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ARTICLE

Measurement of Magnetic Susceptibility and Heavy Metals Concentration in Roadside Topsoil along Amman-Airport Highway, Jordan

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Abstract: This study investigates the relationship between magnetic susceptibility and heavy metal contamination in topsoil along the Amman-Airport highway in Jordan. A total of 44 soil samples were collected and analyzed for heavy metals (Fe, Zn, Cu, Cr, Co, Ni, Mn, Pb, and Cd) using flame atomic absorption spectroscopy (FAAS). The results revealed a significant variability in heavy metal concentrations, with Fe exhibiting the highest average concentration and Cd exhibiting the lowest. The average heavy metal concentrations (mg/kg) were: Fe (12077.9), Mn (464.86), Zn (122.5), Pb (116.98), Ni (67.98), Cu (54.34), Co (39.90), Cr (39.09), and Cd (7.87). Magnetic susceptibility measurement was performed at low and high frequencies to assess correlations between heavy metal accumulation and magnetic properties. The results showed a significant positive correlation between magnetic susceptibility (χlf-F) and heavy metals, notably with Cu ($r = 0.76$), Pb ($r = 0.60$), and Zn ($r = 0.50$), as well as moderate correlations with Co ($r = 0.37$) and Ni ($r = 0.47$). Factor analysis identified three major pollution sources: vehicular emissions, industrial activities, and agricultural inputs (particularly fertilizers). The findings demonstrate the potential of magnetic susceptibility as a cost-effective and rapid proxy for assessing heavy metal contamination in urban roadside environments, supporting large-scale environmental monitoring and pollution mitigation strategies.

Keywords: Heavy metals, Magnetic susceptibility, Anthropogenic sources, Urban soil, Factor analysis, Jordan.

1. Introduction

Heavy metals are naturally occurring elements found throughout the environment. Despite their natural presence in the Earth's crust, anthropogenic activities, including industrial processes, vehicular emissions, mining, and agricultural practices, have significantly increased their concentrations in the environment [1]. These metals are characterized by their high toxicity, persistence in the environment, and non-biodegradability, leading to long-term accumulation in soils and water systems [2, 3]. Contaminated soils can act as reservoirs, releasing heavy metals into surrounding ecosystems through leaching and erosion, thereby threatening groundwater, crop quality, and biodiversity [4-7].

Exposure to heavy metals poses serious risks to human health. For instance, Cd can cause kidney damage, skeletal demineralization, and an increased risk of cancers. Pb is known for its neurotoxic effects, particularly in children, causing developmental delays, reduced IQ, and behavioral disorders. Ni and Cr are associated with carcinogenic risks and respiratory issues when inhaled as fine particles. These metals can

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interfere with enzymatic systems and displace essential trace elements, further exacerbating health impacts. The persistence of these metals in the environment, coupled with their bioaccumulation in living organisms, exacerbates their toxicological risks, making their monitoring and regulation a priority [8-11].

Traditional analytical methods, such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), are widely used to measure heavy metal concentrations. However, these methods are time-consuming, require labor-intensive digestion protocols, and involve high operational costs. Magnetic susceptibility (MS) measurements provide a powerful, rapid, cost-effective, and non-destructive alternative for assessing heavy metal pollution in environmental matrices such as soils, sediments, and street dust. The primary utility of this technique lies in its ability to identify ferrimagnetic minerals, such as magnetite and maghemite, often associated with anthropogenic activities, including industrial emissions and vehicular traffic. The advantage of MS techniques lies not only in their sensitivity but also in their practicality for large-scale surveys. Measurements can be conducted using portable instruments, enabling field-based analyses and reducing the need for extensive laboratory procedures [12-16].

Several studies have demonstrated that MS can serve as a reliable proxy for heavy metal contamination due to the close correlation between magnetic mineral content and the concentration of heavy metals in polluted areas. For example, a study conducted in Al-Karak, Jordan, demonstrated the effective use of magnetic susceptibility to detect pollution sources, revealing strong correlations between magnetic properties and heavy metal concentrations [17]. Similarly, strong correlations were found between magnetic susceptibility and the heavy metal concentrations in topsoil and urban street dust [13, 14, 16, 18-20], in sediments [21-24], and agricultural soil [25, 26]. This study aims to assess heavy metal pollution in topsoils collected along the Amman-Airport highway in Jordan. The concentrations of metals such as Pb, Ni, Co, and Zn were determined using AAS, while magnetic susceptibility measurements were conducted to explore their correlation. The findings were used to evaluate the feasibility of using magnetic susceptibility as a reliable proxy for heavy metal contamination, contributing to more efficient and accessible soil monitoring practices.

2. Methodology

2.1. Study Area

The study area is located along the Amman-Airport Highway, spanning approximately 32 km from the Seventh Circle in Amman to Queen Alia International Airport. This region experiences a Mediterranean climate with semi-arid characteristics. The rainy season extends from October to March, with annual precipitation of less than 200 mm in the study area (Jordan Meteorological Department, 2009). The highway is characterized by high traffic density and lacks major industrial activities, making vehicular emissions the dominant source of pollution. Samples were collected from both sides of the highway, with a minimum spacing of 2 km between sampling points. Figure 1 illustrates the sampling locations within the study area.

2.2. Sample Collection

Forty-four surface soil samples were collected from both sides of the road during January 2021, following a prolonged dry period. Soil samples were taken from a depth of 0–10 cm and stored in clean plastic bags for laboratory analysis. The information for each sample was recorded. In the laboratory, samples were sieved through a 2-mm mesh to remove large particulates and organic debris, dried at 50 °C until a constant weight was achieved, and stored in airtight polyethylene bags.

2.3. Chemicals and Reagents

Analytical-grade chemicals and reagents were used throughout the study. A multi-element standard solution (1000 mg/L) for Cd, Cr, Cu, Mn, Pb, Co, Fe, Ni, and Zn was obtained from Merck KGaA (Darmstadt, Germany). Nitric acid (HNO_3, 70%), hydrogen peroxide (H_2O_2, 35%), and hydrofluoric acid (HF, 40%) were of trace-analysis grade. Ultrapure deionized water was used to prepare standards and sample solutions.

2.4. Sample Preparation

The soil samples were further sieved to particle size of 125 µm. A portion (0.35–0.40 g) of each sieved sample was digested following the EPA 5052 protocol. The digestion involved 9 mL of 70% nitric acid, 2 mL of 30% hydrogen peroxide, and 2 mL of HF. Samples were digested in a Teflon microwave digestion tube using a microwave digestion system (Anton Paar Multiwave Eco) set to 850 W, heating to 200 °C for 10 minutes, and holding for an additional 10 minutes. The digested solutions were filtered, transferred to 50-mL volumetric flasks, and diluted with deionized water. The prepared samples were stored in polyethylene bottles for further analysis.

2.5. Heavy Metal Analysis

The concentrations of Pb, Cd, Cu, Zn, Co, Ni, Cr, Fe, and Mn were determined using a flame atomic absorption spectrophotometer (Varian Spectra AA-55B, Australia) with deuterium background correction. Calibration curves were prepared for each metal using standard solutions. Linearity was excellent, with all elements following Beer's law ($r \geq 0.990$). The limits of detection (LODs), defined as three times the standard deviation of the blank measurements, were: Zn (1.40), Cu (4.80), Fe (4.40), Cr (4.35), Cd (0.25), Co (0.10), Mn (0.10), Pb (0.80), and Ni (0.20) mg/kg.

2.6. Quality Assurance/ Quality Control (QA/QC) Procedures

Rigorous quality control measures were implemented throughout the heavy metal analysis using flame atomic absorption spectroscopy (FAAS). Acid blank samples were processed alongside all analytical batches to account for potential background contamination from reagents. All sample concentrations were blank-corrected by subtracting the mean blank values for each respective element. To verify analytical precision, duplicate analyses were performed on 10% of randomly selected samples, with relative percent differences maintained below 15%. In addition, frequent analysis of standard solutions during the analysis of samples was performed to ensure instrument stability.

2.7. Magnetic Susceptibility Measurements

Samples were sieved into coarse (125–250 µm) and fine (<125 µm) fractions and stored in polyethylene bottles for analysis. Magnetic susceptibility (χ) measurements were performed using a Bartington MS2B dual-frequency susceptibility meter. Measurements were taken at both low frequency (χ_{lf}, 0.47 kHz) and high frequency (χ_{hf}, 4.7 kHz). The measurements were used to determine the qualitative and quantitative properties of superparamagnetic and ferromagnetic minerals. The instrument was calibrated using a certified Bartington Instruments magnetic calibration pellet. The instrument's sensitivity allowed detection of susceptibilities down to approximately 30×10^{-8} SI units, which is appropriate for distinguishing superparamagnetic and ferromagnetic contributions in the samples. SI units were used for all susceptibility measurements [17].

3. Results and Discussion

3.1. Heavy Metal Concentrations

The concentrations of nine heavy metals (Fe, Zn, Cu, Cr, Co, Ni, Mn, Pb, and Cd) were measured on a dry-weight basis using Flame Atomic Absorption Spectroscopy (FAAS). The statistical parameters, including mean, standard deviation (SD), minimum, maximum, and median values, are summarized in Table 1. The average concentrations (mg/kg) for the heavy metals were determined as follows: Fe (12077.9), Zn (122.5), Cu (54.34), Cr (39.09), Co (39.90), Ni (67.98), Mn (464.86), Pb (116.98), and Cd (7.87). Among these, Fe showed the highest average concentration, indicating its dominant presence in the studied soils, while Cd exhibited the lowest average concentration. The descending order of the metals based on their average concentrations is: Fe > Mn > Zn > Pb > Ni > Cu > Co > Cr > Cd.

The standard deviation values across the metals highlight substantial variability in the concentrations, reflecting site-specific differences in pollution sources and deposition patterns. For instance, Fe exhibited a standard deviation of 1203.1 mg/kg, indicating variability across the sampling sites, while Cd showed a lower SD (2.5 mg/kg), suggesting relatively consistent concentrations. The variability and patterns in heavy metal concentrations could be attributed to distinct anthropogenic activities, including emissions from vehicles, industrial discharges, and potential leaching from surrounding areas.

3.2. Results for Magnetic Susceptibility Measurements

Magnetic susceptibility is one of the measurement tools in the field of magnetism. It measures the magnetic response of a material to an applied magnetic field. It has many practical applications, such as environmental magnetism and detection of minerals. The results in Table (2) demonstrate the variability in low-frequency (χ_{lf}) and high-frequency (χ_{hf}) magnetic susceptibility values across the studied roadside topsoils. For fine particles, χlf values ranged from 37.7×10^{-8} to 323.0×10^{-8} SI, with a mean of 113.1×10^{-8} SI, while χ_{hf} values followed a similar trend. The corresponding values for coarse particles were slightly lower (13.0×10^{-8} to 206.8×10^{-8} SI), with a mean of 92.0×10^{-8} SI, reflecting the influence of particle size on magnetic properties.

Fine particles displayed higher magnetic susceptibility compared to coarse particles, aligning with prior studies that report increased magnetic signals in smaller particles due to higher concentrations of anthropogenic magnetic phases, such as magnetite and maghemite [19, 26-28]. This trend is attributed to the enhanced sensitivity of fine-grained soils to ferromagnetic contributions from vehicular emissions and industrial activities, particularly near high-traffic areas. Samples near service stations and heavy traffic zones, such as samples 2, 3, and 8, exhibited the highest χ_{lf} values, confirming the association between magnetic properties and localized pollution sources.

The spatial variability of magnetic susceptibility was evident from the distribution patterns along the Amman-Airport Highway. Samples collected near agricultural areas or farther from the road, such as samples 14, 16, and 27, showed significantly lower magnetic susceptibility values, suggesting reduced anthropogenic input in these regions. This aligns with the observed impact of wind patterns, road proximity, and runoff on pollutant deposition. Specifically, higher χ_{lf} values were noted eastward compared to the west, consistent with the prevailing westerly winds facilitating the dispersion of pollutants in the study area [29, 30].

Frequency-dependent susceptibility (χ_{fd} %) values ranged between 1% and 9%, with an average of 4% for fine particles and 5% for coarse particles. Higher χ_{fd}% values, particularly those exceeding 5%, indicate a significant presence of ultrafine superparamagnetic grains, typically of anthropogenic origin. Conversely, lower χ_{fd} % values in some samples suggest dominance by multidomain (MD) or single-domain (SD) magnetic particles from natural sources, such as bedrock weathering. The variation in χ_{fd} % values corroborates the presence of mixed pollution sources, including both natural and anthropogenic contributions. The elevated magnetic susceptibility values observed in specific areas, particularly near heavy traffic and service zones, highlight the role of vehicular emissions and industrial activities as primary sources of pollution.

TABLE 1. Statistical summary of heavy metal concentrations in collected roadside soils (mg/kg dry weight).

No	Fe	Zn	Cu	Cr	Co	Ni	Mn	Pb	Cd
1	9300	160	87	35	48	96	370	140	8
2	13900	150	140	37	43	81	460	160	11
3	12600	100	51	44	38	67	460	94	12
4	6900	140	110	27	30	63	310	83	20
5	15600	140	91	46	54	87	520	160	7
6	7800	160	100	33	32	57	240	130	7
7	9600	280	69	28	42	69	320	150	10
8	14300	190	100	43	51	90	470	260	7
9	21600	60	43	50	44	73	550	87	15
10	17400	61	32	51	39	60	690	110	4
11	23600	92	37	61	55	88	850	120	5
12	10500	160	120	35	43	71	320	160	16
13	6400	110	58	24	35	55	240	110	13
14	6200	70	38	16	31	56	260	88	7
15	6300	50	39	24	40	61	440	86	5
16	8400	83	40	26	38	63	380	85	1
17	12800	340	97	60	39	82	480	130	6
18	8900	100	42	22	35	56	310	120	4
19	8400	250	74	30	34	60	370	160	9

No	Fe	Zn	Cu	Cr	Co	Ni	Mn	Pb	Cd
20	9300	92	58	28	44	70	390	110	6
21	11600	80	45	44	48	77	600	120	6
22	11700	65	34	36	39	64	460	98	1
23	21400	78	47	53	48	81	730	100	1
24	17800	73	39	50	41	70	730	89	1
25	9800	100	56	23	42	64	490	120	13
26	10300	230	53	33	36	71	400	150	10
27	5600	90	40	20	30	46	210	88	8
28	8200	80	41	35	33	68	550	67	15
29	10000	90	35	26	42	63	410	74	5
30	16500	120	46	43	48	78	630	110	5
31	1700	80	33	16	21	35	350	72	8
32	11400	140	46	42	37	76	400	130	6
33	4200	140	22	47	23	48	160	74	10
34	10000	120	41	46	33	71	380	130	6
35	19100	65	26	59	46	75	680	90	4
36	19300	87	51	52	53	81	710	110	4
37	23800	74	29	62	51	80	770	70	8
38	9000	130	43	33	34	60	300	91	6
39	17000	140	39	43	35	94	610	73	4
40	15700	110	35	45	42	71	600	98	4
41	11900	180	57	39	31	47	440	89	4
42	10900	100	36	44	38	45	420	240	5
43	19100	110	33	64	42	67	780	140	4
44	5800	120	38	47	47	52	200	180	1
Mean	12082	123	54	39	40	68	465	117	7
SD	5369	61	27	13	8	14	174	41	4
Min	1700	50	22	16	21	35	160	67	1
Max	23800	340	140	64	55	96	850	260	20
Median	10700	105	43	40	40	68	440	110	6

TABLE 2. Results of magnetic susceptibility measurements.

No.	χlf-F	χhf-F	χFD%-F	χlf-C	χhf-C	χFD%-C
1	97	93	4	66	64	4
2	320	320	1	210	200	1
3	78	73	6	63	61	3
4	140	140	2	71	70	1
5	270	260	2	170	160	3
6	120	120	2	39	38	4
7	160	150	2	93	89	4
8	250	240	2	160	160	1
9	67	64	5	91	88	4
10	71	67	5	89	84	6
11	130	120	8	120	110	8
12	190	190	2	87	87	0
13	73	72	1	14	13	11
14	38	34	8	34	33	5
15	97	89	9	99	92	6
16	71	65	8	53	52	2
17	150	150	2	150	150	3
18	110	110	2	61	59	3
19	140	140	3	120	120	0
20	71	68	4	67	69	-3
21	95	88	8	97	89	9

No.	χlf-F	χhf-F	χFD%-F	χlf-C	χhf-C	χFD%-C
22	62	57	7	79	73	8
23	97	92	5	110	100	7
24	100	96	6	0	0	0
25	77	71	8	71	76	-7
26	150	140	3	130	130	-4
27	44	42	6	13	12	5
28	89	81	9	78	72	8
29	74	70	6	82	8	90
30	130	120	6	110	79	26
31	50	47	6	37	37	0
32	160	160	2	130	130	2
33	48	47	4	24	21	9
34	130	130	1	130	130	3
35	91	87	5	100	93	9
36	91	87	4	100	95	6
37	95	90	5	100	96	4
38	89	86	3	82	83	-1
39	100	97	5	100	99	1
40	94	92	2	94	93	1
41	120	110	3	100	100	2
42	85	78	9	44	41	6
43	120	110	6	130	120	6
44	140	130	2	140	190	-35
Avg.	113	108	5	90	86	5
SD	57	57	2	44	46	15
Min	38	34	1	0	0	-35
Max	320	320	9	210	200	90
Median	97	92	5	92	88	4

*All magnetic susceptibility values (χlf, χhf, χFD %) are reported in SI units ($\times 10^{-8}$ m³/kg).

3.3. Correlation between Magnetic Susceptibility and Heavy Metals

The correlation analysis demonstrates significant associations between magnetic susceptibility parameters and heavy metal concentrations, highlighting the potential of magnetic measurements as proxies for pollution assessment. Strong positive correlations were observed between Fe and Mn (r = 0.89), Fe and Cr (r = 0.80), and Fe and Co (r = 0.70), suggesting common anthropogenic sources, likely related to vehicular emissions and industrial activities [27]. The positive correlation between these metals and magnetic susceptibility (χlf−F) indicates that ferrimagnetic minerals, such as magnetite, play a critical role in trapping and accumulating heavy metals, consistent with findings from urban pollution studies. The magnetic susceptibility values and heavy metal concentrations in the studied roadside soils were statistically analyzed to evaluate the strength and possible sources of these associations, as presented in Table 3.

The study revealed significant positive correlations between magnetic susceptibility in fine particles (χlf-F) and heavy metal concentrations, particularly for Cu (r = 0.75), Pb (r = 0.60), and Zn (r = 0.50), with moderate correlations for Co (r = 0.37) and Ni (r = 0.47). These results indicate that heavy metals are more strongly associated with fine particles (χlf-F) than with coarse particles (χlf-C). The observed pattern likely stems from the greater surface area and chemical reactivity of fine particles, which promote the adsorption and retention of heavy metals through processes such as ion exchange and organic-inorganic complexation. In contrast, coarse particles exhibit weaker correlations due to their lower susceptibility to weathering and pedogenic processes, which limits both metal retention and magnetic enhancement. This distinction underscores the role of particle size in mediating the relationship between magnetic properties and heavy metal contamination in environmental matrices.

These findings demonstrate that combining magnetic susceptibility measurements with geochemical data provides a powerful tool for environmental management. This integrated approach enables rapid pollution screening, allowing for the efficient identification of contamination hotspots that can then be prioritized for detailed laboratory analysis. By minimizing the need for extensive traditional surveys, this method significantly reduces time and costs [12]. Furthermore, the use of portable devices, such as the Bartington MS2B meter, facilitates real-time, large-scale monitoring, offering a practical solution for timely decision-making in environmental assessments.

3.4. Factor Analysis (FA)

Factor analysis (FA) is a multivariate statistical technique extensively employed to identify predominant source categories influencing a given site. This method analyzes sample-to-sample variations in normalized concentrations, rather than directly quantifying species concentrations from diverse sources [31]. FA was conducted using the Minitab software package, with Varimax rotation applied to enhance the orthogonality of the resolved factors. The dataset, encompassing magnetic parameters and elemental concentrations, was subjected to FA. Principal component analysis (PCA) yielded three factors with eigenvalues exceeding one. The Varimax-rotated factor patterns for these three factors collectively explained 77% of the total variance, as indicated in the final row of Table 4.

The first factor exhibited high loadings for Fe, Co, Ni, and χLF-C, and moderate loadings for Cr, Mn, Pb, and LF-F, accounting for 41% of the total variance. The distribution of some parameters, including Fe, Zn, Cu, Pb, and χLF-F, across factors 1 and 2 suggests the influence of at least two distinct sources on their concentrations. The coexistence of crustal and anthropogenic elements within this factor highlights the combined influence of local dust and vehicular emissions on the observed concentrations. The strong association of these elements with magnetic parameters (χLF-F and χLF-C) is a noteworthy finding, further supported by the score plot for the first two components (Figure 2). This correlation suggests that magnetic parameters can serve as effective indicators of the concentrations of these elements.

The second factor was characterized by strong loadings of Zn and Cu, with moderate loadings of Fe, Pb, and χLF-F. This factor accounted for approximately 26% of the total variance explained. Except for Fe, the heavy metals associated with this factor are predominantly of anthropogenic origin. The score plot (Fig. 2) reinforces this conclusion, as it highlights the close association between Zn, Cu, Pb, and χLF-F. This relationship suggests that the magnetic parameter χLF-F can be employed as a proxy for these elements. Based on the identified elemental associations, this factor is attributed primarily to emissions from automobile sources.

The third factor exhibited high loadings for Cd and weak loadings for Zn, explaining approximately 10% of the total variance. Cd is exclusively derived from anthropogenic activities, originating from sources such as automobile emissions, fertilizers, and metal smelting. However, its weak correlation with other elements suggests a stronger linkage to fertilizer use rather than other anthropogenic sources. The association between Cd and Zn with fertilizer products has been extensively documented in the literature [2]. Consequently, this factor is designated as representing fertilizer-related contributions to heavy metal contamination.

TABLE 3. Correlation between magnetic susceptibility and heavy metal (n = 44, bold red numbers indicate significant correlation at $\alpha = 0.05$).

	Fe	Zn	Cu	Cr	Co	Ni	Mn	Pb	Cd	$\chi_{lf\text{-}F}$
Fe	1.00									
Zn	-0.17	1.00								
Cu	-0.11	0.55	1.00							
Cr	0.80	0.02	-0.14	1.00						
Co	0.70	-0.09	0.13	0.54	1.00					
Ni	0.65	0.16	0.31	0.50	0.72	1.00				
Mn	0.89	-0.29	-0.25	0.71	0.61	0.56	1.00			

	Fe	Zn	Cu	Cr	Co	Ni	Mn	Pb	Cd	χ_{lf-F}
Pb	-0.01	0.44	0.45	0.13	0.34	0.16	-0.13	1.00		
Cd	-0.24	-0.06	0.08	-0.11	-0.02	-0.16	-0.31	0.06	1.00	
χ_{lf-F}	0.17	0.50	0.75	0.18	0.37	0.47	0.04	0.60	-0.09	1.00
χ_{lf-C}	0.50	0.37	0.37	0.51	0.53	0.60	0.41	0.42	-0.04	0.79

TABLE 4. Rotated factor loadings of heavy metals and magnetic parameters in roadside soils of Amman-Airport Highway.

Variable	FAC-1	FAC-2	FAC-3	Communality
Fe	0.80	-0.51	-0.02	0.90
Zn	0.24	0.70	-0.35	0.67
Cu	0.33	0.79	-0.06	0.73
Cr	0.72	-0.38	0.05	0.67
Co	0.81	-0.16	0.27	0.76
Ni	0.83	-0.03	-0.05	0.69
Mn	0.69	-0.63	-0.07	0.89
Pb	0.41	0.59	0.13	0.54
Cd	-0.17	0.23	0.91	0.91
χ_{lf-F}	0.66	0.66	0.00	0.86
χ_{lf-C}	0.82	0.28	0.07	0.75
Variance	4.45	2.87	1.05	8.37
% Variance	41	26	10	77

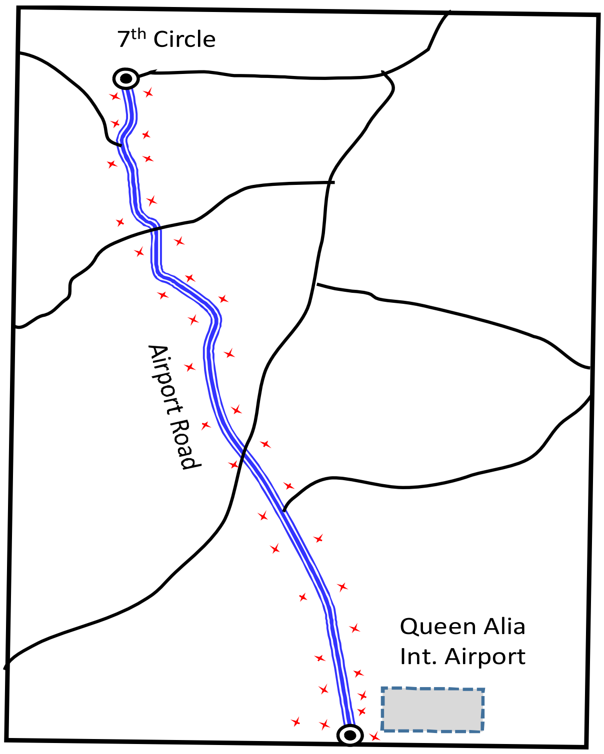

FIG. 1. Map showing the sampling points along the Airport Highway Road, starting from the 7th Circle.

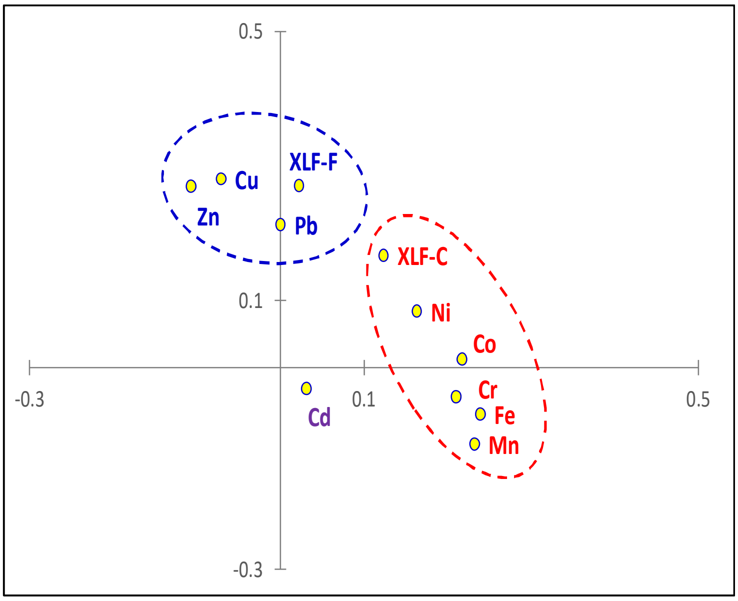

FIG. 2. Rotated components of heavy metals and magnetic parameters in topsoil.

4. Conclusion

The results demonstrated significant heavy metal accumulation, with Fe exhibiting the highest mean concentration (12,077.9 mg/kg), followed by Mn (464.86 mg/kg) and Zn (122.5 mg/kg), whereas Cd exhibited the lowest concentration (7.87 mg/kg). Magnetic susceptibility measurements revealed a strong association with anthropogenic pollutants, particularly in fine particles (<125 µm), where χlf values ranged from 37.7×10^{-8} to 323.0×10^{-8} SI, with the highest readings near high-traffic zones. Statistical analyses confirmed significant correlations between magnetic susceptibility and key heavy metals, including Cu (r = 0.76), Pb (r = 0.60), and Zn (r = 0.50), reinforcing the role of ferrimagnetic minerals as indicators of vehicular and industrial pollution. Factor analysis further identified three primary contamination sources: (1) vehicular emissions (accounting for 41% of the total variance and dominated in Fe, Co, and Ni), (2) industrial activities (26% variance, linked to Zn, Cu, Pb), and (3) agricultural inputs (10% variance, associated with Cd). These results demonstrate that magnetic susceptibility serves as a robust, cost-effective proxy for heavy metal pollution, with fine particles (<125 µm) exhibiting greater sensitivity because of their anthropogenic magnetic phases.

The study supports the integration of magnetic techniques into large-scale environmental monitoring programs to improve pollution assessment and mitigation strategies in urban and industrial regions.

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