



Assessment of Heavy Metal Pollution and Sources Identification in Urban Soil Using Pollution Indices and Statistical Analysis, Mosul, Iraq

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Received: 24 May 2025

Received in revised form: 01 July 2025

Accepted: 03 August 2025

Available online: 01 October 2026

Abstract

This study aims to assess heavy metal pollution and identify its sources in the surface soil of Mosul's left side. Thirty-one composite soil samples were collected using a regular grid distributed over the study area with 2 × 2 km dimensions. Chemical analysis was conducted using the X-ray fluorescence (XRF) technique to determine the concentration of trace elements (V, Nb, Zr, Y, Th, Sn, Cr, Sb, As, Mn, Mo, Co, Cu, Zn, Ni, Pb) and major oxides (MgO, Al₂O₃, SiO₂, K₂O, TiO₂, Fe₂O₃). The calculations of soil pollution indices (contamination factor, degree of contamination, geo-accumulation index, Nemerow pollution index, enrichment factor) indicate that most study samples are contaminated with heavy metals. Principal component analysis shows the influence of geochemical processes such as chemical weathering and surface adsorption, as well as sedimentary processes like river deposition, in redistributing these elements in the environment. Meanwhile, it appears that the heavy metals (Cu, Zn, Pb, Sn, Sb, Mo) were affected by human activities in the city, particularly since these elements are clear indicators of pollution resulting from industrial waste such as batteries, metal coatings, and electronic waste, as well as the impact of military activities during the city's liberation from terrorist gangs. This is supported by the high concentrations of these elements in the industrial area. This study highlights the interaction of natural geological and geochemical factors with human factors in influencing the concentrations of heavy metals in the surface soil of Mosul City. The study also emphasizes the urgent need to take immediate measures to reduce soil pollution in the city, particularly after pollution indices in some areas have recorded high levels of contamination.

Keywords:

Heavy Metals, Urban Soil, Soil Pollution, Pollution Indices.

DOI: [10.33899/injes.v26i4.56158](https://doi.org/10.33899/injes.v26i4.56158), ©Authors, 2026, College of Science, University of Mosul.

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1. Introduction

Pollution is an environmental problem that generally affects life on planet Earth, endangering the lives of living organisms. Various environmental components have recently suffered increasing degradation coinciding with industrial growth and urban expansion. Soil is one of the most important environmental components experiencing increasing degradation, especially since soil often receives pollutants from all other environmental components, leading to their accumulation (Kharkan et al., 2019; Ranjani et al., 2021). Heavy metals also pose significant health risks to humans, especially since they can be

transmitted through the food chain and thus accumulate in large quantities in the bodies of living organisms, even if they are present in the environment at low concentrations (Ibraheem et al., 2024). The sources of heavy metal entry into soil can be identified through two main sources: geological sources resulting from the natural concentration of these elements in soil, through weathering and erosion processes that occur on various types of rocks, minerals, non-metallic deposits, and ores. Anthropogenic sources include those caused by human activity such as industry, agriculture, transportation, urban waste, and occasional military acts. Uncontrolled heavy metal leakage into the land and rivers is a significant

environmental problem. They are hazardous and cannot be broken down into non-toxic forms, causing a global health issue (Al-Khafaji and Jaafar, 2023).

Assessing the level of heavy element pollution in urban soil can provide us with a thorough picture of the soil's condition as well as the magnitude of the potential health risk posed by exposure to these elements. Recently, certain pollution indices have been implemented, including the Geoaccumulation Factor (I_{geo}), the Enrichment Factor (EF), the Contamination Factor (CF), and the Improved Nemerow Index (I_N), which are effective tools for assessing and monitoring soil pollution levels. This has become essential in the field of urban management and planning and the development of sustainable policies to protect the urban environment from pollution (Kazem, 2017). In this context, there is an urgent need to study the surface soil of Mosul, the largest city in northern Iraq. This is especially true since the city has witnessed rapid events in recent years, including its exposure to intensive military operations during the liberation phase from terrorist groups that controlled the city between 2014 and 2017, followed by military operations and widespread destruction, and then rapid reconstruction and urban expansion since 2017. The city has received several environmental studies, including studies of soil pollution. However, these studies followed a selective sampling approach, focusing on collecting samples from industrial and commercial areas and roadsides, and did not delve deeply into identifying the sources of these elements (Al-Sheraefy et al., 2023; Bk et al., 2024a; Bk et al., 2024b; Ibraheem et al., 2024). Accordingly, the current study aims to fill this gap by conducting a comprehensive assessment of the level of soil pollution. The samples in this study were collected along a regular grid on the left side of the city, and statistical techniques were used to identify the most important sources of heavy metals in the soil and distinguish between natural sources and non-natural sources represented by human influence. This contributes to understanding the dynamics of urban soil pollution in the study area and enables appropriate decision-making and action.

2. Materials and Methods

A. Study area

Mosul is located in northern Iraq between longitudes 43°02'59.65" and 43°13'57.89" east, and latitudes 36°17'23.86" and 36°25'45.04" north. It is distinguished by its location on the banks of the Tigris River, which divides it into two parts: the western part, also known as the right side, and the eastern part, known as the left side. The study area is limited to the eastern part (left side) of the city (Fig. 1). The study area falls within an arid to semi-arid climate with hot summers and cold winters. Summer temperatures exceed 45°C, while winter temperatures drop below zero (Al-Ansari, 2021). Therefore, Iraq is affected by its location between the Arabian desert regions' dry subtropical climate and the Arabian Gulf's humid subtropical climate (Hameed and Khalaf, 2024). Geologically, the study area is covered by Miocene and Recent deposits. The oldest deposits are of the Fatha Formation (Middle Miocene), composed of mudstone, marl, limestone, gypsum, and anhydrite. The younger is the Injana Formation (Upper Miocene), composed of mudstone, siltstone, and sandstone, and covered by Quaternary deposits consisting of conglomerates, sand, clay, and gravel, followed by recent clastic deposits derived from the erosion of highlands along with river sediments (Al-Fahaam et al., 2023).

B. Field and laboratory work

Samples were collected on a regular grid measuring 2 x 2 km from 31 locations. Four samples were taken at each location and thoroughly combined to produce a composite sample for each site. Samples were collected at a depth of 0-15 cm. They were stored in plastic bags with coordinates and field notes.

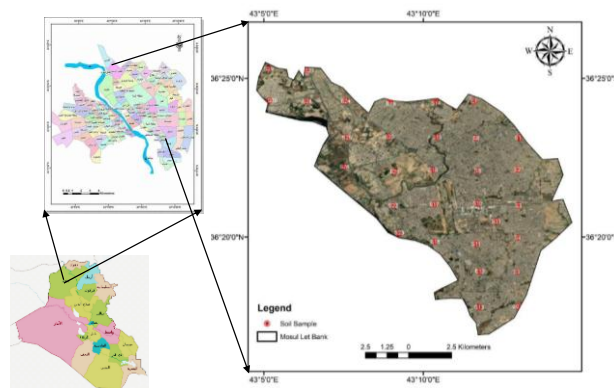


Fig. 1. Map of the study area showing the sampling locations.

Fig. 1: Map of the study area showing the sampling locations.

were recorded and transported to the laboratory. Then, the soil samples were prepared for laboratory analysis by air-drying. Once dried, the samples were crushed with a wooden hammer, ensuring not to turn the soil into a fine powder, and large stones were removed by hand. Next, the soil was sieved using a 2 mm sieve. Then, the sample was divided using a cone and square method, selecting a portion to be ground in a ceramic mortar, and subsequently sieved using a 200-mesh sieve to obtain a uniform powder suitable for chemical analysis. The element concentrations were determined using Spectro XEPOS X-Ray Fluorescence Spectroscopy (German, 2010) in the Iraqi-German Lab at the University of Baghdad. To achieve high analysis accuracy, the device performs an analysis of a standard reference sample. If the analysis matches the standard reference data, the device will move to a stage where the operator can enter samples into the device for analysis. However, if the analysis of the standard sample does not match, the device will not allow the entry of new samples and will instead move the operator to the maintenance steps.

C. Statistical analysis

The chemical data of the study samples are analyzed using SPSS version 20. Principal Component Analysis (PCA) is performed to determine potential causes or sources of heavy metal concentrations in soil. PCA is a popular statistical method for processing raw data to extract fewer and more usable variables for evaluating the main factors influencing element concentrations (Belkhir et al., 2018; Dhannoun and Mahmood, 2019; Alaarajy et al., 2023).

D. Pollution indices

The following pollution indices are used to assess heavy metal soil contamination in the study area: Contamination Factor (CF), Contamination Degree (Cdeg), Geoaccumulation Index (I_{geo}), Improved Nemerow Index (I_N), and Enrichment Factor (EF).

1. Contamination factor (CF) and Contamination degree (Cdeg)

This factor is used to assess the extent of soil contamination with heavy metals and is calculated according to the following equation:

$$CF = \frac{(Cn)_{sample}}{(Bn)_{background}} \dots \dots \dots (1)$$

Where: Cn is the concentration of heavy metals in the soil of the study area, and Bn is the concentration of heavy metals in the Earth's crust according to (Kabata-Pendias, 2011).

Table 1: Classification of (CF) by Hakanson (1980).

Pollution factor	Pollution level classification
$CF < 1$	low pollution
$1 < CF \leq 3$	moderate pollution
$3 < CF \leq 6$	heavy pollution
$CF > 6$	very high pollution

The contamination degree (Cdeg) is used to determine the degree of soil pollution with heavy metals, which represents the sum of the contamination factors for the studied heavy metals (Hakanson, 1980), as in the following equation:

$$Cdeg = CF_1 + CF_2 + \dots \dots \dots + CF_n \dots \dots \dots (2)$$

Where: $Cdeg$ is the contamination degree, CF is the Contamination factor, and n is the number of heavy metals studied:

Table 2: Classification of (Cdeg) according to Hakanson (1980).

Pollution degree factor	Pollution level classification
$Cdeg < 8$	low pollution
$8 \leq Cdeg < 16$	moderate pollution
$16 \leq Cdeg < 32$	heavy pollution
$Cdeg \geq 32$	very high pollution

2. Geo-accumulation Index (I_{geo})

The geo-accumulation Index (I_{geo}) is calculated to determine the extent of soil contamination with heavy metals. It was developed by Muller (1969) and is based on the following equation:

$$I_{geo} = \log_2 \left[\frac{Cn}{1.5 \cdot Bn} \right] \dots \dots \dots (3)$$

Where: Cn is the measured metal concentration, Bn is the concentration of heavy metal in the reference sample, and 1.5 is a constant value used to compensate for natural variations in the geochemical background.

Table 3: Classifications of (I_{geo}) according to Muller (1969).

Ground accumulation coefficient	soil quality
$I_{geo} \leq 0$	Uncontaminated
$0 < I_{geo} < 1$	Unpolluted to moderately polluted
$1 < I_{geo} < 2$	Moderately polluted
$2 < I_{geo} < 3$	Moderately to highly polluted
$3 < I_{geo} < 4$	highly polluted
$4 < I_{geo} < 5$	Highly to very highly polluted
$I_{geo} \geq 5$	Very highly polluted

3. Improved Nemerow Index (I_N)

It describes the state of soil pollution with heavy metals; it is calculated based on Guan et al. (2014) according to the following equation:

$$I_N = \sqrt{\frac{(I_{geo\ max})^2 + (I_{geo\ average})^2}{2}} \dots \dots (4)$$

Where: ***Igeo max*** is the maximum value of the Geoaccumulation index for the studied elements, and ***Igeo average*** is the average concentration of the Geoaccumulation index for the elements.

Table 4: Classification of (I_N) according to Guan et al. (2014).

Nimro Laboratories	soil quality
$0 < I_N \leq 0.5$	Uncontaminated
$0.5 < I_N \leq 1$	Unpolluted to moderately polluted
$1 < I_N \leq 2$	somewhat polluted
$2 < I_N \leq 3$	Moderate to severe pollution
$3 < I_N \leq 4$	heavily polluted
$4 < I_N \leq 5$	heavily polluted
$I_N \geq 5$	highly polluted

4. Enrichment factor (EF)

This factor is used to assess the extent of element accumulation in the soil compared to the source rocks and aims to distinguish whether the sources of the element are of natural origin or human activities, and is calculated according to the following equation:

$$EF = \frac{(Cn/Fe)_{samples}}{(Bn/Fe)_{background}} \dots \dots (5)$$

Where: (Cn/Fe) is the heavy metal concentration to iron concentration in the study sample, and (Bn/Fe) is the heavy metal concentration to iron concentration in the reference sample.

Iron is used as a reference element because it is a geochemically stable element, naturally abundant in soil, minimally influenced by anthropogenic factors, and often associated with heavy metals in soil (Sinex and Helz, 1981). If the EF value is <1 , it indicates that the element comes from natural sources, while if $EF > 1$, it suggests that there is enrichment of the element, which indicates that the element comes from human activities (Jiang et al., 2019).

Table 5: Classification of EF according to (Mmolawa et al., 2011; Barbieri et al., 2015).

Enrichment factor values	Enrichment ratio
$EF < 2$	Low enrichment
$2 < EF \leq 5$	Moderate or medium enrichment
$5 < EF \leq 20$	Great enrichment
$20 < EF \leq 40$	Very high enrichment
$EF > 40$	Very high enrichment

3. Results and Discussion

Table (6) includes the concentrations of the main oxides (Al_2O_3 , Fe_2O_3 , K_2O , SiO_2 , MgO , TiO_2). Al_2O_3 , Fe_2O_3 , and MgO in the studied samples are usually the oxides most associated with clay minerals, while SiO_2 is a major component of sand and clay minerals. Potassium oxide is associated with minerals such as mica, while titanium oxide is associated with ilmenite minerals (Sandler et al., 2015). The trace element contents of (V, Nb, Zr, Y, Th, Sn, Cr, Sb, As, Mn, Mo, Co, Cu, Zn, Ni, Pb) are listed in Table (7).

These elements are characterized by their low natural concentrations in soil, but their importance often exceeds that of major elements from an environmental and geochemical perspective. Some elements, especially those known environmentally as heavy metals, have a significant environmental impact due to their toxicity and accumulation in the biosphere. Others, especially some rare elements (Y, Nb, Th), may be of great geochemical interest regarding element sources in soil (Kabata-Pendias, 2000).

The results indicate elevated concentrations of certain heavy elements in the study area, particularly the elements (Ni, Zn, Cu, Co, Mo, Mn, Cr) which exhibited concentrations surpassing the global average for soil. Additionally, it is observed that the concentrations in the industrial area samples are higher in comparison to the other samples for zinc and copper. This increase may be attributed to industrial waste (Alengebawy et al., 2021) resulting from the indiscriminate disposal of electronic devices and other sources (Kumar et al., 2019; Gebreyesus, 2014; Hasnine et al., 2017).

Table 6: Concentration of the major oxides %.

Sample No.	Fe_2O_3	TiO_2	K_2O	SiO_2	Al_2O_3	MgO
S1	5.19	0.80	1.20	34.36	7.91	3.42
S2	6.50	1.00	1.31	40.34	9.17	5.37
S3	6.12	0.89	1.30	36.84	8.31	5.18
S4	6.23	0.92	1.10	36.23	8.60	5.78
S5	6.62	0.87	1.10	35.97	8.87	4.61
S6	6.59	0.91	1.32	38.05	9.13	5.05
S7	5.64	0.81	0.89	30.64	7.47	3.96

S8	6.33	0.97	1.10	35.79	8.56	5.54
S9	6.86	1.25	1.00	35.50	8.33	4.77
S10	6.10	0.86	0.97	33.18	8.12	4.12
S11	6.77	0.93	1.18	39.22	9.53	5.19
S12	6.48	0.94	1.13	37.35	9.04	4.82
S13	7.18	0.80	1.22	39.34	9.69	5.09
S14	6.87	0.85	1.34	39.91	9.72	6.01
S15	6.57	0.97	1.03	35.47	8.50	4.93
S16	6.37	1.02	1.07	36.15	8.65	5.05
S17	6.93	0.90	1.14	37.37	9.30	4.74
S18	6.38	0.89	1.17	37.62	9.12	5.59
S19	6.60	0.87	1.09	36.23	8.92	4.61
S20	6.37	0.90	1.98	37.44	10.74	4.23
S21	5.83	0.88	1.75	38.00	9.24	4.07
S22	6.03	0.85	1.71	36.33	10.04	4.30
S23	5.23	0.72	1.48	39.77	7.88	3.45
S24	5.42	0.78	1.33	36.34	8.91	3.97
S25	5.13	0.78	1.43	42.52	7.87	4.43
S26	4.87	0.79	1.34	38.45	8.13	4.69
S27	5.35	0.84	1.39	37.14	8.69	4.22
S28	6.50	1.00	1.31	39.34	9.17	5.37
S29	5.82	0.80	1.67	38.58	9.71	4.02
S30	5.26	0.80	1.57	38.18	9.13	4.03
S31	4.93	0.76	0.93	30.46	6.50	2.82
Avg	6.07	0.88	1.27	36.86	8.76	4.59
Max	7.18	1.25	1.98	42.52	10.74	6.01
Min	4.87	0.69	0.89	30.46	6.50	2.82
Av . Crust	5.6	0.64	2.8	66.6	15.4	2.5

Av. Crust: Average Crust given by Rudnick and Gao (2003)

The elevated concentrations of the other elements could be a consequence of human activities such as waste burning and the operation of electrical generators, along with heavy traffic (Wuana and Okieimen, 2011; Arao et al., 2010). Natural processes also play a role in contributing to the high concentrations of some heavy elements via their spread through natural weathering

processes (Bradl, 2005). The average concentration of the elements (Sb-Pb) did not exceed the global soil average across all samples in the study area, except for the industrial area sample, where it surpassed the global soil average. This may be linked to industrial activities, including industrial workshops, battery repair facilities, and battery sales (Ferretti et al., 1995; Ali et al., 2019; Hanif et al., 2025).

Table 7: The concentration of trace elements in ppm.

S. No.	Pb	Ni	Zn	Cu	Co	Mo	Mn	As	Sb	Cr	Sn	Th	Y	Zr	Nb	V
S1	24.0	140.8	143.0	50.8	ND	14.5	733.9	3.7	ND	219.6	0.3	7.0	19.2	156.9	7.5	50.4
S2	10.1	205.5	83.9	36.7	22.3	9.3	909.4	4.0	ND	395.3	ND	4.9	19.8	140.0	7.1	47.6
S3	11.0	199.6	84.1	36.0	14.3	17.5	898.5	3.6	ND	319.7	1.3	4.2	18.2	130.2	6.0	37.5
S4	10.2	197.1	77.3	35.1	12.1	12.4	842.8	4.1	ND	296.3	ND	4.4	18.3	125.9	6.7	61.6
S5	12.3	217.9	84.2	41.4	29.6	24.3	944.2	4.8	ND	269.2	ND	5.6	20.6	130.7	7.6	74.8
S6	11.3	218.8	84.5	41.2	19.2	17.0	925.6	4.6	ND	296.0	ND	5.3	20.6	131.7	7.3	66.9
S7	9.1	183.2	68.6	34.1	ND	24.7	804.0	3.9	ND	231.8	ND	4.7	17.9	105.3	4.9	33.6
S8	11.3	203.4	77.1	36.7	7.9	12.2	859.0	4.1	ND	352.0	ND	4.6	19.5	132.1	6.6	58.5
S9	10.1	196.8	79.7	31.9	19.5	23.8	889.2	4.1	ND	821.7	ND	3.8	21.2	195.3	7.4	76.2
S10	9.4	204.1	76.3	37.2	ND	12.9	919.4	4.5	ND	282.6	0.3	4.8	18.5	116.7	6.3	58.8
S11	11.0	243.8	86.3	44.7	22.9	46.8	904.0	5.0	ND	254.0	ND	5.0	20.6	117.3	7.1	60.8
S12	9.8	253.7	83.2	42.0	30.7	169.3	1013.2	5.2	ND	282.8	ND	4.6	19.8	116.4	7.2	60.2
S13	13.2	260.4	100.7	50.6	27.0	36.3	1079.0	5.5	ND	230.4	ND	5.8	21.1	113.9	6.8	61.1
S14	13.7	237.2	96.7	44.7	20.1	17.6	960.5	5.0	ND	230.7	0.3	5.4	19.9	122.1	6.9	69.5
S15	10.0	219.4	78.3	38.5	34.4	56.7	1024.8	5.5	ND	429.5	1.1	5.1	19.9	147.9	7.7	62.5
S16	9.7	198.4	73.4	34.2	12.3	34.5	865.2	4.3	ND	427.2	0.8	4.1	19.3	134.0	6.8	68.1
S17	10.0	221.8	86.5	44.7	28.5	17.8	907.8	5.7	ND	239.8	2.8	5.7	21.1	129.9	6.7	66.1
S18	11.4	211.3	83.6	40.2	17.5	13.9	917.9	4.4	ND	293.7	ND	4.8	19.6	128.4	6.4	59.4
S19	10.9	219.9	82.6	41.1	22.6	16.5	974.4	5.1	0.2	257.9	3.1	4.9	19.5	124.1	6.8	57.7
S20	14.8	166.9	104.9	40.3	15.7	25.6	893.1	4.4	ND	208.2	ND	7.6	23.9	168.1	8.7	60.5
S21	13.1	150.8	93.8	38.4	12.6	14.5	763.0	4.6	ND	233.0	ND	7.7	22.1	165.5	8.2	56.3
S22	13.4	169.3	92.6	35.0	18.7	11.6	791.6	4.2	ND	244.1	ND	6.3	21.1	149.9	8.6	54.6
S23	12.0	140.2	79.0	33.1	14.5	8.1	624.2	3.7	ND	174.2	ND	6.6	18.4	127.5	7.5	48.2
S24	11.6	143.6	77.9	34.7	14.6	18.0	664.4	4.8	ND	278.3	ND	6.8	19.9	147.3	8.0	57.1
S25	12.3	138.9	80.8	35.0	ND	12.6	665.4	3.9	ND	240.4	ND	5.8	19.1	150.8	8.0	54.6
S26	10.6	133.7	71.7	30.8	14.3	17.5	669.6	3.7	ND	272.9	ND	6.4	18.9	151.5	7.7	46.5

S27	11.4	138.6	78.7	39.1	13.1	7.9	695.0	4.4	ND	417.6	ND	6.6	21.1	176.6	7.3	40.9
S28	10.1	205.5	83.9	36.7	22.3	9.3	909.4	4.0	ND	395.3	ND	5.7	19.8	140.0	7.1	47.6
S29	12.3	158.8	93.1	36.4	15.0	18.9	755.7	4.4	ND	168.3	1.4	7.7	21.1	141.0	8.0	53.2
S30	11.4	140.7	79.1	33.2	14.5	24.6	689.4	4.1	ND	322.0	ND	5.1	19.9	157.0	7.5	56.0
S31	273.2	126.0	340.0	135.9	ND	13.9	665.5	3.8	3.7	292.2	13.2	7.7	17.8	175.8	6.9	40.3
Avg	19.9	188.7	93.1	41.3	16.4	24.2	843.8	4.4	0.3	302.5	0.8	5.6	19.9	139.7	7.2	55.8
Max	273.2	260.4	340.0	135.9	34.4	169.3	1079.0	5.7	3.7	821.7	13.2	7.7	23.9	195.3	8.7	76.2
Min	9.1	126.0	68.6	30.8	7.9	7.9	624.2	3.2	0.2	168.3	0.3	3.8	17.7	105.3	4.9	33.6
Av.Crust	15	20	70	55	10	1.5	900	1.8	0.2	100	2.5	7.2	33	165	20	135
K-P(2011)	27	29	70	38.5	11.3	1.1	488	6.83	0.67	59.5	2.5	9.2	23	267	12	129
Av. Crust: Average Crust (Kabata-Pendias, 2011)																
K-P (2011): Kabata-Pendias (World-Soil Average)																
ND= Not Detected																

A. Sources of heavy metals

The chemical data of the soil samples are analyzed statistically using SPSS version 20, applying principal components analysis (PCA) to identify the potential factors or sources affecting heavy metal concentrations. Components with eigenvalues greater than one are selected (Fig. 2). The PCA results reveal five main components that influence the concentrations of trace elements in the surface soil of the study area. These components account for over 87% of the variance.

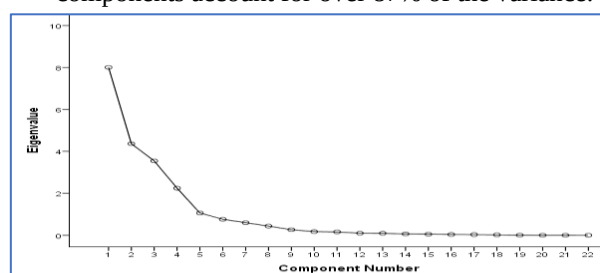


Fig. 2: Scree plot of the eigenvalues showing that the data have five major components with eigenvalues greater than 1.

Where the first component represents 28.52% of the variance, the second component represents 25%, the third 8.622%, the fourth 11.2%, and the fifth 5.99% of the total variance observed (Table 8).

The first component: The first component represents transition metals and iron oxides and comprises the elements Mn, Ni, Fe₂O₃, MgO, As, Co, and V. This reflects the influence of geochemical processes such as chemical weathering and surface adsorption, as well as the role of sedimentary processes, such as river sedimentation, in redistributing these elements into the environment. The close association between Fe₂O₃ and MgO reflects the presence of ferromagnesian minerals, such as pyroxene, amphibole, and biotite, which are major components of mafic igneous rocks (White, 2001) found in the upper Tigris River basin and abundant

in river sediments in Mosul (Mahmood, 2021), indicating that these rocks contribute as a major source of these elements. Furthermore, the presence of Ni, Co, and V in this component suggests the potential presence of these elements within the crystal structure of ferromagnesian minerals, given their geochemical behavior similar to that of iron and magnesium. When these minerals are exposed to weathering processes, these elements are released into the environment, where they may remain in the form of secondary minerals, or these elements, in addition to arsenic, may undergo an adsorption process on the surfaces of iron and manganese oxides (White, 2001), which affects their geochemical availability and transfer to soil and groundwater.

The second component: The second component represents one of the main sources of surface soil pollution in Mosul City, reflecting industrial and military impacts on the environment. Heavy metals such as copper (Cu), zinc (Zn), lead (Pb), tin (Sn), and antimony (Sb) are clear indicators of pollution resulting from industrial waste such as batteries, metallic coatings, and electronic waste (Hou et al., 2025), in addition to the impact of military activities during the period of the city's liberation from terrorist gangs. This is supported by the fact that this component is not associated with the main oxides (Al₂O₃, SiO₂, MgO, Fe₂O₃, K₂O) (Table 8).

The third component is associated with the elements Y, Th, Nb, Al₂O₃, K₂O, and SiO₂. The association of this component with the oxides K₂O, Al₂O₃, and SiO₂ shows a strong association with potassium-rich clay minerals such as illite, indicating a natural source for these elements. The presence of some trace elements such as Y, Nb, and Th with Al₂O₃ and SiO₂ suggests that these elements may be associated with either clay minerals or secondary oxides formed as a result of chemical weathering processes, supporting the hypothesis of a natural source for this component.

From a geochemical perspective, this component reflects a natural geological source resulting from the long weathering of feldspar- and silicate-rich igneous rocks, which are found in the upper Tigris Basin areas (Westaway et al., 2009).

The fourth component: This component appears to indicate the presence of resistant minerals such as chromite (FeCr_2O_4), rutile (TiO_2), and zircon (ZrSiO_4), as the elements Cr, TiO_2 and Zr are observed to be present in this component. Geochemically, this indicates a natural geological source represented by mafic rocks rich in titanium and chromium (Fitzpatrick and Chittleborough, 2002), which were transported by the Tigris River after the source rocks were exposed to chemical and physical weathering. These resistant minerals are common in Tigris River sediments within the study area (Mahmood, 2021).

The fifth component: Related to molybdenum, it is a chemical pollutant associated with molybdenum (Mo). Elevated concentrations of this element indicate the effects of industrial and urban sources. Mo is primarily used to manufacture stainless steel and is also a component of industrial oils and greases. Elevated Mo concentrations may result from industrial discharges or recent metal waste (Geng et al., 2014). It may also be associated with agricultural activities, given its use in some chemical fertilizers. This component reflects the impact of human activities on the environment.

Table 8: Varimax-rotated principal component analysis of the soil samples

Variables	Component				
	1	2	3	4	5
Pb	-0.184	0.97	-0.077	0.007	-0.033
Ni	0.896	-0.172	-0.315	-0.024	0.152
Zn	-0.145	0.971	0.029	-0.03	-0.035
Cu	-0.009	0.986	-0.05	-0.07	0.007
Co	0.713	-0.098	0.183	0.048	0.445
Mo	0.305	-0.048	-0.084	-0.005	0.805
Mn	0.92	-0.087	-0.111	0.11	0.128
As	0.732	0.007	0.251	-0.095	0.413
Sb	-0.17	0.966	-0.1	0.016	-0.029
Cr	0.093	-0.031	-0.124	0.964	0.008
Sn	-0.124	0.937	-0.162	-0.049	0.006
Th	-0.389	0.384	0.686	-0.365	0.013
Y	0.348	0.115	0.83	0.171	0.082
Zr	-0.421	0.309	0.544	0.623	-0.042
Nb	-0.143	-0.018	0.899	0.123	0.17
V	0.616	-0.134	0.278	0.346	0.159
Fe_2O_3	0.947	-0.144	0.005	0.196	-0.004
TiO_2	0.468	-0.138	-0.02	0.827	-0.026
K_2O	-0.172	-0.216	0.862	-0.209	-0.186
SiO_2	0.286	-0.399	0.533	-0.088	-0.233

Al_2O_3	0.573	-0.339	0.66	-0.098	-0.067
MgO	0.731	-0.381	-0.123	0.188	-0.32
Eigen values	8.005	4.364	3.542	2.243	1.058
Variance %	36.385	19.835	16.099	10.193	4.81
Cumulative %	36.385	56.22	72.319	82.512	87.323

B. Pollution Assessment

1. Contamination Factor and Contamination Degree

Pollution factor calculations for the current study samples show significant variations in contamination values from one element to another, as well as clear variations between different locations. The highest rates are for molybdenum, antimony, and nickel, with contamination factor values above 9 for these elements, indicating very high contamination for each in general within the study area. Meanwhile, the contamination factor values for the remaining elements (Cu, Mn, Sn, As, Co, Cr, Pb) are less than or equal to 3, indicating moderate to low contamination (Table 9). The heavy elements can be ranked according to the contamination factor for the study area samples as shown in Fig. 3 as follows:

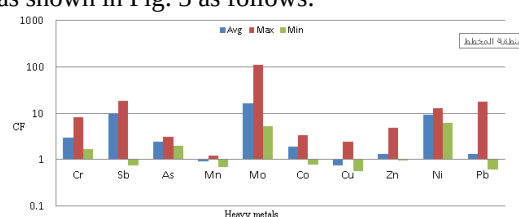


Fig. 3: Upper, lower and average limits of the contamination factor in the studied area

$\text{Mo} > \text{Ni} > \text{As} > \text{Co} > \text{Sb} = \text{Pb} = \text{Zn} > \text{Cu} = \text{Mn}$

The results of the contamination degree for the study samples range between (138.04-20.90) (Table 9 and Fig. 4), indicating that the study area falls within the highly to very highly polluted category (Hakanson, 1980). Twenty-three samples from the study area had a high degree of pollution, while samples (S31, S16, S13, S15, S12, S11, S9, and S5) in the industrial area, Al-Muthanna neighborhood, Al-Wahda neighborhood, Al-Bakr neighborhood, Jdeidat Al-Mufti, Al-Mithaq, Al-Salam and Al-Barid all fall within the very high pollution category. The reason for the increased pollution level in the industrial area is due to industrial waste, which leads to an increase in the concentration of heavy metals in the soil. As for the remaining sites, the reason for the increase may

be that these sites are commercial and have high traffic density, in addition to the recent military operations and the weapons remnants left behind,

which play a major role in increasing the concentrations of heavy metals.

Table 9: Results of calculating the Contamination factor (CF) and the degree of contamination (Cdeg) for each element.

S. No.	Pb	Ni	Zn	Cu	Co	Mo	Mn	As	Sb	Cr	Cdeg
S1	1.597	7.041	2.043	0.924	NA	9.667	0.82	2.062	NA	2.20	26.35
S2	0.675	10.274	1.198	0.668	2.226	6.200	1.01	2.209	NA	3.95	28.41
S3	0.736	9.980	1.202	0.655	1.431	11.667	1.00	1.978	NA	3.20	31.84
S4	0.681	9.854	1.104	0.639	1.211	8.267	0.94	2.272	NA	2.96	27.93
S5	0.817	10.895	1.203	0.752	2.957	16.200	1.05	2.693	NA	2.69	39.26
S6	0.755	10.938	1.207	0.749	1.919	11.333	1.03	2.567	NA	2.96	33.46
S7	0.607	9.162	0.980	0.620	NA	16.467	0.89	2.167	NA	2.32	33.21
S8	0.755	10.168	1.102	0.668	0.786	8.133	0.95	2.272	NA	3.52	28.36
S9	0.675	9.838	1.139	0.580	1.950	15.867	0.99	2.293	NA	8.22	41.55
S10	0.625	10.204	1.090	0.677	NA	8.600	1.02	2.504	NA	2.83	27.55
S11	0.730	12.188	1.233	0.813	2.289	31.200	1.00	2.777	NA	2.54	54.77
S12	0.656	12.683	1.189	0.764	3.067	112.867	1.13	2.861	NA	2.83	138.04
S13	0.879	13.021	1.438	0.921	2.698	24.200	1.20	3.030	NA	2.30	49.69
S14	0.916	11.858	1.381	0.813	2.013	11.733	1.07	2.777	NA	2.31	34.87
S15	0.668	10.970	1.119	0.700	3.437	37.800	1.14	3.072	NA	4.29	63.20
S16	0.650	9.921	1.048	0.622	1.227	23.000	0.96	2.398	NA	4.27	44.10
S17	0.668	11.088	1.236	0.812	2.855	11.867	1.01	3.156	NA	2.40	35.09
S18	0.761	10.565	1.195	0.731	1.746	9.267	1.02	2.419	NA	2.94	30.64
S19	0.724	10.997	1.180	0.748	2.257	11.000	1.08	2.819	0.753	2.58	34.14
S20	0.984	8.345	1.499	0.732	1.573	17.067	0.99	2.419	NA	2.08	35.69
S21	0.873	7.540	1.339	0.699	1.258	9.667	0.85	2.567	NA	2.33	27.12
S22	0.891	8.463	1.323	0.636	1.872	7.733	0.88	2.314	NA	2.44	26.55
S23	0.798	7.009	1.128	0.601	1.447	5.400	0.69	2.083	NA	1.74	20.90
S24	0.774	7.178	1.112	0.630	1.463	12.000	0.74	2.693	NA	2.78	29.37
S25	0.823	6.942	1.155	0.636	NA	8.400	0.74	2.167	NA	2.40	23.27
S26	0.706	6.683	1.025	0.559	1.431	11.667	0.74	2.083	NA	2.73	27.63
S27	0.761	6.931	1.124	0.710	1.306	5.267	0.77	2.462	NA	4.18	23.51
S28	0.675	10.274	1.198	0.668	2.226	6.200	1.01	2.209	NA	3.95	28.41
S29	0.817	7.940	1.330	0.662	1.502	12.600	0.84	2.462	NA	1.68	29.84
S30	0.761	7.033	1.131	0.603	1.447	16.400	0.77	2.251	NA	3.22	33.61
S31	18.214	6.302	4.857	2.471	NA	9.267	0.74	2.104	18.442	2.92	65.32
Avg	1.324	9.437	1.329	0.752	1.907	16.165	0.94	2.435	9.598	3.02	37.86
Max	18.214	13.021	4.857	2.471	3.437	112.867	1.20	3.156	18.442	8.22	138.04
Min	0.607	6.302	0.980	0.559	0.786	5.267	0.69	1.767	0.753	1.68	20.90

NA= Not Available

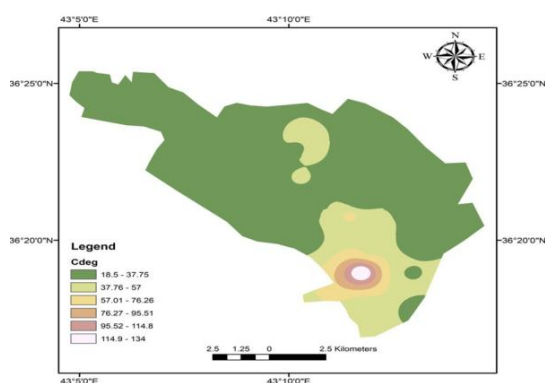


Fig. 4: Spatial distribution of pollution degree (Cdeg) in the surface soil of the study area

2. Geo-accumulation Index (I_{geo})

Calculating the geoaccumulation index (I_{geo}) for the current study samples (Table 10) revealed that the I_{geo} for all studied samples fall within the uncontaminated category for lead, zinc, copper, manganese, chromium, and antimony. Only the industrial area sample is severely contaminated with lead and antimony (Muller, 1969). While the nickel and molybdenum contamination levels in all study area samples range from moderate to severe, the arsenic and cobalt values fall within the moderately contaminated soil classification. Accordingly, the heavy metals can be ranked

according to the I_{geo} for the study area samples shown in Fig. 5 as follows:

$$Mo > Ni > Sb > Cr > As > Co > Zn > Mn > pb > Cu$$

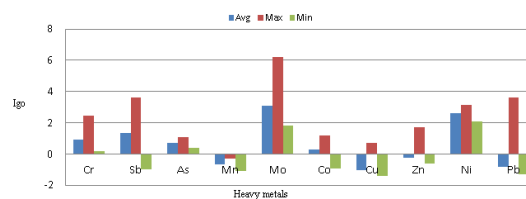


Fig. 5: Upper, lower and average limits of (I_{geo}) in the studied area

Table 10: Results of calculating the Geo-accumulation Index and the Improved Nemerow Index for each element.

S. No.	Pb	Ni	Zn	Cu	Co	Mo	Mn	As	Sb	Cr	I_N
S1	0.090	2.231	0.446	-0.699	NA	2.688	-0.879	0.459	NA	0.550	1.949
S2	-1.153	2.776	-0.324	-1.167	0.569	2.047	-0.570	0.558	NA	1.398	1.990
S3	-1.026	2.734	-0.320	-1.195	-0.068	2.959	-0.587	0.399	NA	1.092	2.116
S4	-1.140	2.716	-0.442	-1.231	-0.309	2.462	-0.680	0.599	NA	0.982	1.935
S5	-0.877	2.861	-0.319	-0.995	0.979	3.433	-0.516	0.844	NA	0.844	2.477
S6	-0.990	2.866	-0.313	-1.001	0.355	2.918	-0.544	0.775	NA	0.981	2.101
S7	-1.306	2.611	-0.614	-1.274	NA	3.457	-0.748	0.531	NA	0.628	2.462
S8	-0.990	2.761	-0.445	-1.167	-0.931	2.439	-0.652	0.599	NA	1.231	1.965
S9	-1.153	2.713	-0.398	-1.372	0.379	3.403	-0.602	0.612	NA	2.454	2.453
S10	-1.263	2.766	-0.460	-1.148	NA	2.519	-0.554	0.739	NA	0.914	1.980
S11	-1.038	3.022	-0.283	-0.883	0.610	4.379	-0.579	0.889	NA	0.760	3.143
S12	-1.193	3.080	-0.335	-0.973	1.032	6.234	-0.414	0.932	NA	0.915	4.468
S13	-0.771	3.118	-0.061	-0.704	0.847	4.012	-0.323	1.014	NA	0.619	2.902
S14	-0.712	2.983	-0.120	-0.883	0.425	2.968	-0.491	0.889	NA	0.621	2.156
S15	-1.166	2.870	-0.423	-1.099	1.196	4.655	-0.398	1.034	NA	1.518	3.354
S16	-1.207	2.725	-0.518	-1.271	-0.290	3.939	-0.642	0.677	NA	1.510	2.812
S17	-1.166	2.886	-0.279	-0.886	0.928	2.984	-0.572	1.073	NA	0.677	2.156
S18	-0.979	2.816	-0.328	-1.038	0.219	2.627	-0.557	0.690	NA	0.969	2.021
S19	-1.051	2.874	-0.346	-1.004	0.590	2.874	-0.470	0.910	-0.995	0.782	2.053
S20	-0.608	2.476	-0.001	-1.035	0.069	3.508	-0.596	0.690	NA	0.473	2.511
S21	-0.782	2.330	-0.163	-1.102	-0.253	2.688	-0.823	0.775	NA	0.635	1.918
S22	-0.751	2.496	-0.181	-1.237	0.319	2.366	-0.770	0.626	NA	0.702	1.787
S23	-0.910	2.224	-0.411	-1.319	-0.052	1.848	-1.113	0.474	NA	0.216	1.574
S24	-0.955	2.259	-0.432	-1.251	-0.036	3.000	-1.023	0.844	NA	0.891	2.137
S25	-0.866	2.210	-0.378	-1.237	NA	2.485	-1.021	0.531	NA	0.681	1.770
S26	-1.088	2.156	-0.549	-1.424	-0.068	2.959	-1.012	0.474	NA	0.864	2.100
S27	-0.979	2.208	-0.417	-1.079	-0.200	1.812	-0.958	0.715	NA	1.477	1.574
S28	-1.153	2.776	-0.324	-1.167	0.569	2.047	-0.570	0.558	NA	1.398	1.990
S29	-0.877	2.404	-0.173	-1.179	0.002	3.070	-0.837	0.715	NA	0.166	2.186
S30	-0.979	2.229	-0.408	-1.315	-0.052	3.451	-0.970	0.586	NA	1.102	2.457
S31	3.602	2.071	1.695	0.720	NA	2.627	-1.020	0.488	3.620	0.962	2.810
Avg	-0.180	2.653	-0.174	-0.997	0.129	3.430	-0.693	0.699	-0.130	0.936	2.300
Max	3.602	3.118	1.695	0.720	1.196	6.234	-0.323	1.073	3.620	2.454	4.468
Min	-1.306	2.071	-0.614	-1.424	-0.931	1.812	-1.113	0.237	-0.995	0.166	1.574

NA= Not Available

3. Improved Nemerow Index (IN)

The results of the Improved Nemerow Index (I_N) show that the values of the study samples range between (4.468-1.574) with an average of (2.440) (Table 10), meaning that this soil is moderately to severely polluted according to this index classification (Guan et al., 2014). It is shown that the sample S12 in Al-Wahda neighborhood falls within the classification of being highly polluted. As for the samples (S15 and S11) in Al-Barid and Al-Mithaq neighborhoods, it falls within the level of being severely polluted (Fig. 6).

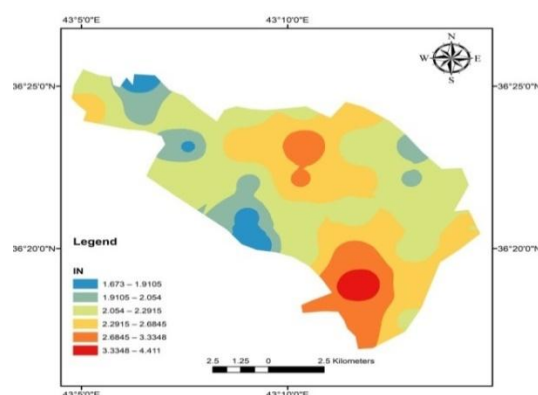


Fig. 6: Spatial distribution of (IN) in surface soil of study area

4. Enrichment factor

Table 11 shows that most of the heavy elements in the study samples, such as lead, zinc, copper, manganese, cobalt, arsenic, and chromium, are within the low to moderate enrichment level according to the classification of Mmolawa et al. (2011) and Barbieri et al. (2015). Nickel, molybdenum, and antimony are highly enriched. Sample S31 shows very high enrichment of lead and high enrichment of zinc, nickel, molybdenum, and antimony. Accordingly, the

elements can be ranked according to the intensity of enrichment as shown in Fig. (7):

Mo>Ni>Sb>Cr>As>Co>pb>Zn>Mn>Cu

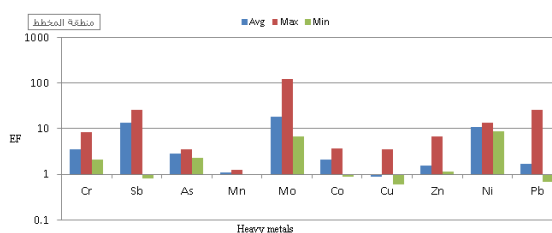


Fig. 7: Upper, lower and average limits of the enrichment factor in the studied area

Table 11: Results of calculating the Enrichment factor values for each element

Sample No.	Pb	Ni	Zn	Cu	Co	Mo	Mn	As	Sb	Cr
S1	2.15	9.49	2.75	1.25	NA	13.03	1.12	2.78	NA	3.02
S2	0.73	11.06	1.29	0.72	2.40	6.67	1.11	2.38	NA	4.35
S3	0.84	11.42	1.38	0.75	1.64	13.36	1.17	2.26	NA	3.73
S4	0.77	11.08	1.24	0.72	1.36	9.30	1.07	2.56	NA	3.40
S5	0.86	11.52	1.27	0.80	3.13	17.14	1.13	2.85	NA	2.91
S6	0.80	11.62	1.28	0.80	2.04	12.04	1.12	2.73	NA	3.21
S7	0.75	11.38	1.22	0.77	NA	20.44	1.13	2.69	NA	2.94
S8	0.83	11.24	1.22	0.74	0.87	8.99	1.08	2.51	NA	3.97
S9	0.69	10.04	1.16	0.59	1.99	16.19	1.03	2.34	NA	8.56
S10	0.72	11.71	1.25	0.78	NA	9.87	1.20	2.87	NA	3.31
S11	0.76	12.60	1.27	0.84	2.37	32.26	1.06	2.87	NA	2.68
S12	0.71	13.71	1.29	0.83	3.31	121.98	1.24	3.09	NA	3.12
S13	0.86	12.69	1.40	0.90	2.63	23.58	1.19	2.95	NA	2.29
S14	0.93	12.09	1.41	0.83	2.05	11.96	1.11	2.83	NA	2.40
S15	0.71	11.69	1.19	0.75	3.66	40.29	1.24	3.27	NA	4.67
S16	0.71	10.90	1.15	0.68	1.35	25.26	1.08	2.63	NA	4.79
S17	0.68	11.20	1.25	0.82	2.88	11.99	1.04	3.19	NA	2.47
S18	0.84	11.60	1.31	0.80	1.92	10.17	1.14	2.66	NA	3.29
S19	0.77	11.66	1.25	0.79	2.39	11.66	1.17	2.99	0.80	2.79
S20	1.08	9.18	1.65	0.80	1.73	18.77	1.11	2.66	NA	2.34
S21	1.05	9.05	1.61	0.84	1.51	11.60	1.04	3.08	NA	2.86
S22	1.04	9.83	1.54	0.74	2.17	8.98	1.04	2.69	NA	2.89
S23	1.07	9.39	1.51	0.81	1.94	7.23	0.95	2.79	NA	2.38
S24	1.00	9.27	1.44	0.81	1.89	15.50	0.97	3.48	NA	3.67
S25	1.12	9.47	1.58	0.87	NA	11.46	1.03	2.96	NA	3.35
S26	1.01	9.61	1.47	0.80	2.06	16.77	1.09	2.99	NA	4.01
S27	1.00	9.06	1.47	0.93	1.71	6.89	1.03	3.22	NA	5.58
S28	0.73	11.06	1.29	0.72	2.40	6.67	1.11	2.38	NA	4.35
S29	0.98	9.55	1.60	0.80	1.81	15.15	1.03	2.96	NA	2.07
S30	1.01	9.36	1.50	0.80	1.93	21.82	1.04	2.99	NA	4.38
S31	25.85	8.94	6.89	3.51	NA	13.15	1.07	2.99	26.17	4.24
Avg	1.53	10.88	1.53	0.87	1.89	18.63	1.10	2.81	1.58	3.55
Max	25.85	13.71	6.89	3.51	3.66	121.98	1.24	3.48	26.17	8.56
Min	0.68	8.94	1.15	0.59	0.87	6.67	0.95	2.26	0.80	2.07

NA= Not Available

4. Conclusion

The current study reveals that the surface soil in the left bank of Mosul City is contaminated with heavy metals. It appears that natural and human factors jointly influence the concentrations of heavy metals in the study area as follows:

The first factor includes the elements Mn, Ni, Fe₂O₃, MgO, As, Co, V, Y, Th, Nb, Al₂O₃, K₂O, SiO₂, TiO₂, Cr, and Zr, reflecting the influence of

geochemical processes such as chemical weathering, adsorption on the surface of clay minerals, and the presence of weathering-resistant minerals. This also encompasses the role of sedimentary processes such as river sedimentation in concentrating and redistributing these elements in the environment. The second factor includes Cu, Zn, Pb, Sn, Sb, and Mo. These elements are clear indicators of pollution resulting from industrial waste, including batteries, metal coatings, electronic waste, and fuel combustion, as well as

waste from military operations. This is especially relevant since industrial and commercial areas, alongside locations that experienced intensive military operations, were among the most contaminated with heavy metals. Accordingly, the current study recommends taking urgent measures to reduce soil pollution in the city, including distancing industrial areas and vehicle repair workshops from residential communities. It also recommends investigating the health risks and effects of heavy metals in the surface soil of Mosul City.

5. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

6. Funding Statement

This research received no external funding.

7. Author Contributions

First Researcher: Ruqaya Bader Mohammed
Sample collection, data analysis, and full preparation and writing of the research manuscript.
Second Researcher: Hazim Jumaa Mahmood
Proposing the research topic, conducting the statistical analysis, and reviewing the manuscript.

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تقييم التلوث بالمعادن الثقيلة وتحديد مصادرها في التربة الحضرية باستخدام مؤشرات التلوث

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تاريخ الاستلام: 24 أيار 2025 تاريخ المراجعة: 01 تموز 2025 تاريخ القبول: 03 آب 2025

تاريخ النشر الإلكتروني: 01 تشرين الأول 2026

الملخص

تهدف الدراسة الحالية الى تقييم وتحديد مصادر تلوث التربة السطحية بالعناصر الثقيلة في الجانب الايسر من مدينة الموصل. تم جمع 31 عينة مركبة من التربة على شبكة منتظمة موزعة على منطقة الدراسة وبأبعاد 2×2 كم. أُجرى التحليل الكيميائي باستخدام جهاز الاشعة السينية الوميضية (XRF) لتحديد تراكيز العناصر الاثرية (V, Nb, Zr, Y, Th, Sn, Cr, Sb, As, Mn, Mo, Co, Cu, Zn, Ni, Pb) والرئيسية (MgO, Al₂O₃, SiO₂, K₂O, TiO₂, Fe₂O₃). أظهرت نتائج حساب مؤشرات تلوث التربة (معامل التلوث ودرجة التلوث ومعامل التراكم الأرضي ومؤشر نيمرو للتلوث ومعامل الاغناء) ان اغلب عينات الدراسة ملوثة بالعناصر الثقيلة. يبين تحليل المركبات الاساسية، ان تأثير العمليات الجيوكيميائية مثل التجوية الكيميائية والامتزاز السطحي، بالإضافة إلى دور العمليات الرسوبية، مثل الترسيب النهري، في إعادة توزيع هذه العناصر في البيئة. في حين يبدو ان العناصر الثقيلة (Cu, Zn, Pb, Sn, Sb, Mo) قد تأثرت بالنشاطات البشرية في المدينة وخاصة ان هذه العناصر تُعتبر مؤشرات واضحة للتلوث الناتج عن النفايات الصناعية مثل البطاريات والطلاءات المعدنية والمخلفات الإلكترونية، إضافة إلى تأثير الأنشطة العسكرية خلال فترة تحرير المدينة من العصابات الارهابية. وما يؤيد ذلك ارتفاع تراكيز هذه العناصر بشكل ملحوظ في المنطقة الصناعية. بينت الدراسة مشاركة العوامل الطبيعية الجيولوجية والجيوكيميائية مع العوامل البشرية في التأثير على تراكيز العناصر الثقيلة في التربة السطحية لمدينة الموصل. كما اظهرت الدراسة الحاجة الملحة الى اتخاذ تدابير عاجلة للحد من تلوث التربة في المدينة، خاصة بعد ان سجلت مؤشرات التلوث في بعض المناطق مستويات عالية من التلوث.

الكلمات المفتاحية:

العناصر الثقيلة، التربة الحضرية، تلوث التربة، مؤشرات التلوث.

DOI: [10.33899/injes.v26i4.56158](https://doi.org/10.33899/injes.v26i4.56158), ©Authors, 2026, College of Science, University of Mosul.

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