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The effect of anthropogenic activities on soil quality (Shafa Badran watercourse) in the Al Zarqa River Basin

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ABSTRACT

The intensive urbanization of terrestrial environments and increased industrial activity significantly contribute to the accumulation of hazardous metals in soil, thereby heightening toxicological risks to soils ecosystems and human health. This study analyzed twenty-two soil samples collected from the Shafa Badran Watercourse within the Zarqa River basin to evaluate the presence and distribution of ten key hazardous metals, namely arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), vanadium (V), lithium (Li), and antimony (Sb). Additionally, anions and cations were assessed to understand broader soil chemistry dynamics. The study explores the hypothesis that land use, particularly the transformation of soil for agricultural purposes industrial use and residential significantly influences soil composition and contamination levels. Findings indicate that soil degradation in the region is primarily driven by industrial pressure and agricultural use, which has exacerbated metal accumulation in the environment. The results revealed that the highest concentrations of As, Pb and Cd, were detected in areas within and surrounding the Zarqa River Basin. Notably, the most polluted regions were identified as active zones adjacent to industrial activities and agricultural lands. The analysis highlights that soil in these areas poses substantial environmental pollution risks, particularly for the elements in the following descending order of concentration: As > Pb > Cd; meanwhile other metals still with acceptable range. Moreover, the hazardous metal content in soils near industrial zones was significantly higher compared to other land-use types, underscoring a pronounced risk of metal migration and accumulation within the Zarqa River basin and its associated groundwater systems. These findings emphasize the urgent need for effective land-use management strategies and industrial pollution mitigation measures to safeguard both environmental and public health in the region.

Keywords: soil pollution, heavy metals, Zara River Basin, soil mitigation, contamination levels.

INTRODUCTION

A defining characteristic of the contemporary era of human development is the rapid pace of urbanization. This phenomenon alters or depletes the natural environment in both quantitative terms (through new land consumption) and qualitative terms (due to environmental degradation). The swift expansion of urban areas and settlements means that the urban environment is continuously subjected to various internal and external influences. As urbanization progresses, an urban ecosystem emerges – a natural-urban system made up of fragments of natural ecosystems that are encircled by buildings, industrial zones, roads, and other infrastructure. This urban ecosystem is marked by the emergence of new types of artificially created geosystems resulting from the degradation, destruction, or replacement of natural systems (Hu et al., 2014).

Focusing on the parameters of the direct study zone, it is essential to examine the soil pollution levels in the Al Zarqa River basin caused by anthropogenic activities during specific periods, particularly the spring-summer season. Several factors must be considered, including geographical location, coordinates, potential pollution sources, and the variability in precipitation levels (Huan et al., 2020).

Urban soils, as integral components of the urban landscape, tend to accumulate various hazardous elements, including heavy metals, metalloids, and toxic organic compounds harmful to living organisms. In technogenic areas, a regressive-accumulative distribution of heavy elements in the soil profile is observed: these elements are fixed in the upper humus layer and decreasing in deeper horizons. The long-lasting nature of these dangerous soil components and their generally hidden mode of existence lead to complications in their recognition, and these metals tend to remain elusive for a long term, seen only when their dangers and toxicities triggered by high metal contents become visible (Cui et al., 2005; Fernandez-Luqueno et al., 2013; Zhang et al., 2020). Heavy elements can migrate across various environments after entering the soil and can be found in urban water bodies, biota, and as dust in the atmosphere (Mamat et al., 2014).

Soil heavy metal content is a significant indicator for assessing environmental quality and health (Liu et al., 2015). However, it is well known that that the accumulation of hazardous elements in years may be hazardous to health of human and sustainable development of ecological systems (Qing et al., 2015; Dong et al., 2018).

Various soil types influenced by its geographical and environmental conditions characterize the Zarqa River basin. Common soil types in the region include Alluvial soils found in areas close to the river, these soils are formed from sediments deposited by water and are often nutrient-rich but prone to contamination from pollutants. Clayey soils retain moisture and are common in low-lying areas, but their structure can make them susceptible to heavy metal accumulation. Sandy Soils found in certain parts of the basin, these soils have high permeability, making them less fertile but also more prone to leaching of pollutants into groundwater. Calcareous soils characterized by a high calcium carbonate content, these are prevalent in semi-arid regions of the basin and influence the soil's buffering capacity against acidity. Urban soils in areas affected by industrial and urban development; soils often exhibit anthropogenic alterations, including higher concentrations of hazardous metals. (Kuisi et al., 2014; Alkhawaldeh et al., 2024; Shammout et al., 2022).

The active transportation of industrial products, along with the use of fertilizers and pesticides in the soil, are primary sources of heavy metals. Identifying the sources of hazardous elements' spatial distribution in soil – particularly in industrial and agricultural regions – is crucial for implementing effective management strategies to control pollution levels and enhance soil quality (Qing et al., 2015; Dong et al., 2018).

The objective of this study is to assess the pollution levels in areas within and around the Zarqa River basin, specifically focusing on the Shafa Badran Watercourse. To achieve this aim, specific goals have been established to evaluate the extent of soil contamination by hazardous elements by comparing measured concentrations with established threshold values. Additionally, the study will analyze anions and cations to gain insights into the broader dynamics of soil chemistry.

MATERIALS AND METHODS

Study area

Shafa Badran situated in northern Amman and has been integrated with other towns and suburbs, including Khirbat Badran. The area features a mix of residential neighborhoods and agricultural lands. Like many areas in Jordan, Shafa Badran faces challenges related to water quality. Heavy metals contamination from natural processes such as weathering and leaching can affect local water sources. The area's development plans aim to address these environmental concerns while improving overall living conditions.

A total of 22-soil samples taken from the closed to the watercourse and conducted to different soil quality analysis along the path length of 25 km as shown in the Figure 1.

Methodology

Sample collection

The selection of soil sampling sites was based on land use patterns – residential (R), agricultural (A), and industrial (I) areas – as well as their proximity to potential sources of pollution. All samples were analyzed in laboratory for determining the hazardous metals as presented in Table 1; cations as shown in Table 2 and anions as shown in Table 3.

Pollution source identification

Geographic Information System (GIS) mapping and field surveys were utilized to pinpoint potential sources of pollution, including wastewater discharge sites, agricultural runoff, and industrial effluents. An analysis of land use patterns was performed to explore the relationship between different activities and the deterioration of soil quality.

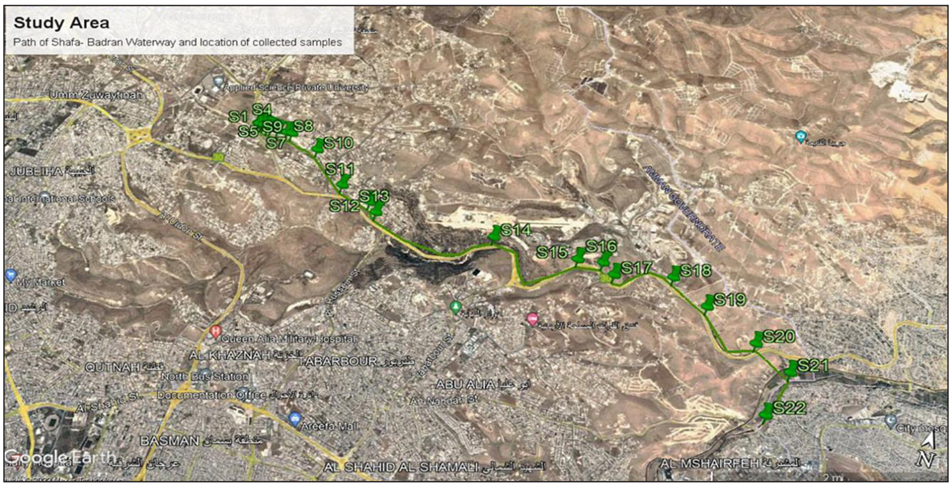

Figure 1. Soil samples and their locations in the study watercourse

Table 1. Analysis of soil samples in the study area revealed elevated levels of hazardous metals, mg/kg

No	Class	AS	Pb	Cd	Cr	Ni	Cu	Zn	V	Li	Sb
1	R; I	41.8	136.1	2.5	30.81	17.81	16.51	53.3	46.15	14.25	0.22
2	R; A	43	142.9	.2.4	38.27	21.71	19.18	45.91	54.59	16.59	0.41
3	R; A	45.4	139.9	2.2	39.35	22.27	110.65	57.13	54.76	17.57	0.41
4	R; I	47.1	10.0	1.5	22.38	16.15	12.86	33.96	48.87	12.87	0.41
5	A; I	59.4	137.2	3.2	34.52	26.18	18.18	49.89	63	15.47	0.41
6	A; I	40	161.0	1.9	40.14	24.64	20.92	55.89	45.36	15.64	0.41
7	A; I	39.4	138.8	2.5	33.8	19.82	18.82	52.06	47.58	15.36	0.41
8	A; I	42.8	130.6	2.4	36.39	20.87	13.91	50.11	54.75	16.29	0.41
9	A; I	43.7	146.1	2.7	45.29	25.9	15.6	45.2	64.16	20.6	0.41
10	A; I	35	99.0	2.8	30.11	18.69	20.07	44.2	43.42	14.57	0.41
11	A; I	36.5	121.1	2.4	34.13	20.42	15.72	54.03	49.1	16	0.41
12	A; I	44.7	122.6	2.5	38.13	23.64	15.19	47.96	57.77	18.22	0.41
13	A; I	49.1	157.4	3.1	53.43	30.15	15.66	64.31	70.7	23.18	0.41
14	A; I	41.2	124.0	3.4	35.5	22.71	14.01	44.39	55.37	15.77	0.41
15	A; I	29.5	90.0	2.9	29.13	15.97	11.32	49.31	44.92	11.6	0.41
16	A; I; R	28.0	84.1	2.6	23.52	13.87	10.65	41.82	39.78	9.9	0.41
17	A; I; R	34.2	154.7	3.1	44.18	38.11	18.64	48.05	38.06	22.3	0.41
18	A; I; R	28.3	82.2	3.3	23.86	13.86	10.35	33.42	39.9	9.29	0.41
19	A; I; R	4..9	137.5	3.5	42.88	26.52	16.8	55.84	51.22	18.97	0.41
20	A; I; R	33.1	142.5	2.9	43.77	31.4	16.43	42.92	48.06	21.64	0.41
21	A; I; R	59.5	226.2	42.1	47.32	33.89	150.34	159.1	64.09	13.69	0.41
22	A; I; R	78.4	143.4	21.7	50.03	33.54	19.33	43.98	72.92	32.14	0.41

Note: Class: residential (R), agricultural (A), and industrial (I) areas.

RESULTS AND DISCUSSION

The concentrations of As in the 22 soil samples collected from the Shafa Badran Watercourse in the Zarqa River basin are indicate a range of arsenic values, with the highest recorded concentration being 78.4 mg/kg and the lowest at 4.9 mg/kg. The permissible limit of arsenic in soil, as recommended by WHO, is typically around 10 mg/kg (Asma et al., 2017). Many of the samples exceed this limit, indicating potential environmental and health risks associated with arsenic contamination. The presence of high arsenic concentrations can have detrimental effects on soil quality and may pose risks to human health, particularly in agricultural areas where crops may absorb these toxic metals. Potential sources of arsenic contamination in the region could include industrial activities and agricultural runoff. Given the elevated levels of arsenic found in these soil samples, there may be a need for further investigation and potential remediation efforts to mitigate the risks associated with arsenic exposure in the Zarqa River basin. The data provided aligns with findings from various studies assessing heavy metal distributions in soils along the Zarqa River, highlighting the importance of ongoing monitoring and management strategies to address soil contamination issues (Nabil and Abu-Rukah, 2007).

The Pb concentrations vary significantly among the samples, with the highest concentration recorded at 226.2 mg/kg and the lowest at 10.0 mg/kg. The presence of lead at such high concentrations raises concerns regarding soil contamination and potential health risks for local communities, particularly in agricultural areas where crops may absorb these toxic metals. The permissible limit for lead in soil varies by region, but many guidelines suggest that levels above 100 mg/kg can pose risks to human health and the environment. Potential sources of lead contamination in the Zarqa River basin may include industrial activities, urban runoff, and historical mining operations. Given the elevated levels of lead found in these soil samples, ongoing monitoring and potential remediation efforts are essential to mitigate risks associated with lead exposure in the area. The data aligns with findings from various studies assessing heavy metal distributions in soils along the Zarqa River, highlighting the importance of continuous monitoring and effective management strategies to address soil contamination issues (Michel, 2019)

The Cd concentrations show a significant range, with most values clustered between 1.5 to 3.5 mg/kg, while two samples exhibit much higher concentrations of 42.1 mg/kg and 21.7 mg/kg. The elevated levels of cadmium in some samples, particularly the high values, raise concerns regarding soil contamination and potential health risks, especially in agricultural areas where crops may absorb these toxic metals. The permissible limit for cadmium in soil varies, but many guidelines suggest that levels above 1 mg/kg can pose risks to human health and the environment. Potential sources of cadmium contamination may include agricultural practices (such as the use of phosphate fertilizers), industrial activities, and urban runoff. Given the presence of elevated cadmium levels in certain samples, ongoing monitoring and potential remediation, efforts are essential to mitigate risks associated with cadmium exposure in the area. The data aligns with findings from various studies assessing heavy metal distributions in soils along the Zarqa River, highlighting the importance of continuous monitoring and effective management strategies to address soil contamination issues related to cadmium and other heavy metals. However, it is important to note that the Zarqa River is known to be heavily polluted due to various anthropogenic activities. identified pollution sources include wastewater treatment plants, overflow of wastewater pumping stations, leaks from sewer lines and manholes, and industrial, commercial, domestic, and agricultural activities along the river course. The main pollutants released to the river from these sources are organics, nutrients, heavy metals, raw wastewater, solids, and solid waste (Al-Omari et al., 2019).

The concentrations of Cr in soil samples range from 22.38 mg/kg to 53.43 mg/kg, which is within the acceptable limits for most standards range from 1–100 mg/kg. Chromium occurs naturally in soil as a result of the weathering of ultramafic rocks and minerals like chromite. The findings align with studies focused on heavy metal pollution in the Zarqa River basin, including research on hexavalent chromium (Cr (VI)) and other heavy metals in soils and water resources: (Shammout et al., 2022).

The concentrations of Ni in soil samples (13.86–38.11 mg/kg) are within the typical range for uncontaminated soils 50 mg/kg and well below harmful thresholds for both residential and industrial use. The concentrations suggest low-to-moderate contamination, likely influenced by both natural and human activities. Variability in concentrations (from 13.86 to 38.11 mg/kg) may reflect localized pollution or differences in soil properties.

The majority of the soil samples concentrations of Cu are well within the acceptable range for uncontaminated soils. However, the two highest values (110.65 mg/kg and 150.34 mg/kg) exceed the typical background range, possibly indicating localized contamination. The risk of Cu leaching into groundwater depends on soil pH and organic matter content, as acidic conditions can increase its mobility.

The values of Zn, V, Li and Sb indicate a range of concentrations for each metal, with notable extremes such as a maximum Zinc concentration of 159 mg/kg, suggesting significant variability among the samples.

In the context of heavy metal pollution in the Zarqa River basin, studies have indicated that urbanization and industrial activities are major contributors to elevated levels of heavy metals in the environment, including Zn, V, Li, and Sb. These variations can be attributed to several factors, including industrial activities, natural geological formations, and anthropogenic influences such as agricultural runoff or urbanization. Regular monitoring and management strategies are essential to address these contamination issues effectively and protect public health and the environment (Reem, 2021).

Studies have shown that urban areas often exhibit higher concentrations of certain trace elements due to anthropogenic activities such as industrial emissions, traffic, and construction. For instance, a study highlighted that urban environments tend to accumulate pollutants more than rural settings, leading to higher concentrations of elements like lead and barium in urban areas compared to rural ones (Girshevitz et al., 2022).

Aluminum, iron, copper, and chromium were found in higher concentrations in rural populations compared to urban ones. This could be attributed to environmental exposures specific to rural settings, such as agricultural practices and exposure from surrounding fields. From other hand lead and arsenic were found at elevated levels in urban populations, likely due to emissions from vehicles and industrial processes.

The distribution of elements, including Zn, V, Li, and Sb, is governed by several specific rules and principles that influence their behavior in various environments in study area. These rules categorize elements based on their affinities and behaviors during geological processes (Strosnider et al., 2017).

Variations in heavy metal concentrations among samples from the Zarqa River area result from a range of factors tied to contamination sources, environmental conditions, and land use patterns. Samples collected near industrial zones often show elevated levels of heavy metals, as effluents from wastewater treatment facilities and industrial discharges frequently affect these areas. Studies (Abderahman and Abu Rukah, 2006; Shammout et al., 2022) have identified such sites as localized hotspots for contamination, where metal concentrations are significantly higher than in samples from more distant locations.

In agricultural regions, the extent of contamination varies based on the use of fertilizers and pesticides containing heavy metals. Runoff from treated fields can lead to higher concentrations of certain metals (Dabaibeh, 2021). Conversely, areas with less intensive agricultural activity generally show lower contamination levels.

Soil characteristics, including texture and organic matter content, also influence heavy metal retention and mobility. Research by Abderahman and Abu Rukah (2006) shows that fine particles, such as silt and clay, tend to retain more contaminants than sandy soils, leading to distinct concentration patterns in areas with higher clay content.

Hydrological dynamics also play a role, as water flow and irrigation practices can affect metal distribution. For instance, irrigation with treated wastewater has been linked to increased heavy metal accumulation in nearby soils. Shammout et al. (2022) emphasize the significant contribution of industrial activities to heavy metal pollution in the Zarqa River. Their study, which analyzed water samples from 2016 to 2019, highlights pollutants such as Pb and Cd, attributing elevated concentrations to the high density of industries in the area.

These findings underline the interplay of factors influencing heavy metal variability, including proximity to pollution sources, land use practices, soil properties, hydrology, seasonal changes, and regulatory enforcement. Notably, extremely high Pb (226.2 ppm) and Cd (42.1 ppm) levels point to industrial and agricultural contamination hotspots, likely caused by overlapping land uses. Similarly, elevated arsenic levels (78.4 ppm) suggest contributions from agricultural activities or past industrial uses of arsenic. Interestingly, the detection of low Pb levels (10 ppm) in one industrial area suggests either a less severe pollution source or effective environmental controls.

Cations Table 2 and anions Table 3 play crucial roles in the distribution patterns of Zn, V, Li, and Sb in various environments. Electrostatic interaction influence the mobility and availability of these elements in soil and water systems. For instance, the presence of cations can help stabilize anions in solution, affecting how these elements distribute in the environment.

Table 2. Analysis of soil quality in the study area revealed elevated levels of cations in mg/kg

No	Class	Ba	Be	Ag	Al	Sn	K	Na	Ca	Mg
1	R; I	89.11	0.84	63.5	24326.7	0.21	4570.46	255.16	200478	11327.31
2	R; A	83.62	0.99	87.04	32178.7	0.72	5275.83	161.87	143325.5	9458.48
3	R; A	82.17	1	82.26	34917.2	6.02	5262.12	161.87	123007.9	8633.53
4	R; I	72.97	0.77	28.63	20984.8	0.005	4024.2	161.87	202095.3	7308.39
5	A; I	154.41	0.93	73.96	30740.1	0.005	4518.95	161.87	162117.4	8428.53
6	A; I	123.93	0.91	83.28	31316.9	0.38	5371.64	161.87	146603.4	9011.53
7	A; I	91.21	0.93	7.59	31038.2	0.34	4969.91	161.87	146402	8505.48
8	A; I	91.74	0.96	80.3	29813.4	0.16	4333.94	161.87	144212.6	8295.21
9	A; I	87.73	1.13	95.14	39141.1	0.22	5581.84	161.87	106316.1	8982.19
10	A; I	92.38	0.9	63.45	26489.9	0.16	6007.89	161.87	179534.8	10377.49
11	A; I	85.44	0.91	72.32	26967.7	0.005	4815.23	161.87	148131.7	8150.66
12	A; I	96.15	1.06	80.12	34301.1	0.005	5712.75	161.87	152468.8	8463.03
13	A; I	121.26	1.25	107.17	44110.4	0.44	5711.27	161.87	94531.1	9149.7
14	A; I	90.43	0.94	76.89	2885.8	0.33	4493.07	161.87	133097.6	13233.75
15	A; I	76.6	0.75	70.65	22920.4	0.17	3487.75	161.87	138757.1	8298.77
16	A; I; R	64.52	0.69	54.13	18577.4	0.005	2830.49	161.87	164346.9	9441.95
17	A; I; R	201.41	1.09	14.89	35794.9	0.005	5163.54	161.87	126838.4	12265.77
18	A; I; R	23.86	0.67	58.54	17119.2	0.005	2768.44	161.87	147477.2	8698.11
19	A; I; R	90.03	0.94	33.7	26985.0	0.005	5031.17	161.87	162937	9943.09
20	A; I; R	100.47	0.98	20.85	28835.6	0.005	5026.08	161.87	164281	16813.79
21	A; I; R	163.18	0.85	23	18760.3	6.19	3320.34	161.87	20641.17	12969.75
22	A; I; R	66.05	1.17	13.36	31459.8	0.005	4904.99	161.87	194114.5	7062.83

Table 3. Analysis of soil quality in the study area revealed elevated levels of anions in mg/kg

No	Class	F	BrO_3	Cl^-	NO_2	Br	NO_3	HCO_3	SO_4	PO_4	CLO_4	Se	B
1	R; I	1.48	0.31	100.5	0.25	0.95	728.21	346.47	126.25	1.11	‹0.01		12.79
2	R; A	2.66	0.11	14.7	0.81	0.34	96.93	401.88	38.78	0.01	0.01	0.005	12.98
3	R; A	2.66	0.28	131.0	1.33	0.81	166.63	341.81	127.47	0.64	0.01	0.005	11.81
4	R; I	2.66	0.07	378.5	1.72	1.95	49.96	257.47	287.31	0.13	0.01	0.005	8.26
5	A; I	2.66	0.24	290.3	0.18	1.94	3.9	340.13	270.79	0.35	0.01	0.005	9.82
6	A; I	2.66	0.13	158.5	0.3	0.75	761.32	237.49	489.77	0.76	0.01	0.005	16.17
7	A; I	2.66	0.15	143.9	0.5	0.84	136.22	354.52	174.22	0.56	0.01	0.005	13.33
8	A; I	2.66	0.18	43.13	0.29	0.32	43.37	276.5	435.49	1.05	0.01	0.005	9.64
9	A; I	2.66	0.22	85.56	0.3	0.5	46.96	366.76	89.35	0.3	0.01	0.005	11.04
10	A; I	2.66	0.06	373.7	2.12	2.03	403.19	302.6	238.01	0.14	0.01	0.005	19.49
11	A; I	2.66	0.6	268.8	0.48	1.21	208.9	204.71	589.54	1.6	0.18	0.005	10.13
12	A; I	2.66	0.07	192.8	0.61	0.73	424.9	290.5	149.13	1.67	0.01	0.005	13.86
13	A; I	2.66	0.1	499.3	1.99	2.28	350.25	280.68	463.99	0.07	0.01	0.005	11.69
14	A; I	2.66	0.14	304.5	0.71	0.97	2465.57	296.27	206.6	1.63	0.01	0.005	11.99
15	A; I	2.66	0.77	397.6	0.69	0.94	2695.62	183.08	914.74	5.51	0.01	0.005	7.42
16	A; I; R	2.66	0.19	45.39	0.34	0.14	146.25	246.48	135.82	2.53	0.01	0.005	6.23
17	A; I; R	2.66	0.14	88.8	0.84	0.44	130.67	538.07	334.81	0.34	0.01	0.005	3.99
18	A; I; R	2.66	0.57	135.1	8.94	0.48	58.4	188.45	222.47	2.74	0.01	0.005	5
19	A; I; R	2.66	0.11	58.71	0.67	0.64	200.89	215.19	432.53	2.22	0.01	0.005	9.76
20	A; I; R	2.66	0.18	255.5	14.64	2.16	335.6	304.28	200.14	0.81	0.01	0.005	8.83
21	A; I; R	2.66	0.23	917.5	1.21	120.17	676.44	60.29	2433.7	2.15	0.01	0.005	3.4
22	A; I; R	2.66	0.32	1036	3.42	3.19	317.24	95.44	1758.6	0.01	0.01	0.005	9.4

The data you provided in Table 2 and Table shows the concentrations of various elements in soil samples, including heavy metals like barium (Ba), beryllium (Be), silver (Ag), aluminum (Al), tin (Sn), potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg). Heavy metal cations such as arsenic (As^{3+}), lead (Pb^{2+}), and cadmium (Cd^{2+}) can form complexes with various cations present in the soil. For instance, cations like calcium (Ca^{2+}) and potassium (K^{+}) may interact with these heavy metals, affecting their mobility and bioavailability in the soil environment. The presence of cations can influence the sorption dynamics of heavy metals, as seen in studies where metal cation adsorption influenced by the ionic strength and composition of the solution. Heavy metals can also interact with anions in the soil. Oxyanions formed by heavy metals can bind to negatively charged sites on soil particles or organic matter. This interaction alter the speciation of heavy metals and their availability to plants. Anions such as phosphate (PO_4^{3-}) and sulfate (SO_4^{2-}) may compete with heavy metal cations for binding sites, influencing their retention in soils (Zhang et al., 2024).

As interacts with various cations and anions in soil, influencing its solubility and mobility. Complexation with organic matter can reduce As bioavailability. Meanwhile Pb forms stable complexes with anions like chloride (Cl^{-}) and interacts with cations such as Ca^{2+}, affecting its retention in soils. Furthermore, Cd mobility is influenced by competing cations and anions; higher concentrations of Ca^{2+} may reduce Cd uptake by plants and then increased in soil matrix (Nguyen et al., 2020).

Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}) as presented in Figure 2 are often retained in soils through cation exchange mechanisms. The presence of other cations as calcium (Ca^{2+}) and magnesium (Mg^{2+}) influence the retention and mobility of these heavy metals. Higher concentrations of competing cations may reduce the bioavailability of heavy metals by occupying binding sites on soil particles. Elevated concentrations of heavy metals in conjunction with certain anions can lead to phytotoxic effects. High levels of nitrates or sulfates may exacerbate the toxic effects of heavy metals on plant health by altering nutrient availability or causing oxidative stress.

Based on the results obtained from the research, anthropogenic activities that have led to a significant increase in the concentration of heavy and toxic elements can be analyzed, as shown in Figure 3. Eleven samples indicated that the increase in the toxicity of elements in the soil is attributed to industrial and agricultural activities. Meanwhile, seven samples indicated that agriculture and residential expansion have clearly contributed to increasing environmental pressures on the soil of the Zarqa River. In all cases, industrial, agricultural, and residential activities collectively contributed to the decline in soil quality and its saturation with high concentrations of heavy elements. The soil continues to face further contamination due to ongoing poor practices up to the present time.

The heavy metal concentrations in the soil along the Zarqa River area exhibit significant variation based on land use classifications, specifically industrial (I), agricultural (A) and

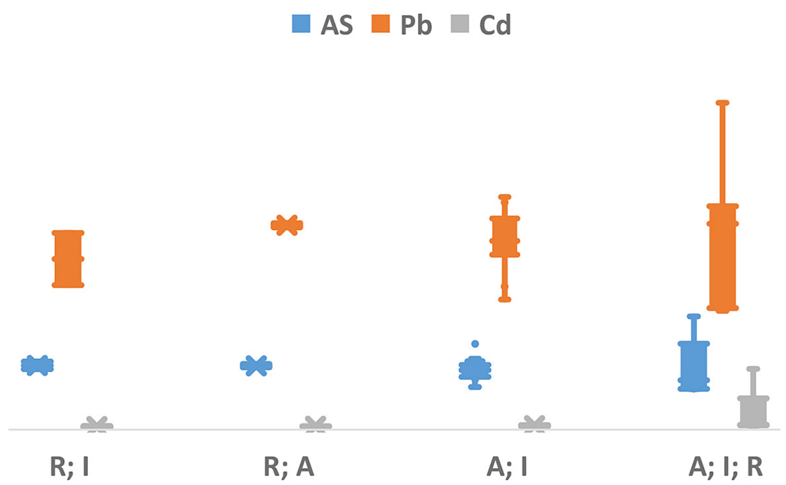

Figure 2. Lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}) as per classes' contributions

residential (R). The analysis of 22 soil samples reveals distinct patterns in the levels of As, Pb, and Cd across these land use categories. Industrial sites generally show elevated levels of heavy metals due to emissions and discharges from factories. Samples from industrial areas exhibited high lead concentrations, with some samples reaching up to 226.2 mg/kg. The highest concentrations of lead were predominantly found in industrial areas, suggesting that industrial activities are a major source of lead pollution in the region. Cadmium levels were also notable, with values as high as 42.1 mg/kg in specific samples. Agricultural land use presents a mixed scenario where heavy metals are influenced by both soil amendments and runoff from nearby industrial activities. The average concentrations of lead in agricultural areas ranged from 90.0 mg/kg to 161.0 mg/kg, indicating significant contamination. Cadmium levels were lower overall but still raised concerns, especially in industrial and agricultural contexts. Arsenic levels were also concerning, with maximum values around 59.4 mg/kg. Residential areas showed varying levels of contamination, often reflecting a combination of agricultural runoff and urban pollution. The highest recorded levels of lead in residential areas reached 142.9 mg/kg, while arsenic concentrations were up to 47.1 mg/kg in some samples. Elevated arsenic levels were observed across all land use classes, with agricultural lands showing particularly high values, likely due to pesticide use and runoff.

As summarized in Figure 3, mixed-use areas (A; I; R) recorded the highest concentrations of all three heavy metals, reflecting the combined impact of multiple pollution sources. Industrial zones (I) are marked by high lead and arsenic levels, while agricultural areas (A) show moderate yet variable contamination due to pesticides and irrigation practices. Residential areas (R), though exhibiting relatively lower concentrations, are still influenced by nearby industrial and urban activities.

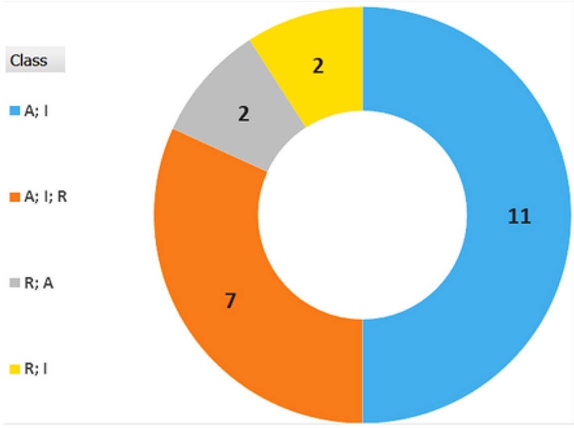

Figure 3. Distribution of toxic elements according to anthropogenic activities

The CF is a useful metric for assessing the degree of heavy metal pollution in different land use areas and zones, as this factor reflect the measured concentration of the metal to the background concentration of the metal in unpolluted soil. Based on the achieved results and available results from (Radaideha, 2022) comparison of CF values across these land use classes in the Zarqa River basin presented in Table 4.

Industrial areas typically exhibit the highest CF values due to significant emissions and discharges from factories. Heavy metals such as Pb, Cd, and Cr are commonly found at elevated levels in these regions. (Kuisi et al., 2014; Alkhawaldeh et al., 2024) have shown lead concentrations ranging from 80 to 190 µg/L, which indicates severe contamination levels directly attributable to industrial activities. Industries related to textiles, food processing, and chemical manufacturing are major contributors to heavy metal pollution in the Zarqa River basin. The proximity of industrial facilities to the river exacerbates this issue.

Agricultural areas show moderate CF values compared to industrial sites. While heavy metals can accumulate in soils due to the use of fertilizers and pesticides, the concentrations are

Table 4. Summary of CF for different classes

Land use class	Lead (Pb)	Arsenic (As)	Cadmium (Cd)	Pollution sources
Industrial (I)	Very high (CF ≥ 6)	High (CF ≤ 3)	Moderate to high 1 ≤ CF < 3	Industrial discharges
Agricultural (A)	Moderate to high 1 ≤ C F < 3	Moderate to high 1 ≤ C F < 3	Moderate 1 ≤ C F < 3	Fertilizers, pesticides, runoff
Residential (R)	Moderate 1 ≤ C F < 3	Low contamination CF < 1	Low contamination CF < 1	Urban runoff, household waste

generally lower than those found in industrial zones. Lead concentrations in agricultural areas were observed to range from 90 to 161 µg/L. The use of contaminated irrigation water and runoff from fields treated with chemicals can contribute to the accumulation of heavy metals in agricultural soils. However, the impact is often less severe than that seen in industrial areas.

Residential areas typically exhibit the lowest CF values among the three land use classes. Although urban runoff can introduce some heavy metals into these areas, the concentrations are generally much lower than those found in industrial or agricultural zones. Lead concentrations in residential samples were reported between 136.1 and 142.9 µg/L. The primary sources of contamination in residential areas include urban runoff, household waste, and occasional nearby industrial activities. However, these sources tend to have a less direct impact on soil quality compared to industrial discharges.

CONCLUSIONS

The highest level of soil contamination with metals was registered in classes A and I areas. In these samples, the highest values of gross concentrations in the watercourse were noted for the detected metals (As, Pb and Cd). The study emphasizes the critical relationship between urbanization, industrial activity, and soil contamination with hazardous metals in the Zarqa River basin. It highlights the necessity for comprehensive environmental management strategies to address these challenges effectively.

The analysis identified high concentrations of hazardous metals, particularly As, Pb, and Cd, in soil samples from areas adjacent to industrial activities and agricultural lands. The study supports the hypothesis that land use transformation – specifically for agricultural and industrial purposes – affects soil composition and contamination levels.

The results indicate that soil in heavily polluted areas poses substantial environmental risks, particularly concerning the mobility and bioavailability of heavy metals. Elevated concentrations of these metals can lead to toxicity in plants, impairing growth and reducing agricultural productivity. Moreover, the accumulation of heavy metals in urban soils can pose health risks to humans through food chains and direct contact.

The concentrations of hazardous metals in the Zarqa River basin were found to be significantly higher near industrial zones compared to other land-use types, highlighting a pronounced risk of metal migration and accumulation within groundwater system. This is consistent with global trends where urbanization leads to increased pollution levels due to anthropogenic activities such as vehicle emissions, waste disposal, and industrial discharges.

The findings underscore the urgent need for effective land-use management strategies and pollution mitigation measures to safeguard both environmental quality and public health. This includes implementing stricter regulations on industrial emissions, promoting sustainable agricultural practices, and enhancing soil remediation efforts in contaminated areas.

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