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Assessment of trace and heavy metals pollution indicators in surface soils nearby an oil refineries and industrial activities

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ABSTRACT

Industrial activities related to the extraction of petroleum in the Kurdistan Region of Iraq (KRI) have raised concerns about heavy metal pollution of soils, but comprehensive assessment studies in the region are remain limited. The present work evaluated the concentrations, spatial distribution, pollution, ecological risk, and contamination status of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), vanadium (V), and zinc (Zn) in surface soils (0–30 cm) collected from 16 sites about 200 m from oil refineries and industries in Erbil, Sulaymaniyah, Duhok Governorates, and Koya Town, KRI. The elemental concentrations from soil samples after the digestion process were measured using inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer ELAN 9000, USA), and contamination was evaluated by comparing measured concentrations to world mean soil background concentrations and FAO/WHO limits. The evaluation was based on Pearson correlation analysis, enrichment factors (EF), contamination factors (CF), degree of contamination, pollution load index (PLI), geoaccumulation index (Igeo), quantification of contamination (QoC), potential ecological risk indices (PERI), risk index (RI), and soil pollution index (SPI). The average concentrations of the elements studied decreased in the order of Fe (30,179.38 mg kg^{-1}) > Ni (145.43 mg kg^{-1}) > Cr (99.50 mg kg^{-1}) > Zn (98.58 mg kg^{-1}) > V (64.31 mg kg^{-1}) > Cu (31.65 mg kg^{-1}) > Co (19.78 mg kg^{-1}) > Pb (15.31 mg kg^{-1}) > As (6.92 mg kg^{-1}) > Cd (0.61 mg kg^{-1}) > Hg (0.02 mg kg^{-1}). Compared with world mean concentrations of soils, Ni, Cr, Co, Cu, As, and Zn were relatively enriched, with Ni showing the highest mean EF (11.89) and CF (up to 16.67). The nickel concentrations were above the FAO/WHO reference limit in all 16 sites, Cr in 37.5% of sites, and V in 93.8%. Ni and Cr concentrations were elevated above background at all sites, and Co, As, and Cu also showed widespread background enrichment. The results also showed strong relationships between Ni–Co ($r = 0.989$), Ni–Cr ($r = 0.967$), Co–Cr ($r = 0.960$), Pb–Zn ($r = 0.966$), and Cd–Pb ($r = 0.876$), revealing the presence of different geochemical and anthropogenic/lithogenic associations. In addition, the Igeo results also revealed Ni as being the most accumulated element, with concentrations of 3.47 at S10 and 1.46 at S3, while Zn and Cd were found to be locally accumulated, with highest concentrations at S6 and S13, respectively. The range of contamination was between 12.4 and 31.9 with the highest levels at S10, S13 and S6. PLI was rated as moderate pollution at 69% of the locations, and less than 1 at 31% locations. S6, S10, and S13 had the highest overall contamination and ecological risk responses. The cumulative potential ecological risk consisted mainly of Ni and Cd (about 58.3%). The RI varied from 76.55 at S14 to 279.18 at S13; moderate ecological risk was found at S6, S10, and S13, and low risk at all the other sites. Nickel and Cr follow a positive trend with all sampling locations, while As is present at levels exceeding the world soil background at 15 of 16 sampling locations for the sites examined by the QoC. The most prevalent pollutant (SPI) was Ni, with all sites showing exceedances, followed by V, which was exceeded at 93.8% of the sites, and then exceeded at several sites for Cr. Localized SPI exceedances were also seen for Cd at S6, S13, and S16 and for Zn at S6. Generally, the indices indicate that Ni is the element that is most frequently enriched, while Cr and Co are generally enriched, and Zn and Cd are locally enriched. The results of these investigations show significant spatial variation in soil contamination and indicate S6, S10 and S13 as priority areas for additional environmental investigation and monitoring.

Keywords: soil contamination, oil refinery, heavy metals, pollution indices, ecological risk.

INTRODUCTION

Soil is the major sink for potentially toxic element releases from anthropogenic activities. Unlike many organic contaminants, inorganic soil contaminants such as heavy metals and metalloids cannot be decomposed or degraded in soil by microbial or photochemical reactions and may cause risk to plants, animals and humans (Tariq, 2021; Rasheed 2026). Chemical forms and physico-chemical properties of the soil influence their mobility, bioavailability, and persistence (Wuana and Okieimen, 2011; Alloway, 2013). Some elements can be accumulated in the soils and can enter the food webs through plant uptake, which may affect soil fertility, microbial activity, and ecosystem functioning (Haghighizadeh et al., 2024). Long-term exposure to some potentially toxic elements has also been linked to adverse health effects, including nephrotoxicity, neurotoxicity, carcinogenicity, and endocrine disruption. Therefore, it is necessary to monitor their concentrations, spatial distribution, and the potential ecological risks (Saleem et al., 2024).

Refining, petroleum production, and associated industrial activities are considered potential sources of heavy and trace-element contamination in surrounding soils. Elements like vanadium, nickel, cobalt, zinc, and chromium can be found naturally in crude oil or be released to the environment during the refining process, through gas flaring, fuel combustion, catalysts, sludge, and industrial wastes. These processes can cause redistribution of elements via airstreams and deposition of elements on surrounding land (Nematollahi et al., 2022). Refinery wastewater has been found to contain high levels of Ni, V, Cr, lead (Pb), and cadmium (Cd) in the soils around refineries, and potentially associated human health risks have been reported in the Middle East (Grmasha et al., 2023; Dilekoğlu and Azeez, 2026). The ranges of distribution and environmental importance of these elements, however, may be different in relation to industrial activities and local geology and soil properties. As a result, regional investigations should be carried out to address potential contamination hot spots and determine environmental monitoring priorities.

In the Kurdistan Region of Iraq, the oil-producing industry has been growing, and today, there are several oil refineries and related industrial plants in various governorates such as Erbil, Sulaymaniyah and Duhok. The development is of concern due to possible effects from industrial emissions and waste disposal on surrounding soils. The bioavailability, retention, and mobility of toxic elements might also be affected by a variety of locally affecting geological and soil conditions, such as the calcareous and alkaline properties of many soils (Rasul et al., 2026). Previous studies have focused on environmental contamination in the region of Erbil and Koy Sanjaq and the potential geogenic and anthropogenic sources of contamination (Al-Jaleel et al., 2025; Nematollahi et al., 2022; Dilekoğlu & Azeez, 2026). However, there is still limited evidence with respect to spatial coverage and the elements and environmental indicators being assessed. To the best of our knowledge, we could not find a comparative study (across governorates) that includes element concentration, enrichment, contamination, pollution status, and potential ecological risk that is not thoroughly documented for the study area (Hamad et al., 2019; Rasul et al., 2026). This restricts the possibility of a consistent comparison of sites and prioritizing sites for additional study.

Soils may be contaminated, but the concentrations alone are not enough to indicate the extent or significance of contamination. A combination of complementary indices can provide a more comprehensive assessment. Enrichment factor (EF) is used to assess the enrichment of an element relative to a reference element and background concentrations, while the contamination factor (CF) is used to compare the measured concentration with selected background concentrations. The degree of contamination of a single element (Müller, 1969) is defined by the geo-accumulation index (Igeo). The pollution load index (PLI) is a composite measure of the pollution factors at a site to describe the overall pollution status (Tomlinson et al., 1980). The potential ecological risk assessment scheme developed by Hakanson (1980) considers element-specific ecological risk factors and uses the relative toxicity of selected elements to calculate an element-specific ecological risk factor and an overall risk index (RI). Pearson correlation analysis can also be used to detect associations between elements but cannot determine the source of such associations. When combined, these methods can be useful for providing the characteristics of the contaminant pattern, identifying elements of concern, and assisting in

comparisons between sites (Liu et al., 2021; Hamid et al., 2022; Zhao et al., 2022; Haghighizadeh et al., 2024; Saleem et al., 2024).

Accordingly, this study aimed to evaluate 11 elements (As, Cd, Co, Cr, Cu, Fe, Hg, Ni, Pb, V, and Zn) in surface soil samples collected near oil refineries and related industries of selected sites in Erbil, Sulaymaniyah, Duhok, and Koya in the Kurdistan Region of Iraq. Specific objectives were: (i) to ascertain concentrations of elements and the spatial distribution of these elements and their comparison with the mean world soil concentrations and the soil-quality reference limits adopted in this study; (ii) to evaluate the enrichment/contamination/geo-accumulation and overall pollution status using EF, CF, Igeo, PLI and related indices; (iii) to assess the potential ecological risk using the Hakanson framework and to identify the main contributors to the calculated potential ecological risk; (iv) to assess the association among elements through Pearson correlation analysis; (v) to identify site-specific elements of concern and to establish baseline data for future environmental monitoring and risk-management planning using the single pollution index (SPI). The study hypothesized that a subset of elements would exhibit elevated concentrations or enrichment at certain locations, and that element concentrations and pollution indices would vary among sample sites.

MATERIALS AND METHODS

Study area

The study was carried out in four areas of the Kurdistan Region of Iraq (KRI) in Erbil, Sulaymaniyah, Duhok, and Koya (Figure 1). The study area extends approximately between 43°14′37″ and 45°37′41″ E longitude and 35°28′04″ and 36°46′18″ N latitude. The climate of the region is Mediterranean-type climate with hot and dry summer, while the winter is relatively cold (IOM, 2024). The average annual temperature is around 19.3 °C, and the annual precipitation is generally 350–600 mm. The selected locations represent and cover all areas influenced by petroleum-related and other industrial activities (Figure 1).

Soil sampling and preparation

Surface soil samples (0–30 cm) were collected from six sites in Erbil governorate, four sites in Sulaymaniyah governorate, four sites in Duhok governorate, and two sites in Koya town (Figure 1). The sampling sites were selected at a distance of about 200 m from major potential pollution sources, according to the results of Ahmed and Gülser (2019), who studied the spatial distribution of heavy metals in soils around oil refineries in the Kurdistan Region of Iraq.

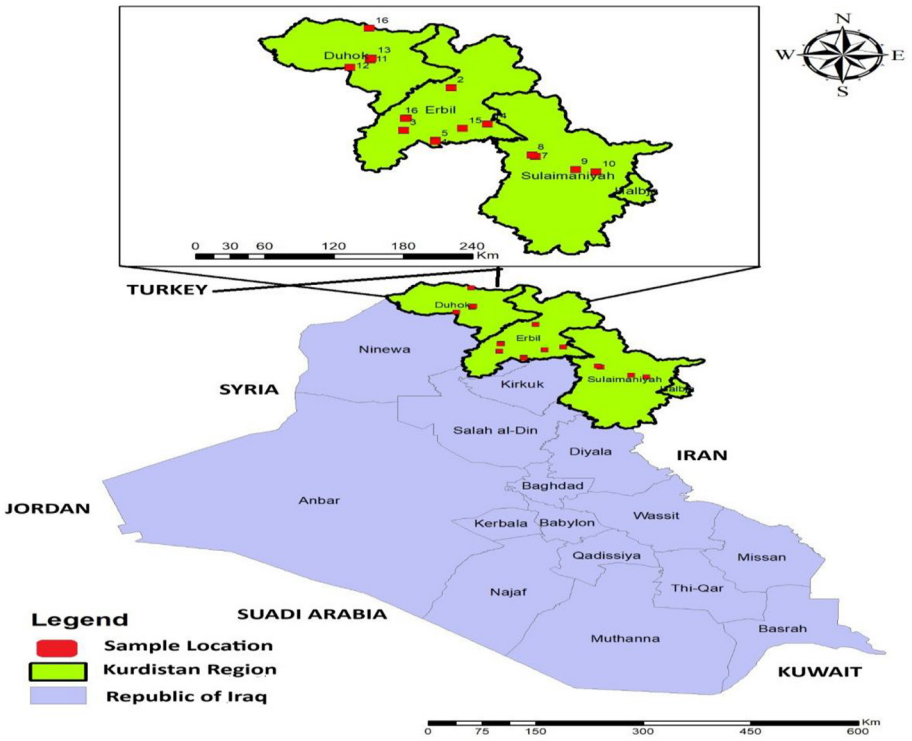

Figure 1. Map of the geographic location of the Kurdistan Region of Iraq and the soil sampling locations

Soils sampled at a distance of about 200 m from refinery sources were found to be more contaminated with heavy metals than those sampled at 600 and 1200 m. In the present study, the 200 m distance was selected to target soils that are possibly exposed to relatively high contamination levels from petroleum-related and other industrial activities. Approximately 1 kg of composite soil was sampled at each site. Each composite sample was made up of five subsamples collected within a 10 × 10 m area using a stainless-steel auger. A representative composite sample was prepared by thoroughly mixing the subsamples. Upon arrival in the laboratory, soil samples were air-dried at room temperature, gently crushed with a mortar and pestle. The samples were then passed through a 2-mm stainless-steel sieve. Subsequently, representative subsamples were finely ground and passed through an 80-mesh sieve to obtain a homogeneous fine fraction before chemical analysis for the concentrations of total heavy and trace elements

Soil digestion and metal analysis

Heavy metal concentrations in soil samples were determined by the wet digestion method as described by Tariq (2021). In brief, 1 g of each soil sample was ground, digested with 8 mL of 30% hydrogen peroxide and 2 mL of concentrated sulfuric acid at 95 °C for 30 min on a hot plate, and then 2 mL of hydrogen peroxide was added and heated until the solution was transparent. The mixture was cooled, filtered through Whatman No. 42 filter paper, and made up to 50 mL with distilled water. The concentrations of the elements (Mo, Cu, Pb, Zn, Ag, Ni, Co, Mn, Fe, As, U, Au, Th, Sr, Cd, Sb, Bi, V, La, Cr, Ba, Ti, Al, Na, Sc, Tl, Hg, Se, Te, and Ga) analyzed were measured by an inductively coupled plasma mass spectrometer (ICP-MS, PerkinElmer ELAN 9000, USA). The measured elemental concentrations in the digest solutions (mg/L) were converted into soil concentrations (mg/kg) using the following equation:

$$C\left(\frac{mg}{kg}\right) = C\left(\frac{mg}{L}\right) \times \frac{V\,(L) \times DF}{W\,(kg)} \qquad (1)$$

where: C represents the metal concentration (mg/L), V is the final volume of the digested solution, DF is the dilution factor, and W is the dry soil weight (kg).

Environmental risk indicators

Enrichment factor

This pollution index was used for the assessment of the extent of heavy metal contamination from anthropogenic sources. It is also used for differentiation between natural and anthropogenic-induced causes. Also, iron (Fe) is used as the normalization reference (Darko et al., 2017; Ayobami, 2022).

$$EF = \frac{HM_s \times F_{er}}{HM_r \times F_{es}} \qquad (2)$$

where: EF – enrichment factor, HM_s – heavy metal concentration in test soil, F_{er} – concentration of iron in reference/control soil, HM_r – heavy metal concentration in reference/control soil, F_{es} – concentration of iron in test soil.

Enrichment factor is defined as $EF > 1$, which indicates enriched heavy metal concentration relative to average continental crustal and surface soil values, suggesting anthropogenic origin of micro-pollutant metal. $EF < 1$ indicates the absence of metal concentration enrichment, emanating from natural sources.

Finally, $EF - 1$ means the concentration of the metal and its reference comparison is similar (Swarnalatha et al., 2015).

Contamination factor and degree of contamination

Contamination factor and degree of contamination were calculated using the method developed by Hakanson (1980).

$$CF_i = \frac{C_i}{B_i} \qquad (3)$$

where: CF_i – contamination factor of element i; C_i – measured concentration of element i in the soil sample (mg/kg); B_i – background concentration of element i (mg/kg).

Values obtained were categorized as: CF < 1 (low contamination), 1 ≤ CF < 3 (moderate contamination), 3 ≤ Cf < 6 (considerable contamination), and CF ≥ 6 (very high contamination).

$$\text{Degree of contamination } (C_d) = \Sigma\left(\begin{matrix} CF_{Cu} + CF_{Pb} + CF_{Zn} + CF_{Ni} + CF_{Co} \\ +CF_{Fe} + CF_{As} + CF_{Cd} + CF_{V} + CF_{Cr} + CF_{Hg} \end{matrix}\right) \qquad (4)$$

Meanwhile, the extent of contamination was categorized as: $C_d < 8$ (low risk), $8 \leq C_d < 16$ (moderate risk), $16 \leq C_d < 32$ (considerable risk), and $C_d > 32$ (very high risk).

Pollution load index (*PLI*)

The estimations of pollution load index were carried out following the methods given by Bhutiani et al. (2017). The pollution load index was graded as: PLI < 1 (no pollution); 1 < PLI ≤ 3 (moderate pollution); 3 < PLI ≤ 5 (heavy pollution); and PLI > 5 (extremely heavy pollution).

$$(PLI) = \left(\begin{matrix} C_{Cu} \times C_{Pb} \times C_{Zn} \times C_{Ni} \times C_{Co} \times C_{Fe} \\ \times C_{As} \times C_{Cd} \times C_V \times C_{Cr} \times C_{Hg} \end{matrix}\right)^{\frac{1}{11}} (5)$$

Geo-accumulation index

The computation of the geo-accumulation index (I_{geo}) was based on the procedures proposed by Muller (1969) and the formula is given by Bhutiani et al. (2017). Hence, reflecting that $I_{geo} \leq 0$ (uncontaminated), $0 < I_{geo} \leq 1$ (tending from uncontaminated to moderate contamination), $1 < I_{geo} \leq 2$ (moderate contamination), $2 < I_{geo} \leq 3$ (tending from moderate to heavy contamination), $3 < I_{geo} \leq 4$ (heavy contamination), $4 < I_{geo} \leq 5$ (tending from heavy to extreme contamination) and $I_{geo} \geq 5$ (extreme contamination).

$$\text{Geo-accumulation index} = \log_2\left(\frac{\text{HM}_s}{1.5 \times \text{HM}_c}\right) (6)$$

where: *HMs* is the metal concentration in oil-contaminated soil, and *HMc* is the metal concentration in control (or baseline soil).

Quantification of contamination

The contamination in terms of quantification was calculated as per the method previously suggested by Bhutiani et al. (2017). Generally, positive values are an indication of contamination, while negative values reflect non-contamination.

$$\text{Quantification of contamination, QoC(\%)} = \left(\frac{\text{C}_\text{m} - \text{B}_\text{m}}{\text{C}_\text{m}}\right) \times 100 \quad (7)$$

where: C_m and B_m are heavy metal concentrations in the oil-contaminated and baseline soil, respectively.

Potential ecological risk index (PERI)

The potential ecological risk index was calculated in accordance with the mathematical formula elaborated by Hakanson (1980). The potential ecological risk is the toxic response factor multiplied by the contamination factor:

$$PERI = T_{rf} \times C_f \quad (8)$$

When T_{rf} for the various metals studied include Cu = 5, Pb = 5, Zn = 1, Ni = 5, Co = 5, Fe = 1, As = 10, Cd = 30, V = 2, Cr = 2, and Hg = 40. The ecological risks were categorized as PER < 40 (low risk), 40 ≤ PERI < 80 (moderate risk), 80 ≤ PERI < 160 (considerable risk), 160 ≤ PERI < 320 (high risk), and PERI ≥ 320 (very high risk) (Qing et al., 2015; Wu et al., 2015; Darko et al., 2017).

$$\text{Risk index, } RI = \Sigma\, Er_{Cu} + Er_{Pb} + Er_{Zn} + Er_{Ni} + \\ + Er_{Co} + Er_{Fe} + Er_{As} + Er_{Cd} + Er_V + Er_{Cr} + Er_{Hg} \quad (9)$$

The values are categorized as follows: *RI* < 150 (low *RI*), 150 ≤ *RI* < 300 (moderate *RI*), 300 ≤ *RI* < 600 (significant *RI*), and *RI* > 600 (extremely high *RI*).

Sum of pollution index

A contamination assessment tool for determining single-element contamination indicators is the sum of pollution index (SPI). SPI is computed as follows:

$$\text{SPI} = \frac{\text{Actual soil metal concentration}}{\text{Permissible soil metal concentration}} \quad (10)$$

While residual heavy metal values were classified as *SPI* ≤ 1 (low contamination), 1 < *SPI* ≤ 3 (moderate contamination), and *SPI* > 3 (high contamination) (Darko et al., 2017; Ayobami, 2022), acceptable levels of heavy metals for soil were established (Kabata-Pendias and Pendias, 2001).

Statistical analysis

All data were checked for normality and homogeneity of variances before statistical analysis. All statistical analyses were carried out using SPSS version 26 at α = 0.05, and comparisons of means were determined using Tukey's test. The potential ecological risk index and environmental risk indicators were computed using Microsoft Excel.

RESULTS AND DISCUSSION

Background and reference concentrations

Due to the absence of standardized soil background concentrations and permissible limits for heavy and trace elements in the Kurdistan region and Iraq at present, the internationally reported reference values were used for comparison and calculation of the pollution indices. The reference background values were the World mean soil background concentrations (SWM). Comparison was made with the FAO/WHO permissible limits (PL) for internationally recognized soil-quality thresholds. Published geochemical and environmental literature was used for derivation of the reference values (Bowen, 1979; Kabata-Pendias and Mukherjee, 2007; Kabata-Pendias, 2011; Alloway, 2013). The SWM values represent the reported world mean concentrations of elements in soils and were used as the background concentrations (Bi) in the calculation of the pollution index (PI), pollution load index (PLI), Enrichment factor (EF), and geoaccumulation index (I_{geo}), where applicable. The FAO/WHO permissible limits were used independently to assess whether the measured concentrations exceeded internationally recognized permissible concentrations in soil. For Fe, concentrations reported as percentage (%) were converted to mg/kg (ppm) before their use in the enrichment-factor calculations to maintain consistency with the units of the other elemental concentrations.

Concentration of heavy and trace elements in soil samples

The full analytical data set included 31 elements, but only 10 elements, As, Cd, Pb, Hg, Cr, Ni, Cu, Zn, Co, and V, were included in the pollution assessment. These elements were chosen because they are known to be toxic and are commonly linked to anthropogenic and petroleum-based activities. Moreover, background values, environmental guideline values, and/or toxicological data are available for these elements, which allows a quantitative assessment of their environmental significance (Alloway, 2013; Kabata-Pendias, 2011; Tchounwou et al., 2012). The other elements were kept in the geochemical data set but not used for the pollution indicator assessment. This exclusion was due to their lithogenic or geochemical occurrence, or for comparatively lower environmental concern under typical soil circumstances, or for the lack of reference parameters necessary for the selected pollution-assessment approaches. The selection of elements for environmental assessment thus followed the principle of focusing on metals and metalloids that have been found to have a specific environmental significance while keeping the remaining set of elements for geochemical interpretation (Hakanson, 1980; Kabata-Pendias, 2011).

The quantitative concentrations of the 11 heavy and trace elements (Cu, Pb, Zn, Ni, Co, Fe, As, Cd, V, Cr, and Hg) in the 16 surface-soil sampling locations and descriptive statistics are presented in Table 1. The mean concentrations followed the order Fe (30,179.38 mg kg^{-1}) > Ni (145.43 mg kg^{-1}) > Cr (99.50 mg kg^{-1}) > Zn (98.58 mg kg^{-1}) > V (64.31 mg kg^{-1}) > Cu (31.65 mg kg^{-1}) > Co (19.78 mg kg^{-1}) > Pb (15.31 mg kg^{-1}) > As (6.92 mg kg^{-1}) > Cd (0.61 mg kg^{-1}) > Hg (0.02 mg kg^{-1}). Soil contains the highest amount of iron based on its medium concentration of 2.1%, which corresponds to its major soil mineral matrix part (Rose et al. 1979; Kabata-Pendias 2011). There was large variation by location in concentrations. Copper ranged from 17.78 to 53.67 mg kg^{-1}, while Pb ranged from 6.71 to 56.03 mg kg^{-1}. Comparisons revealed that the zinc level was significantly higher at S6 (483.28 mg kg^{-1}) than at the other sampling sites. Nickel ranged from 74.32 mg kg^{-1} at S3 to 299.98 mg kg^{-1} at S10. Cobalt ranged from 12.99 to 29.67 mg kg^{-1}, whereas Fe ranged from 19,600 to 43,300 mg kg^{-1}. The maximum concentration of As observed was at S13 (11.09 mg kg^{-1}), and the lowest was at S7 (4.30 mg kg^{-1}). Cadmium levels were in the range of 0.12-2.23 mg kg^{-1} with the highest concentration of 2.23 mg kg-1 at S13 and S6. Vanadium ranged from 43.95 to 104.89 mg kg^{-1}, while Cr ranged from 62.73 to 184.40 mg kg^{-1}. The concentrations of mercury were found to be relatively low (0.005 to 0.040 mg kg^{-1}). The variation of the studied metals suggests that these metals were elevated by anthropogenic activities (Miletic et al., 2025). However, the high Zn concentration was most likely affected by parent materials.

Elevated levels of multiple elements were found at several sites. S6 was characterized particularly by high Zn (483.28 mg kg^{-1}), Pb (56.03 mg kg^{-1}), and Cd (1.98 mg kg^{-1}), whereas S10 showed the highest Ni (299.98 mg kg^{-1}) and Cr (184.40 mg kg^{-1}) concentrations. Another

Table 1. Heavy and trace element concentrations and descriptive characteristics in surface soils surrounding the oil refinery (mean of three replications)

Sample	Cu	Pb	Zn	Ni	Co	Fe	As	Cd	V	Cr	Hg
1	53.67	15.61	144.45	121.17	18.18	27570.00	4.30	0.28	73.92	88.21	0.023
2	29.36	10.89	62.63	126.27	20.08	28500.00	6.49	0.60	58.94	93.00	0.024
3	25.32	6.71	45.55	74.32	12.99	19600.00	5.99	0.20	53.94	62.73	0.026
4	22.85	11.35	60.54	108.58	14.78	23400.00	6.49	0.27	55.94	74.22	0.005
5	22.11	9.74	46.35	105.89	16.08	22300.00	6.49	0.34	53.94	64.73	0.006
6	49.49	56.03	483.28	119.07	17.38	32000.00	7.79	1.98	57.94	87.61	0.026
7	33.42	13.41	90.10	144.45	21.18	33400.00	7.19	0.39	65.93	103.39	0.019
8	32.20	11.49	64.43	196.59	22.48	30070.00	6.49	0.44	60.93	119.37	0.006
9	30.48	13.04	88.01	133.16	19.58	30090.00	7.59	0.40	62.93	94.60	0.007
10	37.36	10.62	72.82	299.98	29.67	38000.00	6.09	0.35	74.92	184.40	0.016
11	31.29	12.67	71.72	176.11	24.77	33700.00	6.99	0.40	71.92	117.17	0.014
12	31.46	11.36	75.72	174.31	21.48	33500.00	7.29	0.62	71.92	119.67	0.005
13	42.22	27.59	84.91	186.10	25.57	43300.00	11.09	2.23	104.89	144.65	0.04
14	17.78	10.09	58.84	98.00	14.88	26100.00	6.39	0.12	43.95	65.23	0.012
15	20.33	12.53	64.63	119.87	17.98	31300.00	7.59	0.16	51.94	74.62	0.005
16	27.14	11.93	63.23	143.05	19.38	30040.00	6.39	1.05	64.93	98.39	0.005
Mini	17.78	6.71	45.55	74.32	12.99	19600.00	4.30	0.12	43.95	62.73	0.01
Max	53.67	56.03	483.28	299.98	29.67	43300.00	11.09	2.23	104.89	184.40	0.04
Mean	31.65	15.31	98.58	145.43	19.78	30179.38	6.92	0.61	64.31	99.50	0.02
SE	2.43	2.84	25.45	12.90	1.06	1422.41	0.34	0.15	3.37	7.83	0.00
* SWM	25	25	64	18	8	40,000	4.7	0.5	90	42	0.06
PL**	100	60	300	50	50	50000	20	1	50	100	1

Note: Fe converted from % to ppm. * SWM is world mean soil background concentration (mg/kg) and PL** is FAO/WHO permissible limit in soil (mg/kg) (Bowen, 1979; Kabata-Pendias and Mukherjee 2007; Kabata-Pendias 2011; Alloway, 2013).

significant multi-element hotspot was S13, with relatively high concentrations of several elements, including Cu, Pb, Ni, Co, Fe, As, Cd, V, and Cr, including the maximum concentrations of As, Cd, V, and Fe recorded in the study. The spatial variations found within the elements show that the elements were not sampled evenly, and there may be different amounts of metals in the locations sampled. Major variations in these soils are also predicted due to the differences in maximum levels and site extents of metal deposits depending on site-specific environmental factors (atmospheric deposition, distance from possible emission sources, soil properties, etc.). These results are in agreement with the results found by (Rasheed, 2022; Kareem and Goran, 2023; Vijay et al., 2026), who found large variations in heavy metal concentrations between surface soil samples. This variation may be due to the agriculture activities and type of industrial that present in those areas. Basha and Issa (2025) studied pollution indices in the soil near refineries in Najaf city in the middle of Iraq and found that concentrations of the studied heavy metals were different and were close to the limited level. They indicated that the wind direction and gases released were the main factors for elemental pollution in the studied area. Thus, variation in the studied sites is due to the type of activities, the presence of original rocks, and may also be due to fertilizer use by farmers (Ahmed et al., 2025).

Measured concentrations of the elements investigated were compared to two soil-quality reference values – world soil mean (SWM) and internationally reported soil-quality reference values (PL) shown in Table 2. The international references were used to compare the results obtained considering all investigated elements, for which there are no specific soil background concentrations and permissible limits for Iraq and the Kurdistan Region. The literature review of standardized soil background concentrations and

permissible limits specifically for Iraq and the Kurdistan area is not available for all the investigated elements, so the internationally recommended reference values were used which were reported by FAO/WHO. The SWM values were chosen as reference background concentrations for the pollution-index computations, while the PL values were assumed independently to check the concentration against reported soil-quality thresholds. For each element, the mean concentration shown in Table 1 is the overall average of all 16 sampling locations, with percentages showing the percent of samples that exceeded the corresponding SWM/PL.

The overall mean concentration of Ni, which showed the highest increase when compared to the SWM of 18 mg kg^{-1} and PL of 50 mg kg^{-1}, was 145.43 mg kg^{-1}. The concentrations of Cr and Co were also higher than their respective SWMs, with all the samples exceeding the SWM. But the percentage of samples that were above the PL varied significantly: 37.5% of Cr samples were above the PL, while Co did not have any samples exceeding the PL. As and Cu were also higher than their SWM values. The mean As concentration was found to be 6.92 mg $kg^{-1,}$ which is higher than the SWM of 4.7 mg kg^{-1}; 93.8% of samples had concentrations above the SWM. Likewise, the mean concentration of Cu was 31.65 mg kg^{-1} as compared to the SWM of 25 mg $kg^{-1,}$ and 75% of the samples showed a concentration above the SWM. As and Cu, however, were both below the corresponding PL. The concentrations of Zn and Cd were moderately elevated from their SWM values. The mean concentration of Zn was 98.58 mg kg^{-1}, higher than the SWM (64 mg kg^{-1}); 62.5% of the samples were more than the SWM, while only 6.3% were more than the PL (300 mg kg^{-1}). The mean concentration of Cd was 0.61 mg kg^{-1}, marginally higher than the SWM of 0.50 mg kg^{-1}; 31.3% of samples exceeded the SWM, while 12.5% exceeded the PL of 1 mg kg^{-1}. However, V did not exhibit the same trend. The mean concentration of 64.31 mg kg^{-1} was also below the SWM of 90 mg kg^{-1}, and only 6.3% of the samples exceeded the SWM. However, 93.8% of the samples contained more than the PL (50 mg kg^{-1}). This illustrates how different interpretations can result from comparing concentrations with a background concentration versus a soil-quality threshold. The concentrations of Pb, Fe, and Hg were generally low compared to their reference values. The mean concentration of Pb was 15.31 mg kg^{-1}, which was below the SWM and PL, and 12.5% of the samples exceeded the SWM; none exceeded the PL. The mean Fe concentration (30,179.38 mg kg^{-1}) was also below both the SWM (40,000 mg kg^{-1}) and PL (50,000 mg kg^{-1}). Likewise, the mean Hg concentration was 0.02 mg kg ^{1}, which fell below the SWM (0.06 mg kg ^{1}) and PL (1 mg kg ^{1}), and no samples exceeded either value.

Overall, all samples had higher concentrations of Ni, Cr, and Co than their world soil background values, and most samples had higher concentrations of As and Cu than their SWM concentrations. This may be due to the fact that all industries use steel that contains these types of heavy metals. These results are in agreement with the results reported by Al Kilaby (2026), who studied the heavy metals and found that Cd, Ni, and Pb increased in the area close to an oil refinery

Table 2. The 16 sampling locations' mean element concentrations were compared to the world soil mean (SWM) and globally published soil-quality reference values (PL)

Element	Mean (mg kg^{-1})	SWM (mg kg^{-1})	PL (mg kg^{-1})	Samples > SWM (%)	Samples > PL (%)
Cu	31.65	25	100	75.0	0
Pb	15.31	25	60	12.5	0
Zn	98.58	64	300	62.5	6.3
Ni	145.43	18	50	100.0	100.0
Co	19.78	8	50	100.0	0
Fe	30179.38	40000	50000	6.3	0
As	6.92	4.7	20	93.8	0
Cd	0.61	0.5	1	31.3	12.5
V	64.31	90	50	6.3	93.8
Cr	99.50	42	100	100.0	37.5
Hg	0.02	0.06	1	0	0

in Najaf, Iraq. This is due to the factory waste, as confirmed by Endalkachew et al. (2025), who state that Pb will be more stable in the soil than other elements. In calcareous soil, heavy metals exhibit variability due to complexation with calcium carbonate (Khoudhair et al., 2026). There were less widespread elevations for Zn and Cd. V, on the other hand, had a mean concentration that was below its SWM, but higher than the reported PL in most samples. The exceedance of Ni was highest and most prevalent, with V, then Cr, Cd, and Zn, exceeding the corresponding PLs in decreasing order of prevalence.

Pearson correlation analysis

Table 3 shows that a good number of the elements investigated were strongly correlated with each other, and this was confirmed by the Pearson correlation matrix. The strongest correlation was observed between Ni and Co (r = 0.989), followed by Ni–Cr (r = 0.967), Co–Cr (r = 0.960), Ni–V (r = 0.904), and Co–V (r = 0.899). These high correlations suggest that these elements have the same spatial variations at the sampling sites under study. There were also strong positive correlations between Cu- Pb, Zn- Cd, and Cu- Zn-Cd. The results show that Cu was very well correlated with Zn (r = 0.867), and that the same was observed for the case of Pb and Zn (r = 0.966) and Cd (r = 0.876). There was also a strong correlation between zinc and Cd (r = 0.849). These relationships suggest these elements showed similar trends at the sampling sites. Iron showed positive correlations with several of the investigated elements, including Cu (r = 0.799), Pb (r = 0.756), Zn (r = 0.805), Ni (r = 0.765), Co (r = 0.754), As (r = 0.824), and other elements. The general pattern was a low correlation of mercury with the major groups, but with some elements, it had positive relationships. Strong correlations should not be interpreted as a sign of a common pollution source but as evidence of co-variation. The distinction between the common anthropogenic source, the natural mineral associations, and similar geochemical behavior is not possible by correlation analysis alone. Hence, the relationships observed in the correlation analysis must be used in conjunction with the enrichment factor, contamination factor, geoaccumulation index, spatial distribution, and information about the industrial activities in the vicinity of the site.

Enrichment factor

Due to the absence of standardized soil background concentrations and permissible limits for heavy and trace elements in the Kurdistan region and Iraq at present, the internationally reported reference values were used for comparison and calculation of the pollution indices. The reference background values were the world mean soil background concentrations (SWM). Comparison was made with the FAO/WHO permissible limits (PL) for internationally recognized soil-quality thresholds. Published geochemical and environmental literature was used for derivation of the reference values (Bowen, 1979; Kabata-Pendias and Mukherjee, 2007; Kabata-Pendias, 2011; Alloway, 2013). The SWM values represent the reported world mean concentrations of elements in soils and were used as the background concentrations (Bi) in the calculation of the pollution index (PI), pollution load index (PLI), enrichment

Table 3. Pearson's correlation coefficient of metals

Element	Cu	Pb	Zn	Ni	Co	Fe	As	Cd	V	Cr	Hg
Cu	1										
Pb	0.781	1									
Zn	0.867	0.966	1								
Ni	0.814	0.512	0.625	1							
Co	0.802	0.5	0.622	0.989	1						
Fe	0.799	0.756	0.805	0.765	0.754	1					
As	0.817	0.639	0.728	0.779	0.777	0.824	1				
Cd	0.588	0.876	0.849	0.38	0.363	0.712	0.531	1			
V	0.831	0.592	0.681	0.904	0.899	0.812	0.837	0.44	1		
Cr	0.807	0.504	0.618	0.967	0.96	0.769	0.796	0.384	0.887	1	
Hg	0.735	0.587	0.669	0.682	0.681	0.71	0.661	0.466	0.748	0.681	1

factor (EF), and geoaccumulation index (Igeo), where applicable. The FAO/WHO permissible limits were used independently to assess whether the measured concentrations exceeded internationally recognized permissible concentrations in soil. For Fe, concentrations reported as percentage (%) were converted to mg/kg (ppm) before their use in the enrichment-factor calculations to maintain consistency with the units of the other elemental concentrations.

The enrichment factors normalized to Fe are shown in Table 4. Nickel was the most enriched element among the elements studied. The EF values for Ni ranged from 6.00 to 24.18, with the highest value obtained in S10. Hence, Ni was highly concentrated at all the sampling sites. There were also sites with enrichment factors that were higher for both cobalt and Cr. Cobalt reached EF = 4.64 at S13, while Cr reached EF = 5.00 at S13. The enrichment factors were higher for Zn (10.96) at S6, and higher for Cd (5.74) at S6 and S13. These sites are then sources of potential local enrichment for these elements. The enrichment of Cu, As, and other elements was generally low as compared to Ni. The EF values of the majority of the locations were < unity for lead and close to unity for Hg, and also close to unity for V. These variations show that enrichment was element-specific and spatially confined. According to the EF results, Ni is the most consistent enrichment signal in the soils investigated, while Zn, Cd, Cr and Co are important localized enrichment signals. EF values should be interpreted with caution, however, as they cannot be considered proof of an anthropogenic source, due to the different natural geochemical variability that can influence the result, depending on the normalization element selected.

Contamination factor

The contamination factors are shown in Table 5 and are relative to the WMS Background. Nickel had the greatest and most uniform deviation from its background concentration, with CF values ranging from 4.13 to 16.67. Thus, Ni was determined to be considerable to very high at all sampling sites. Some sites attained the high contamination class for Co and Cr, while others were moderately contaminated. Zinc and Cd were more localized. The highest Zn CF was recorded at S6 (7.55), while Cd reached CF values of 3.96 at S6 and 4.46 at S13. These values are consistent with the high concentrations measured at these locations. The CF values for most samples of Cu and As were low to moderate, while these values tended to be below unity for most samples of Pb, Fe, V, and Hg. An interesting comparison is the contrast between V and its permissible limit, which was very striking: in most places V exceeded the permissible limit, but the ratio of V to the world soil background was generally less

Table 4. Enrichment factor of metals near oil refinery soils

Sample	Cu	Pb	Zn	Ni	Co	As	Cd	V	Cr	Hg
S1	3.11	0.91	3.27	9.77	3.30	1.33	0.81	1.19	3.05	0.56
S2	1.70	0.63	1.42	10.18	3.64	2.00	1.74	0.95	3.21	0.58
S3	1.47	0.39	1.03	5.99	2.36	1.85	0.58	0.87	2.17	0.63
S4	1.33	0.66	1.37	8.75	2.68	2.00	0.78	0.90	2.56	0.12
S5	1.28	0.57	1.05	8.53	2.92	2.00	0.99	0.87	2.24	0.15
S6	2.87	3.25	10.96	9.60	3.15	2.41	5.74	0.93	3.03	0.63
S7	1.94	0.78	2.04	11.64	3.84	2.22	1.13	1.06	3.57	0.46
S8	1.87	0.67	1.46	15.85	4.08	2.00	1.28	0.98	4.12	0.15
S9	1.77	0.76	2.00	10.73	3.55	2.34	1.16	1.01	3.27	0.17
S10	2.17	0.62	1.65	24.18	5.38	1.88	1.01	1.21	6.37	0.39
S11	1.82	0.74	1.63	14.20	4.49	2.16	1.16	1.16	4.05	0.34
S12	1.83	0.66	1.72	14.05	3.90	2.25	1.80	1.16	4.13	0.12
S13	2.45	1.60	1.92	15.00	4.64	3.42	6.46	1.69	5.00	1.04
S14	1.03	0.59	1.33	7.90	2.70	1.97	0.35	0.71	2.25	0.29
S15	1.18	0.73	1.47	9.66	3.26	2.34	0.46	0.84	2.58	0.12
S16	1.58	0.69	1.43	11.53	3.51	1.97	3.04	1.05	3.40	0.12

than one. This reflects the fact that the two reference methods measure different aspects of environmental status. Albadry et al. (2024) studied the effect of pollutants from industrial facilities and found that the contamination factor for most heavy metals was high close to the oil refinery and decreased with increasing distance from the activity area. Also, the degree of contamination depends on the qualitative and quantitative characteristics of the byproducts from the industries and the fluid waste released by the industries to nearby lands.

Degree of contamination and pollution load index

Figures 2 and 3 present the results of the degree of contamination and pollution load index, respectively. The degree of contamination (Cd) values were summed up over the 11 elements included in the present assessment (Cu, Pb, Zn, Ni, Co, Fe, As, Cd, V, Cr and Hg (Hakanson, 1980)) and ranged from 12.4 at S3 to 31.9 at S10. The highest values occurred at S10 (31.9), S13 (30.9), and S6 (30.1), while the lowest value occurred at S3 (12.4). Considerable-risk ($16 \leq Cd < 32$) and moderate-risk ($8 \leq Cd < 16$) are the two classes for which all but five samples (about 50%) fell. Samples 3, 4, 5, 14 and 15 were in the moderate-risk class; samples S10 (31.9), S13 (30.9) and S6 (30.1) came close to the very-high-risk ($Cd > 32$) threshold. The pollution load index also showed a similar trend; 69% of all the samples (eleven of sixteen) were moderately polluted ($1 < PLI \leq 3$), with PLI values at samples 13 and 6 showing the highest degree of pollution (2.05 and 1.94, respectively); the remaining five samples (3, 4, 5, 14, and 15), the same locations identified as least contaminated by the degree-of-contamination index) had PLI values < 1, indicating no measurable pollution at these points. The consistency of the spatial pattern of high contamination at two locations, samples 6 and 13, and low contamination at three locations, 3–5, 14 and 15, is also suggestive of a consistent random or artefactual contamination distribution otherwise, and argues for a true, localized anthropogenic source that is superimposed upon the background of moderate contamination (as has been argued elsewhere) (Ayobami, 2022).

Geoaccumulation index

The results of the I_{geo} are shown in Table 6. Nickel had the highest Igeo value of the elements investigated, with values varying from 1.46 at S3 to 3.47 at S10. This means Ni was moderately accumulated at lower levels and highly accumulated at higher sampling stations. The accumulation of Co and Cr was generally quite low compared to Ni and was positive at many sites. Zn and Cd showed localized accumulation at

Table 5. Contamination factor of heavy metals in oil refinery contaminated soil

Sample	Cu	Pb	Zn	Ni	Co	Fe	As	Cd	V	Cr	Hg
S1	2.15	0.62	2.26	6.73	2.27	0.69	0.91	0.56	0.82	2.10	0.38
S2	1.17	0.44	0.98	7.01	2.51	0.71	1.38	1.20	0.65	2.21	0.40
S3	1.01	0.27	0.71	4.13	1.62	0.49	1.28	0.40	0.60	1.49	0.43
S4	0.91	0.45	0.95	6.03	1.85	0.59	1.38	0.54	0.62	1.77	0.08
S5	0.88	0.39	0.72	5.88	2.01	0.56	1.38	0.68	0.60	1.54	0.10
S6	1.98	2.24	7.55	6.62	2.17	0.80	1.66	3.96	0.64	2.09	0.43
S7	1.34	0.54	1.41	8.02	2.65	0.84	1.53	0.78	0.73	2.46	0.32
S8	1.29	0.46	1.01	10.92	2.81	0.75	1.38	0.88	0.68	2.84	0.10
S9	1.22	0.52	1.38	7.40	2.45	0.75	1.62	0.80	0.70	2.25	0.12
S10	1.49	0.42	1.14	16.67	3.71	0.95	1.30	0.70	0.83	4.39	0.27
S11	1.25	0.51	1.12	9.78	3.10	0.84	1.49	0.80	0.80	2.79	0.23
S12	1.26	0.45	1.18	9.68	2.68	0.84	1.55	1.24	0.80	2.85	0.08
S13	1.69	1.10	1.33	10.34	3.20	1.08	2.36	4.46	1.17	3.44	0.72
S14	0.71	0.40	0.92	5.44	1.86	0.65	1.36	0.24	0.49	1.55	0.20
S15	0.81	0.50	1.01	6.66	2.25	0.78	1.62	0.32	0.58	1.78	0.08
S16	1.09	0.48	0.99	7.95	2.42	0.75	1.36	2.10	0.72	2.34	0.08

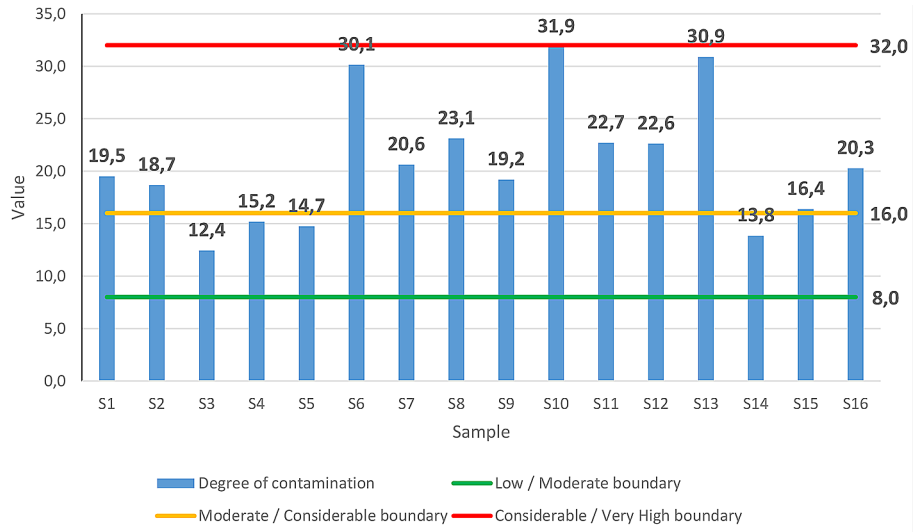

Figure 2. Degree of contamination of heavy metals in oil refinery-contaminated soil

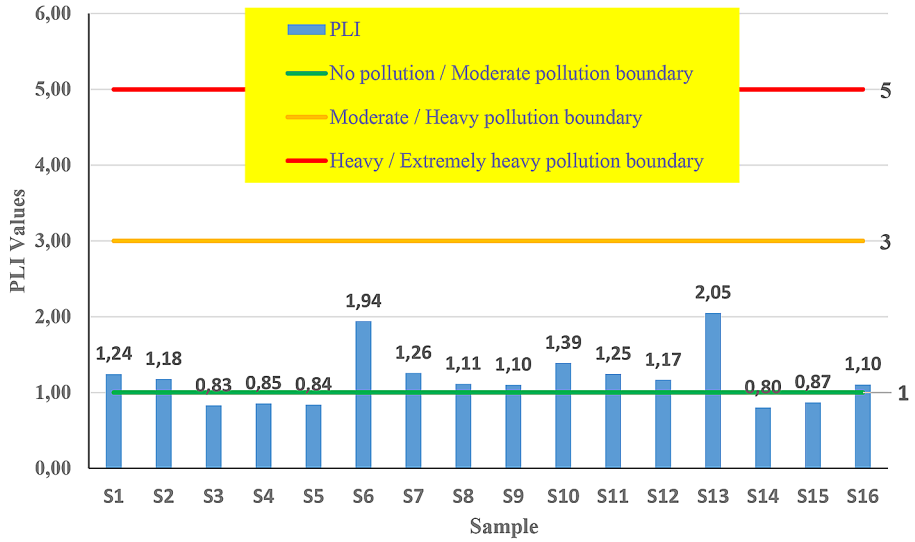

Figure 3. Pollution load index of heavy metals in soil affected by oil refineries

S6 and S13, respectively. At S6, the I_{geo} of zinc was around 2.33, and Cd was positive at sites having high measured levels. The I_{geo} values of other pollutants, such as Pb, Fe, V, and Hg, were generally negative, suggesting accumulation below the background-normalized levels. The concentrations of copper and As were mostly within the uncontaminated to moderately contaminated range, with some positive values recorded at specific points. The overall I_{geo} results thus generally confirm the patterns identified through EF and CF. Specifically, Ni had the highest accretion, while Cr, Co, Zn, and Cd were considered the secondary elements with moderate or localized accretion. This is in agreement with the results reported by (Kabir et al. 2012), who studied heavy metal pollution by industrial activities and found that I_{geo} of Pb and Cd were significant. This is due to accumulation of these metals in the soil and react with soil components.

Integrated interpretation of the pollution indicators

The concentration comparison, EF, CF, and Igeo data show a consistent pattern throughout the soils under investigation. Nickel was the most prominent element of concern, showing the highest mean concentration among the trace metals, exceedance of both the SWM and permissible limit at all sampling locations, high EF values, considerable-to-very-high CF values, and the

Table 6. Geo-accumulation index (I_{geo}) of heavy metals in oil refinery-polluted soils

Sample	Cu	Pb	Zn	Ni	Co	Fe	As	Cd	V	Cr	Hg
S1	0.52	-1.26	0.59	2.17	0.60	-1.12	-0.71	-1.42	-0.87	0.49	-1.97
S2	-0.35	-1.78	-0.62	2.23	0.74	-1.07	-0.12	-0.32	-1.20	0.56	-1.91
S3	-0.57	-2.48	-1.08	1.46	0.11	-1.61	-0.23	-1.91	-1.32	-0.01	-1.79
S4	-0.71	-1.72	-0.67	2.01	0.30	-1.36	-0.12	-1.48	-1.27	0.24	-4.17
S5	-0.76	-1.94	-1.05	1.97	0.42	-1.43	-0.12	-1.14	-1.32	0.04	-3.91
S6	0.40	0.58	2.33	2.14	0.53	-0.91	0.14	1.40	-1.22	0.48	-1.79
S7	-0.17	-1.48	-0.09	2.42	0.82	-0.85	0.03	-0.94	-1.03	0.71	-2.24
S8	-0.22	-1.71	-0.58	2.86	0.91	-1.00	-0.12	-0.77	-1.15	0.92	-3.91
S9	-0.30	-1.52	-0.13	2.30	0.71	-1.00	0.11	-0.91	-1.10	0.59	-3.68
S10	-0.01	-1.82	-0.40	3.47	1.31	-0.66	-0.21	-1.10	-0.85	1.55	-2.49
S11	-0.26	-1.57	-0.42	2.71	1.05	-0.83	-0.01	-0.91	-0.91	0.90	-2.68
S12	-0.25	-1.72	-0.34	2.69	0.84	-0.84	0.05	-0.28	-0.91	0.93	-4.17
S13	0.17	-0.44	-0.18	2.79	1.09	-0.47	0.65	1.57	-0.36	1.20	-1.07
S14	-1.08	-1.89	-0.71	1.86	0.31	-1.20	-0.14	-2.65	-1.62	0.05	-2.91
S15	-0.88	-1.58	-0.57	2.15	0.58	-0.94	0.11	-2.23	-1.38	0.24	-4.17
S16	-0.47	-1.65	-0.60	2.41	0.69	-1.00	-0.14	0.48	-1.06	0.64	-4.17

highest Igeo values. Chromium and cobalt represented the next most consistently elevated elements relative to their world soil backgrounds. Copper and As were also frequently above their respective SWM values, although their concentrations remained below the stated permissible limits. Enrichment in space of Zn and Cd was more localized, especially at S6 and S13. Vanadium exhibited a reverse trend, with most of the samples exceeding the reported permissible limit but with lower concentrations than the world soil means in general. Lead, Fe, and Hg generally showed low contamination and accumulation compared to their respective background values. Spatial patterns were most pronounced at S6, S10, and S13. S6 had the highest concentration of Zn and high concentrations of Pb and Cd; S10 had the highest concentrations of Ni and Cr, and S13 had high concentrations of several elements and high concentrations of Fe, As, Cd, and V. Thus, these sites are important hotspots for further environmental investigation. Taken together, the results indicate that the investigated soils do not exhibit uniform contamination by all elements. Rather, the pollution indicators identify Ni as the most consistently elevated element, with Cr and Co showing widespread background enrichment and Zn and Cd showing localized hotspots. This integrated interpretation is more appropriate than attributing all observed metal concentrations to a single pollution source solely on the basis of correlation or enrichment-factor values.

Quantification of contamination (QoC), potential ecological risk index (PERI), risk index (RI), and soil pollution index (SPI)

The deviation from the world mean soil concentrations for each element was expressed by the quantification of contamination. Significant differences were found between the calculated QoC values (Table 7) for the elements investigated. At all 16 sampling locations, both nickel and chromium had positive QoC values; 100% of samples had positive values, and the mean values were 86.3% for Ni and 54.0% for Cr. Cobalt had 57.7% positive mean values. The sample map for arsenic had positive QoC values at 15 of 16 sampling locations (93.8%) with a mean of 29.7%. The mean value of copper was 13.8% and zinc was 10.4% at 12 sampling locations and 10 sampling locations, respectively, with positive QoC values at 12 (75.0%) and 10 (62.5%) sampling locations. In contrast, Pb, Fe, Cd, V, and Hg generally exhibited negative QoC values, with mean values of −105.0%, −37.5%, −49.2%, −45.3%, and −549.3%, respectively. The consistently high quality of concentrations for Ni, Co, and Cr suggest that these elements were present at higher than the background concentrations in soil of the respective world mean found throughout the area investigated. The method of Hakanson (1980)

was used to calculate the potential ecological risk (PER) of the individual elements by multiplying the contamination factor with the corresponding toxic-response coefficient. Ni and Cd were found to be the main components of the cumulative ecological risk as suggested by the PER values (Table 6). Based on the summed PER values across the 16 sampling locations, Ni contributed approximately 30.5% of the total PER, followed by Cd (27.8%), As (11.1%), Co (9.3%), Hg (7.6%), Cu (4.8%), Cr (3.6%), Pb (2.3%), Zn (1.2%), V (1.1%), and Fe (0.6%). Therefore, the cumulative ecological risk came out to be about 58.3% for Ni and Cd. The relatively higher contribution of Cd was related to its higher PER values at certain locations such as S6 (Cd PER value = 118.67) and S13 (Cd PER value = 133.66).

The PER for each element of the risk assessment varied significantly between the sampling locations, with the sum of all 11 elements (the risk index, RI) ranging widely (Table 6; Figure 4). The calculated RI values ranged from 76.55 at S14 to 279.18 at S13. Fifteen of the 16 sampling sites (93.7%) were rated as low ecological risk (RI < 150), while three sites (18.6%) were rated as moderate ecological risk (150 ≤ RI < 300). The moderate-risk locations were S6 (RI = 231.44), S10 (RI = 168.60), and S13 (RI = 279.18). None of the sampling locations were in the very high-risk (RI ≥ 600) or considerable-risk (300 ≤ RI < 600) categories. The results of the RI experiment, as shown in Figure 4, indicated that the best results were obtained at S13, S6, and S10, while the lowest results were obtained at S14. The remaining sites had relatively similar low-risk RI values ranging from 76.55 to 147.40. The spatial variation of the composition of the RI was also found among sampling locations. The consistently higher PER values for Ni indicated it was the biggest individual contributor to ecological risk for most sites. At S6 and S13, however, Cd was the dominant contributor, with a PER of 118.67 and 133.66, respectively. Cd also had a substantial contribution to the overall RI and a PER of 62.93 at S16. In part, these localized Cd elevations are responsible for the increased RI values at these sites. In general, the RI results showed that the ecological risk in the soils analysed was mainly low, with moderate risk found at only three sampling sites.

An index of soil pollution (SPI) was calculated based on measured concentrations against the adopted permissible limits for soil to give additional information on soil contamination (Table 6). Only the element nickel had SPI values above 1 at all 16 sample stations. Its ranges of SPI were from 1.49 at S3 through 6.00 at S10 with an average value of about 2.91. In addition, 11 sample sites had moderate Ni contamination (1 < SPI ≤ 3), while 5 sites (31.3%) had high Ni contamination (SPI > 3). The highest Ni SPI was recorded at S10 (6.00), followed by S8 (3.93), S13 (3.72), S11 (3.52), and S12 (3.49). In the case of Vanadium (V), the SPI values were also found to be higher when compared to the adopted permissible limit. The mean SPI was around 1.29, while 15 of the 16 sampling sites (93.8%) had SPI values above 1. The highest V SPI was observed at S13 (2.10), followed by S10 (1.50). The average SPI for chromium (Cr) was near the contamination threshold, with several sampling locations having an SPI greater than 1. The highest Cr SPI was recorded at S10 (1.84), followed by S13 (1.45), S12 (1.20), S8 (1.19), and S11 (1.17). SPI values for the rest of the elements were generally below 1. The mean SPI values were approximately 0.31 for Cu, 0.26 for Pb, 0.33 for Zn, 0.40 for Co, 0.60 for Fe, 0.34 for As, 0.61 for Cd, and 0.02 for Hg. However, a few isolated exceedances were noted. Cadmium had SPI values greater than 1 at S6 (1.98), S13 (2.23), and S16 (1.05), while Zn exceeded an SPI of 1 only at S6 (1.61). The results showed that overall SPI of these elements was below the contamination level at most sites; however, the SPI at individual sites was above the element-specific permissible levels.

Overall, the results of the three tests, QoC, PERI/RI and SPI, give complementary information regarding the contamination status of the soil(s) investigated. The consistency of the elevation was shown in Ni, as it had all the positive QoC values at all the sampling points, the maximum cumulative contribution to the ecological risk, and the highest SPI values at all the sampling sites. The other metals, Cr and Co, had consistently positive QoC values, but their contributions to total ecological risk were much lower than that of Ni. Cd was a significant ecological-risk factor at S6 and S13, where its PER values were significantly above normal. The values for vanadium had a contrasting distribution with mainly negative QoC values, but the SPI values were higher than 1 in most places, due to the difference between the natural background concentrations and the adopted permissible limits. Thus, the background-based and permissible-limit-based indices together

Table 7. Quantification of contamination, QoC (%), potential ecological risk index, PERI, and soil pollution index, SPI of heavy metals in oil refinery-polluted soils

HM	Cu	Pb	Zn	Ni	Co	Fe	As	Cd	V	Cr	Hg
Quantification of contamination, QoC (%)											
S1	53.42	-60.12	55.69	85.14	56.00	-45.09	-9.42	-78.76	-21.75	52.38	-160.87
S2	14.85	-129.60	-2.18	85.74	60.16	-40.35	27.62	16.58	-52.71	54.84	-150.00
S3	1.28	-272.42	-40.50	75.78	38.40	-104.08	21.58	-150.27	-66.84	33.05	-130.77
S4	-9.43	-120.31	-5.72	83.42	45.89	-70.94	27.62	-85.38	-60.89	43.41	-1100.00
S5	-13.09	-156.68	-38.08	83.00	50.26	-79.37	27.62	-47.22	-66.84	35.12	-900.00
S6	49.48	55.38	86.76	84.88	53.97	-25.00	39.68	74.72	-55.34	52.06	-130.77
S7	25.20	-86.49	28.97	87.54	62.22	-19.76	34.65	-28.34	-36.51	59.38	-215.79
S8	22.35	-117.62	0.67	90.84	64.41	-33.02	27.62	-13.76	-47.70	64.82	-900.00
S9	17.97	-91.78	27.28	86.48	59.14	-32.93	38.09	-25.13	-43.01	55.60	-757.14
S10	33.08	-135.43	12.11	94.00	73.04	-5.26	22.87	-43.01	-20.13	77.22	-275.00
S11	20.09	-97.37	10.77	89.78	67.71	-18.69	32.79	-25.13	-25.13	64.16	-328.57
S12	20.52	-120.11	15.48	89.67	62.75	-19.40	35.55	19.27	-25.13	64.90	-1100.00
S13	40.79	9.39	24.63	90.33	68.72	7.62	57.61	77.55	14.19	70.96	-39.53
S14	-40.60	-147.79	-8.77	81.63	46.25	-53.26	26.48	-317.11	-104.76	35.61	-400.00
S15	-22.98	-99.57	0.98	84.98	55.51	-27.80	38.09	-212.83	-73.26	43.72	-1100.00
S16	7.89	-109.60	-1.21	87.42	58.72	-33.16	26.48	52.33	-38.61	57.31	-1100.00
Potential ecological risk index, PERI											
S1	10.73	3.12	2.26	33.66	11.36	0.69	9.14	16.78	1.64	4.20	15.33
S2	5.87	2.18	0.98	35.07	12.55	0.71	13.82	35.96	1.31	4.43	16.00
S3	5.06	1.34	0.71	20.64	8.12	0.49	12.75	11.99	1.20	2.99	17.33
S4	4.57	2.27	0.95	30.16	9.24	0.59	13.82	16.18	1.24	3.53	3.33
S5	4.42	1.95	0.72	29.41	10.05	0.56	13.82	20.38	1.20	3.08	4.00
S6	9.90	11.21	7.55	33.08	10.86	0.80	16.58	118.67	1.29	4.17	17.33
S7	6.68	2.68	1.41	40.12	13.24	0.84	15.30	23.38	1.47	4.92	12.67
S8	6.44	2.30	1.01	54.61	14.05	0.75	13.82	26.37	1.35	5.68	4.00
S9	6.10	2.61	1.38	36.99	12.24	0.75	16.15	23.97	1.40	4.50	4.67
S10	7.47	2.12	1.14	83.33	18.54	0.95	12.96	20.98	1.66	8.78	10.67
S11	6.26	2.53	1.12	48.92	15.48	0.84	14.88	23.97	1.60	5.58	9.33
S12	6.29	2.27	1.18	48.42	13.42	0.84	15.52	37.16	1.60	5.70	3.33
S13	8.44	5.52	1.33	51.69	15.98	1.08	23.59	133.66	2.33	6.89	28.67
S14	3.56	2.02	0.92	27.22	9.30	0.65	13.60	7.19	0.98	3.11	8.00
S15	4.07	2.51	1.01	33.30	11.24	0.78	16.15	9.59	1.15	3.55	3.33
S16	5.43	2.39	0.99	39.74	12.11	0.75	13.60	62.93	1.44	4.69	3.33
Soil pollution index, SPI											
S1	0.54	0.26	0.48	2.42	0.36	0.55	0.21	0.28	1.48	0.88	0.02
S2	0.29	0.18	0.21	2.53	0.40	0.57	0.32	0.60	1.18	0.93	0.02
S3	0.25	0.11	0.15	1.49	0.26	0.39	0.30	0.20	1.08	0.63	0.03
S4	0.23	0.19	0.20	2.17	0.30	0.47	0.32	0.27	1.12	0.74	0.01
S5	0.22	0.16	0.15	2.12	0.32	0.45	0.32	0.34	1.08	0.65	0.01
S6	0.49	0.93	1.61	2.38	0.35	0.64	0.39	1.98	1.16	0.88	0.03
S7	0.33	0.22	0.30	2.89	0.42	0.67	0.36	0.39	1.32	1.03	0.02
S8	0.32	0.19	0.21	3.93	0.45	0.60	0.32	0.44	1.22	1.19	0.01
S9	0.30	0.22	0.29	2.66	0.39	0.60	0.38	0.40	1.26	0.95	0.01
S10	0.37	0.18	0.24	6.00	0.59	0.76	0.30	0.35	1.50	1.84	0.02

S11	0.31	0.21	0.24	3.52	0.50	0.67	0.35	0.40	1.44	1.17	0.01
S12	0.31	0.19	0.25	3.49	0.43	0.67	0.36	0.62	1.44	1.20	0.01
S13	0.42	0.46	0.28	3.72	0.51	0.87	0.55	2.23	2.10	1.45	0.04
S14	0.18	0.17	0.20	1.96	0.30	0.52	0.32	0.12	0.88	0.65	0.01
S15	0.20	0.21	0.22	2.40	0.36	0.63	0.38	0.16	1.04	0.75	0.01
S16	0.27	0.20	0.21	2.86	0.39	0.60	0.32	1.05	1.30	0.98	0.01

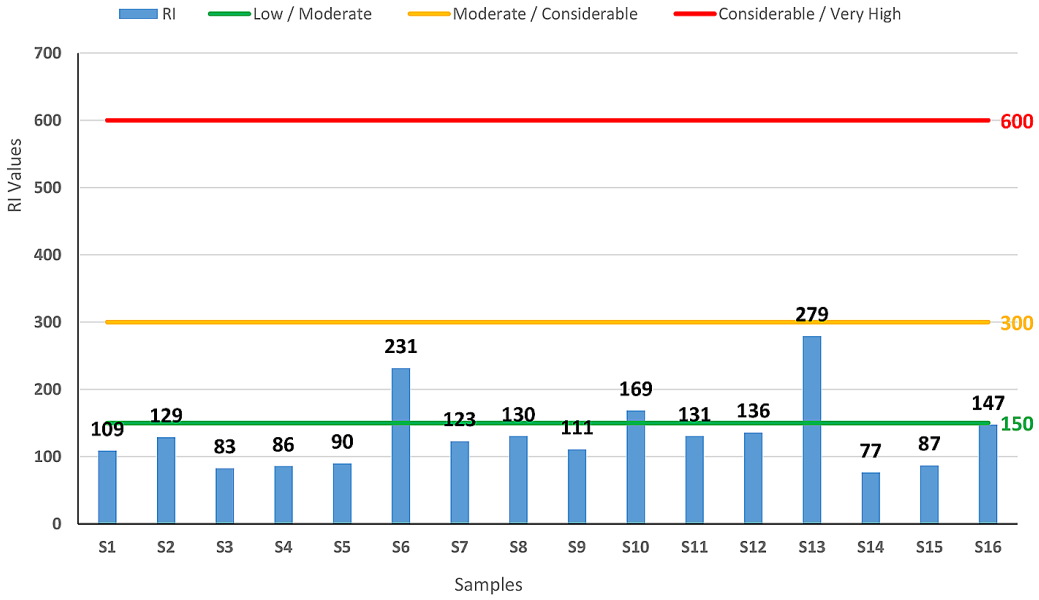

Figure 4. Risk index (RI) of heavy metals in surface soils surrounding the investigated oil refinery

can give a more complete picture of the levels of contamination in the soil due to the refinery.

CONCLUSIONS

The results show that surface soils in the KRI surrounding oil refineries and other industrial operations are contaminated with trace and heavy metals to varied degrees. With positive QoC values at all 16 sampling sites, nickel (Ni) was the most consistently increased element, followed by Cr and Co. QoC values were positive at 94% of the sites. S6, S10, and S13 had the greatest overall levels of contamination, while the degree of contamination and pollution load index showed significant contamination and moderate pollution at 69% of the sampling locations, respectively. Additionally, the combined potential ecological danger of Ni and Cd was about 58.3%. Although contamination levels varied spatially among test locations, Ni was consistently recognized as the primary element of concern by the various pollution indices.

It is consequently advised to regularly inspect potentially hazardous elements near petroleum and industrial locations. Priority should also be given to establishing regional soil-background concentrations and suitable soil-quality standards. To differentiate between anthropogenic pollution sources and natural geological contributions, future research should employ source-apportionment approaches and uncontaminated reference locations. These actions would assist environmental authorities in creating suitable strategies for remediation and pollution control.

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