8. The elbow method for the normalized pollutants dataset.

Running the *k*-means algorithm with $k = 2$, all the sites, but the first one, are contained in the same cluster. Running the *k*-means algorithm with $k = 4$, the following sites have been included in the clusters: (1) 1; (2) 2–4, 6, 8, 9, 11–13; (3) 14–31; (4) 5, 7, 10 (Figure 9).

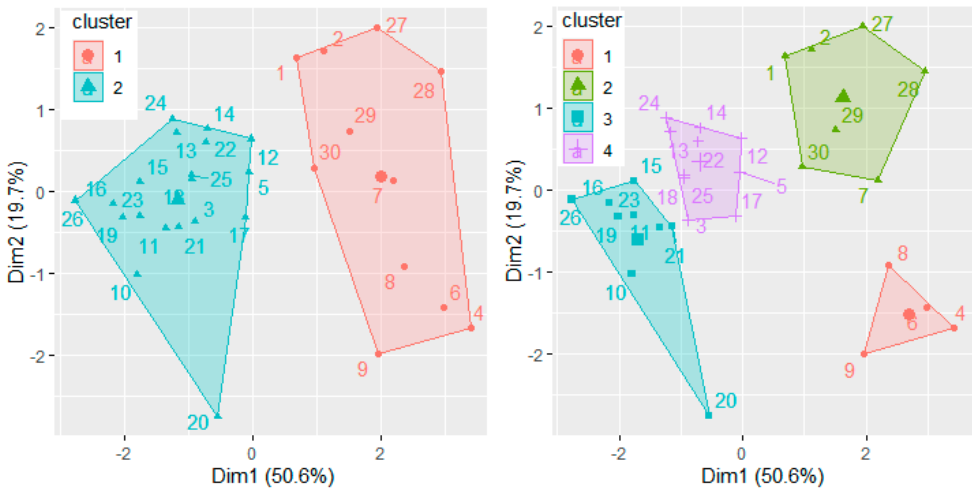

Figure 9. Clusters determined by the k-means algorithm with $k = 2$ (in the left) and $k = 4$ (in the right), based on the pollutants' concentrations.

Using $k = 2$, it resulted that the sites with the highest concentrations of Zn (4, 6, 9), Ni (7, 8), and Cu (27, 28) are in the same cluster. Still, sites 5, 18, and 22 with high concentrations of Ni and Zn are contained in the second cluster. Using $k = 4$, the sites with the highest concentrations of Zn (4, 6, 9) and Ni (8) are in the first cluster.

Samples 27 and 28 (high concentration of Cu) are kept in another cluster, while the samples with the lowest concentrations are in Cluster 3. Comparing the clustering based on the sum of squares of the distances between the groups (SSD) over the total sum of distances (TSD), the best clustering is the second (SSD/TSD = 41.5% when $k = 2$, and 60.8% for $k = 4$).

All the indices previously computed were utilized for clustering the sites. The procedure was performed using the *k*-means algorithm with $k = 2$ and $k = 4$ (determined by the elbow method). Figure 10 shows the sites' clustering (based on the health indexes).

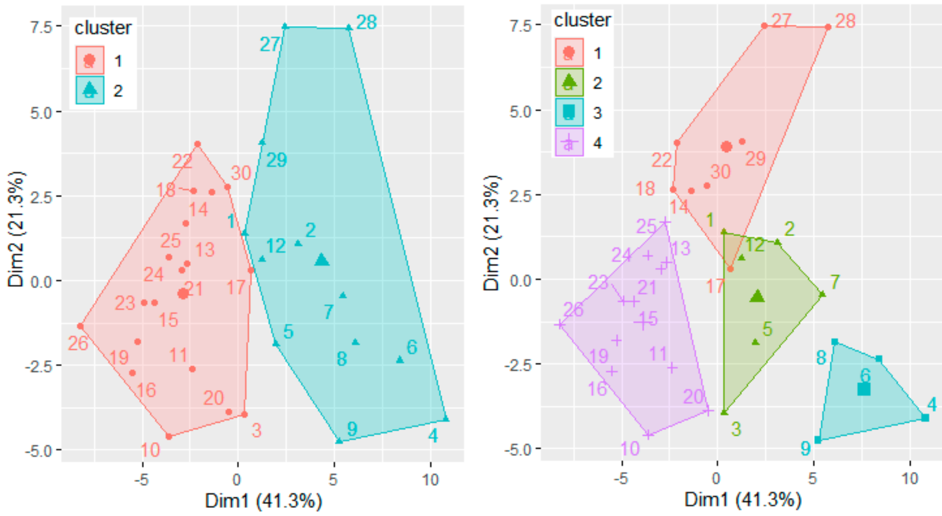

Figure 10. Clusters determined by the k-means algorithm with $k = 2$ (in the left), and $k = 4$ (in the right) based on the health risk indicators.

For $k = 2$, the sites with the highest concentrations with Ni (5, 7, 8), Zn (4, 6, 9), 27, and 28 are in the same cluster, confirming an increased risk impact on health due to high pollution with different elements in the air. For $k = 4$, the samples with the highest values of the health indices are mainly situated in clusters 1 (sites 18, 22, 27, 28), 2 (5, 7), and 3 (4, 5, 8, 9). For $k = 4$, the samples with the largest values of the health indices are mainly situated in clusters 1 (sites 18, 22, 27, 28), 2 (5, 7), and 3 (4, 5, 8, 9). The best clustering corresponds to $k = 4$ because SSD/TSD is 29.2% for $k = 2$, compared to 54.9%, for $k = 4$.

Cluster 3 from Figure 10 and Cluster 1 from Figure 9 have the same members, so the highest health risk is due to high concentrations of Zn and Ni. The sites 27–30 belong to the same cluster in Figures 9 and 10, showing a similar effect of the same pollutants on human health. Cluster 4 in Figure 10 contains the sites with the lowest impact on population health.

4. Conclusions

This study investigated the existence of heavy metals in the samples of atmospheric dust collected in the Sharjah and Ajman emirates, of the United Arab Emirates. It assessed the impact of pollutants on human health. This type of study is very significant for the residents of the UAE since the economic, industrial, and commercial development has increased the volume of exhausted gases and dust in the environment, which is severely impacting air pollution within the country.

The results show that the average concentration of heavy metals in the collected and analyzed dust samples can be ordered in decreasing order as follows: Zn > Ni > Cr > Cu > Pb > Cd. Compared with the recommended maximum allowable limits, Zn, Ni, and Cr concentrations exceeded the admissible concentrations at some locations—mainly situated in the industrial zones—indicating anthropogenic pollution. Still, at this stage of the research, the contribution of desert sand to the heavy metals pollution cannot be distinguished from that produced by anthropogenic sources.

Hazard quotient values for single and hazard index values for all studied metals are lower than the safe level for adults, indicating a non-significant non-carcinogenic. The mean values of HI through ingestion, dermal contacts, and inhalation adsorption showed a low non-carcinogenic risk to residents' health.

The clustering of the sites based on raw data and computed indices indicated four locations with the highest risks for human health (mainly due to the high concentrations of Zn and Ni).

Since many health issues of the population have been linked to air pollution with heavy metals, some measures have been proposed and are necessary to prevent such health risks [60]. They include developing detection protocols, guidelines and practices, and legislation to reduce emissions, particularly in areas with high levels of heavy metal pollution.

Since the Sharjah and Ajman cities are continuously developing, a monitoring program should be implemented. Automatic stations that record the concentrations of the most important pollutants should be placed in crowded areas and industrial zones. These should provide real-time information to the population, through electronic devices placed on visible displays. They also might be connected to a system that sends alerts to the population when the admissible pollution limit is exceeded.

Furthermore, engineering solutions are critical to both minimize pollution and prevent occupational exposure. An essential stage towards prevention is the early monitoring of human exposure to environmental pollution for a prompt action to reduce emissions and, by consequence, the adverse health effects. National collaborative efforts are needed to shape effective strategies, policies, and practices to control and prevent heavy metal toxicity.

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