Environmental Resources Research (ERR)
Print ISSN: 2783-4832
Online ISSN: 2783-4670

# Spatial variability and ecological risk assessment of heavy metal contamination in southeastern Iran

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**Article Info**

**Article type:**
Research Article

**Article history:**
Received: November 2024
Accepted: December 2024

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**Keywords**:
Soil contamination
Enrichment factor
Potential ecological risk
Pollution source
Soil degradation

**Abstract**

Assessing heavy metal risk is essential for protecting public health and preserving environmental quality and sustainable development. This study focused on spatial distribution and contamination levels of seven major heavy metals (HMs) including lead (Pb), zinc (Zn), cadmium (Cd), iron (Fe), manganese (Mn), arsenic (As), and copper (Cu), in Jiroft, a city in southeastern Iran. The diethylene triamine Penta acetic acid method was applied for the determination of heavy metals concentrations after the collection of surface soil samples. Inverse distance weighting was performed for mapping the spatial distribution. Potential ecological risk index and principal component analysis were carried out to identify the risk level and the primary source of heavy metals, respectively. Mean concentrations of all the heavy metals were higher compared to their mean crustal values. Zinc and manganese were considered the major pollutants due to high enrichment factor and pollution index. More than 45% of the soil samples presented noticeable ecological risk according to the calculated potential ecological risk index values, which ranged between 80 and 160. The highest value corresponded to cadmium (Ei=103.9). Principal component analysis suggested that anthropogenic and natural factors were responsible for heavy metal accumulation in soil. These results show the urgent need for an intervention targeted at soil pollution to protect the environment and public health in Jiroft.

**Cite this article:** Mosavi, Seyedeh Tayebeh; Parsa-Motlagh, Bahare; Ebrahimi-Khusfi, Zohre. 2025. Spatial variability and ecological risk assessment of heavy metal contamination in southeastern Iran. *Environmental Resources Research*, 13(1), 61-81.


DOI: 10.22069/ijerr.2025.22932.1454
Publisher: Gorgan University of Agricultural Sciences and Natural Resources

## Introduction

Soil degradation primarily results from the accumulation of heavy metals, influenced by both natural and anthropogenic sources (Krami et al., 2013; Zhang and Wang, 2020; Zheng et al., 2023). Geology-formation is considered an important natural factor influencing the distribution of heavy metals and soil pollution (Negahban et al., 2021). Some heavy metals (HMs), including lead, cadmium, and arsenic, are usually released by such activities as erosion, volcanic activity, and movement of groundwater, thus contaminating soil and food products. Moreover, human activities like mining (Arefi Ardakani et al., 2023; Hosseinniaee et al., 2023), land use changes (Korkanç et al., 2024), and misuse of fertilizers increase the level of HMs in soil (Faraji et al., 2023). This accumulation reduces soil quality and threatens food security and human health (Anani et al., 2020; Sweta and Singh, 2024; Zhou et al., 2024).

Heavy metal pollution in Iran poses a serious threat to public health, agriculture, and economic productivity, exacerbated by significant socio-economic challenges (Moradi et al., 2016; Taghavi et al., 2024). Soil and water contamination with heavy metals such as lead, cadmium, and mercury cause numerous health problems, including neurological disorders and chronic diseases (Juozulynas et al., 2008; Papadimou et al., 2023; Taghavi et al., 2024), thereby increasing the cost of healthcare while diminishing productivity among the workforce. Heavy metal accumulation also lowers crop yield and quality in agricultural land, which in turn increases food insecurity and economic loss among farmers (Jahandari and Abbasnejad, 2023). These long-term deteriorations have, over time, exacerbated the issues and further hindered the attainment of sustainable development within the region. Therefore, there is a great need for the continued monitoring and gathering of information about the changes in various regions.

A number of studies has been implemented in Iran over the last two decades, which, in essence, has focused on ecological risk assessment and the identification of the main sources of pollution. For example, Sabet Aghlidi et al. (2020) investigated the levels of arsenic, cadmium, chromium, copper, lead, and zinc in agricultural soils in Eghlid County, southern Iran, with the aim of assessing the soil pollution, the potential ecological risk index, and the spatial distribution of these elements. In the above study, concentration for cadmium was above the background values, while arsenic and copper were comparable to background levels. They reported that cadmium had anthropogenic sources, while other elements were from natural origins. The values of PI were variable showing that 65% of the soil samples were moderately contaminated, while 35% were little contaminated.

Hamid et al. (2022) calculated the potential ecological risk (PER) of heavy metals such as zinc, copper, cobalt, molybdenum, manganese, and selenium in the coastal soils of southwest Iran. The results indicated that these metals posed a low ecological risk. The risk index (RI) ranged from 1.296 to 3.845, confirming a poor-risk classification. Most of the metal contamination was attributed to agricultural activities and industrial processes, while some originated from human activities. However, manganese appeared to have a natural origin, likely due to geological sources.

Ghaneei-Bafghi et al. (2024) examined soil pollution in villages surrounding a mining area in Bafaq, Yazd province, specifically Sayyed Abad and Koushk. Their findings revealed that agricultural soils were significantly more contaminated than pasture soils. The variation in contamination levels was primarily attributed to the geochemical characteristics of parent materials, although agricultural management practices also played a major role.

Soltani-Gerdefaramarzi et al. (2021) investigated the contributions of geogenic and anthropogenic sources to soil pollution in Yazd, Iran. The study found that elements such as arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn) were primarily linked to human activities. In contrast, elements like iron (Fe), manganese (Mn), nickel (Ni), chromium (Cr), cobalt (Co), copper (Cu), and cesium (Cs) were of natural origin. While significant enrichment was observed for As, Cd, and Pb, the ecological risk was low for most metals—moderate for Pb and high for As and Cd.

Mahvi et al. (2022) assessed heavy metal pollution in urban soils under various land uses in Kerman, Iran, using multiple ecological risk indices. The highest pollution levels for Cd and modified contamination degree (mCd) were found at the new terminal, with values of 26.8 and 3.35, respectively, indicating severe contamination. The ecological risk factor (Er) showed a high risk for mercury (Hg) and a moderate risk for Cd. The calculated RI values were 1632.7 for Hg, 536.02 for Cd, and 180.64 for Pb, each reflecting varying levels of ecological risk in the region.

Jiroft is a major agricultural region in Iran where heavy metal pollution can affect crop safety and reduce farmers' income. Continuous monitoring and risk assessment are essential to improve agricultural practices and minimize economic losses. Since no prior study has been conducted in this context, the present study addresses this gap. The primary objectives are:

1. To map the spatial distribution of seven heavy metals—Pb, Zn, Cd, Fe, Mn, As, and Cu—in Jiroft city, southeastern Iran.
2. To assess pollution levels using the single-element enrichment factor and the multi-element mean soil pollution factor index.
3. To analyze the influence of both natural and anthropogenic factors on heavy metal contamination in the study area.

## Materials and methods

### *Study area*

The study area is Jiroft city in the south of Kerman province. This area extends from 57°36′15″ to 57°53′45″ east longitude and from 28°35′00″ to 28◦45′35″ north latitude . The geological formations in the study area are associated with the Quaternary period (Fig 1). The elevation in this area ranges from 623 to 926 meters. According to statistics from the Jiroft synoptic station in 2021, the average temperature and rainfall were 27.4 degrees Celsius and 185 mm, respectively (Statistical yearbook of Kerman province, 2021). The maximum wind speed recorded is 13 meters per second from the south Jiroft city is bordered to the north, northeast, and east by the heights of Jabalbarz and Delfard, while to the south it leads to the Jiroft plain. The region has a cold mountainous climate and semi-temperate foothills in the northern highlands, transitioning to warm and semi-humid conditions in the plains.

### *Soil sampling and laboratory analysis*

We provided 40 surface soil samples (0-10 cm) from Jiroft, as well as several samples from areas distant from human activities to establish background element levels in the soil. In the laboratory, 10 grams of each soil sample was placed in a 125 ml Erlenmeyer flask. Then, 20 ml of DTPA (diethylene triamine Penta acetic acid) solution was added, and the container was sealed. To prepare the DTPA solution, 0.05 mol of DTPA ($C_{14}H_{23}N_3O_{10}$), 0.01 mol of calcium chloride, 0.1 mol of triethanolamine (TEA), along with 149.2 grams of pure triethanolamine, 19.6 grams of DTPA, and 17.4 grams of calcium chloride ($CaCl_2 \cdot 2H_2O$) were dissolved in 200 ml of distilled water. This mixture was shaken for two hours, then filtered through Whatman 42 filter paper. The resulting extracts were analyzed for concentrations of zinc, iron, manganese, copper, cadmium, and nickel using atomic spectrometry. The DTPA method was employed to determine the extractable amounts of Zn, Mn, Fe, Cu, Ni, and Cd in the soil. In this method, DTPA forms stable chelates with iron, manganese, zinc, and copper, while also chelating nickel and cadmium, allowing for the assessment of heavy metals in the extracts.

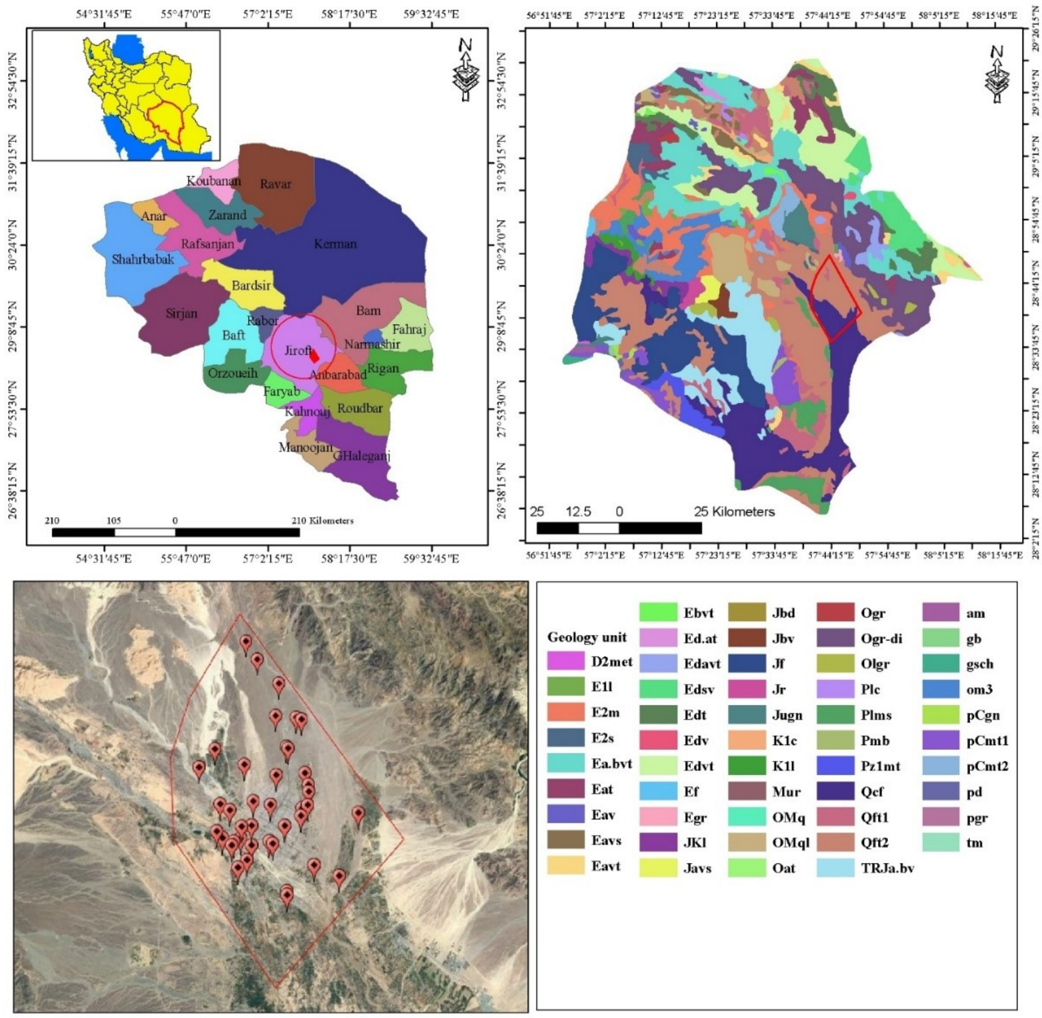


**Figure 1.** Study area in Iran (top left), geology (top right) and sampling locations.

***Heavy metals mapping***

We employed the inverse distance weighting (IDW) technique to create maps illustrating spatial variations in the study area. It is important to note that the semi variogram, which is developed through the Ordinary Kriging (OK) interpolation method, tends to be influenced by subjective choices and necessitates a significantly larger quantity of soil samples for its construction. In contrast, the Inverse Distance Weighting (IDW) method is a more appropriate and effective option for the spatial prediction of heavy metal contamination in soil environments. Therefore, when assessing the levels of heavy metal pollution in soils, IDW proves to be a more practical alternative due to its minimal requirements and less subjective nature (Al Hamdani et al., 2024; Qiao et al., 2018). Also, IDW has been widely used in previous research (Bux et al., 2023; Hazarika et al., 2024); accordingly this method was used in the present study and the maps were generated using concentration data from all sampling sites in ArcGIS 10.8 software. The resulting heavy metal maps were reclassified to enhance the understanding of contamination patterns linked to these metals.

***Pollution Assessment and Ecological Risk***

We used the Enrichment Factor (EF) to evaluate heavy metal contamination in the study area. The single-element index, Ei, assessed ecological risk for all heavy metals, while the multi-element index, MSPF, examined contamination levels across all sampling sites. Additionally, the Potential Ecological Risk Index (PERI) was calculated for sampling sites and the entire study area. The calculations for these indicators are detailed below.

***Enrichment factor (EF)***

The evaluation of the EF reflects the degree of metal contamination in soil, serving as an effective means to differentiate between natural and anthropogenic sources of metals. To compute the metal EF, both the normalized metal value and the background value for each metal must be established(Adamo et al., 2005). The EF for each metal was calculated using the ratio of the normalized element to its background value. EF values <1 indicate natural (crustal) origins, values >10 suggest anthropogenic sources, and values between 1 to 10 reflect a combination of both (Wang et al., 2015; Zhao et al., 2021). This method compares the concentration of a study metal to a reference metal, such as Al, Fe, Mn, Si, or Ti.

Previous studies have mostly employed iron (Hamid et al., 2022) and aluminum (Shirani et al., 2020), which exhibit minimal human impact, as normalizers. In this paper, iron was used to distinguish the human contribution from the natural background, and the EF was computed by the following equation:

$$EF = \frac{(C_e/Fe)_{Soil}}{(C_e/Fe)_{Background}} \quad (1)$$

In Eq (1), $(Ce/Fe)_{soil}$ refers to the concentration ratio of the studied metal to Fe in the soil samples, while $(Ce/Fe)_{Background}$ indicates their ratio in the earth's crust. The EF values categorize the pollution level of each soil sample into one of the classes presented in Table (1).

**Table 1.** Soil pollution level based on enrichment factor (EF) values (Shirani et al., 2020).

| EF value | Soil pollution level |
|---|---|
| EF<2 | Low |
| 2≤EF<5 | Moderate |
| 5≤EF<20 | High |
| 20≤EF<40 | Very high |
| EF≥40 | Extremely |

***Mean of soil pollution factor (MSPF)***

We not only assessed the pollution level from each heavy metal using the Enrichment Factor (EF) but also evaluated soil pollution due to the accumulation of various heavy metals via a multi-element indicator, the Mean Soil Pollution Factor (MSPF), expressed as Equation 2 (Shirani et al., 2020).

$$MSPF = \frac{\sum_{i=1}^{n}(C_{e(soil)}/C_{e(background)})_i}{n} = \frac{\sum_{i-1}^{n} PF}{n} \quad (2)$$

Here, PF (pollution factor) is the ratio of the heavy metal concentration in the soil sample ($Ce_{(soil)}$) to its concentration in the Earth's crust ($Ce_{(background)}$), with n representing the number of heavy metals. Based on MSPF values, soil pollution levels can be classified into seven categories, as shown in Table 2.

**Table 2.** Soil pollution level based on mean of soil pollution factor (MSPF)(Shirani et al., 2020)

| MSPF | Soil pollution level |
|---|---|
| <1.5 | Very low |
| 1.5-2 | Low |
| 2-4 | Moderate |
| 4-8 | High |
| 8-16 | Very high |
| 16-32 | Extremely high |
| ≥32 | Ultra-high |

***Potential ecological risk assessment***

We used specific relationships to evaluate the potential ecological risk (PER) of soils in Jiroft city. The potential ecological risk index (PERI) is commonly used to assess the PER of heavy metals globally (Hadzi et al., 2024; Zhou et al., 2023).

$$PERI = \sum_{i=1}^{n} E_i \quad (3)$$

$$Ei = \frac{C_{e(se\dim ent)}}{C_{e(background)}} \times T_c = Cf \times T_c \quad (4)$$

In the context of these relationships, Ei specifically refers to the Potential Ecological Risk (PER) associated with the $i^{th}$ heavy metal. Meanwhile, Tr represents the toxic-response factor for each respective heavy metal (HM), which takes into consideration both the necessary toxic requirements as well as the sensitivity requirements that need to be assessed. The values for Tr vary depending on the specific heavy metal, and they are assigned as follows: for arsenic (As), the factor is equal to 10; for cadmium (Cd), it is set at 30; for chromium (Cr), the value is 2; for copper (Cu), the value is 5; for lead (Pb), it is also 5; and finally, for zinc (Zn), the toxic-response factor is designated as 1(Hakanson, 1980; ZHU et al., 2012). These distinct factors play a crucial role in evaluating the ecological risks posed by these heavy metals. Based on PERI values, risk ecological levels can be classified into five categories, as shown in Table 3.

**Table 3.** Ecological risk levels using potential ecological risk index values (Hadzi et al., 2024)

| PERI value | Ecological risk |
|---|---|
| ≤40 | Low |
| 40-80 | Moderate |
| 80-160 | Considerable |
| 160-320 | High |
| >320 | Very high |

### *Heavy metals source identification*

The correlation analysis is an effective and valuable technique employed for identifying the associations and relationships among various variables, as noted by Gogtay and Thatte (2017). By utilizing correlation analysis, researchers can observe how different factors interact and influence one another, which is crucial for gaining insights into complex data sets. In addition to correlation analysis, the principal component analysis (PCA) stands out as another highly useful technique. Principal components are linear combinations of original variables that best explain their variance, allowing for an approximate representation of the data using just these key components (Greenacre et al., 2022). PCA is particularly adept at separating highly correlated heavy metals (HMs) into distinct groups. This methodological approach allows researchers to analyze and discern patterns within the data, ultimately aiding in the identification of the possible sources or origins of these HMs, as detailed by Hoshyari et al. (2023). In light of these considerations, the present study employed both of the aforementioned analytical methods to explore and uncover the correlations between the heavy metals and to determine their potential origins. The analyses carried out in this study were conducted using SPSS version 20 and R software version 4.0.3. Through these analyses, we aimed to contribute valuable findings to the understanding of heavy metal associations and their sources.

## Results

### *Heavy metals mapping*

The spatial variation pattern of heavy metal concentration within the study area is illustrated in Figure (2). From the results obtained, it can be observed that the concentration levels of arsenic are significantly higher in the eastern half of the studied area, whereas the concentration of zinc is notably elevated in the central regions when compared to other parts of the study area. Additionally, it is evident that the concentration levels of other heavy metal elements show a trend whereby they are greater in the southern regions, in contrast to the northern areas of Jiroft city, where these concentrations are comparatively lower. This spatial distribution underscores the variability in heavy metal presence throughout the different sections of the study area.

Table (4) shows the descriptive characteristics of heavy metals in the study area compared to the background values of the earth's crust. According to the findings, iron exhibits the most significant range of concentration variations (0.46-30.18mg/kg), followed by magnesium (0.12-17.98 mg/kg) and zinc (0-4.98 mg/kg). Conversely, cadmium (0-0.04 mg/kg), and arsenic (0.2-1.02 mg/kg) show the smallest range of concentration changes. The mean concentration of Fe and Mn exceeds 3.5 mg/kg, while the remaining elements have concentrations below 0.7 mg/kg. This indicates a notable distinction in the average concentrations of Fe and Mn compared to the other heavy metals in the soil samples of the study area.

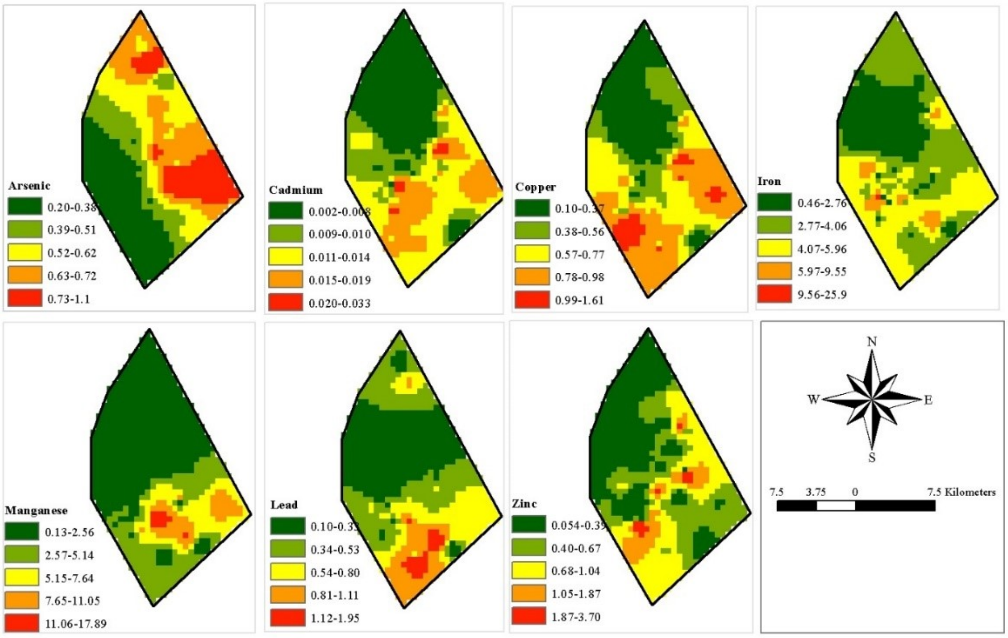


**Figure 2.** Spatial distribution of heavy metal concentrations in the study area (mg/kg).

**Table 4.** Descriptive statistics of heavy metals concentrations in the study area

| Heavy metals (mg/kg) | min | max | mean | SD | CV | Background value |
|---|---|---|---|---|---|---|
| Zn | 0.05 | 4.98 | 0.66 | 1.09 | 0.61 | 0.04 |
| Mn | 0.12 | 17.98 | 3.61 | 4.60 | 0.79 | 0.27 |
| Fe | 0.46 | 30.18 | 4.08 | 4.96 | 0.82 | 1.17 |
| Cd | 0.00 | 0.04 | 0.01 | 0.01 | 1.51 | 0.003 |
| Cu | 0.11 | 1.66 | 0.65 | 0.41 | 1.58 | 0.37 |
| Pb | 0.10 | 2.17 | 0.48 | 0.42 | 1.16 | 0.19 |
| As | 0.20 | 1.02 | 0.51 | 0.23 | 2.18 | 0.2 |

***Pollution assessment using EF***

In our comprehensive study, the EF was employed as a single-element index, while the MSPF was utilized as a multi-element index to thoroughly assess and evaluate the level of pollution within the area, particularly focusing on various heavy elements present in the environment. The EF values calculated for all of the heavy metals under investigation in regard to all sampling sites throughout Jiroft city are detailed in Table (5). As seen in this table, each sample is associated with multiple heavy metals, indicating varying levels of pollution. Some of the highest levels were observed in Zinc and Manganese, especially in samples 5, 20, and 14. Moderate pollution is seen in Arsenic, Cadmium, and Manganese across a number of samples, indicating areas that should be monitored further. While most samples have low levels for most metals, the significant numbers of high readings for Zinc and Manganese suggest possible sources of pollution that may require further investigation.

Arsenic pollution is predominantly low, with a small portion at moderate levels. Similar to arsenic, cadmium levels are mostly low, with a notable moderate presence. Copper pollution is primarily low, with very few instances of moderate levels. Lead levels are also mostly low, with a small percentage at moderate levels. Zinc shows a more varied distribution, with significant portions in moderate, high, and very high categories. Manganese has a more concerning profile, with a considerable percentage in high levels and a small portion in very high levels (Table 6). Generally, most heavy metals in the study area show low pollution levels, with zinc and manganese being exceptions, indicating potential environmental concerns that may require further investigation or action.

**Table 5.** Enrichment factors and pollution levels for heavy metals at sampling sites

| Samples | As | Cd | Cu | Pb | Zn | Mn |
|---|---|---|---|---|---|---|
| 1 | 0.26(Low) | 0.42(Low) | 0.27(Low) | 0.96(Low) | 1.47(Low) | 5.14(High) |
| 2 | 1.2(Low) | 2.27(Moderate) | 2.1(Moderate) | 2.83(Moderate) | 1.61(Low) | 5.9(High) |
| 3 | 0.56(Low) | 0.43(Low) | 0.29(Low) | 0.59(Low) | 10.13(High) | 5.91(High) |
| 4 | 0.76(Low) | 1.88(Low) | 1.33(Low) | 0.84(Low) | 0.71(Low) | 5.8(High) |
| 5 | 0.33(Low) | 1.73(Low) | 0.98(Low) | 0.57(Low) | 30.03 | 9.33(High) |
| 6 | 0.81(Low) | 1.56(Low) | 2.33(Moderate) | 0.67(Low) | 7.01(High) | 1.43(Low) |
| 7 | 0.05(Low) | 0.15(Low) | 0.07(Low) | 0.12(Low) | 0.34(Low) | 0.08(Low) |
| 8 | 0.76(Low) | 0.97(Low) | 0.33(Low) | 0.49(Low) | 1.17(Low) | 1.09(Low) |
| 9 | 0.91(Low) | 0.94(Low) | 0.65(Low) | 0.94(Low) | 1.7(Low) | 8.38(High) |
| 10 | 0.65(Low) | 1.39(Low) | 0.91(Low) | 1.41(Low) | 2.64(Moderate) | 2.92(Low) |
| 11 | 1.62(Low) | 2.2(Moderate) | 2.19(Moderate) | 1.44(Low) | 4.56(Moderate) | 16.73(High) |
| 12 | 0.78(Low) | 4.62(Moderate) | 0.39(Low) | 1.63(Low) | 1.26(Low) | 12.45(High) |
| 13 | 0.31(Low) | 0.44(Low) | 0.19(Low) | 0.5(Low) | 3.26(Moderate) | 6.48(High) |
| 14 | 0.62(Low) | 1.64(Low) | 0.84(Low) | 2.51(Moderate) | 8.92(High) | 25.16(Very high) |
| 15 | 1.57(Low) | 2.16(Moderate) | 0.51(Low) | 1.48(Low) | 4.85(Moderate) | 14.04(high) |
| 16 | 4.48(Moderate) | 2.98(Moderate) | 1.88(Low) | 1.73(Low) | 2.56(Moderate) | 4.15(Moderate) |
| 17 | 1.2(Low) | 0.66(Low) | 0.52(Low) | 0.59(Low) | 0.48(Low) | 9.29(High) |
| 18 | 2.95(Moderate) | 2.77(Moderate) | 0.87(Low) | 1.12(Low) | 4.51(Moderate) | 3.81(Moderate) |
| 19 | 0.79(Low) | 0.43(Low) | 0.71(Low) | 0.76(Low) | 2.97(Moderate) | 3.38(Moderate) |
| 20 | 0.96(Low) | 1.02(Low) | 0.63(Low) | 0.5(Low) | 33.58(Very high) | 6.55(High) |
| 21 | 1.11(Low) | 2.72(Moderate) | 1.4(Low) | 0.56(Low) | 2.19(Moderate) | 0.92(Low) |
| 22 | 1.53(Low) | 0.84(Low) | 0.49(Low) | 0.69(Low) | 1.83(Low) | 1.97(Low) |
| 23 | 1.74(Low) | 0.63(Low) | 0.29(Low) | 0.53(Low) | 38.59(Very high) | 1.77(Low) |
| 24 | 0.37(Low) | 0.64(Low) | 0.37(Low) | 0.17(Low) | 0.24(Low) | 0.48(Low) |
| 25 | 0.88(Low) | 0.92(Low) | 0.54(Low) | 1(Low) | 8.51(High) | 2.78(Moderate) |
| 26 | 1.1(Low) | 0.55(Low) | 0.16(Low) | 0.45(Low) | 1(Low) | 2.67(Moderate) |
| 27 | 1.54(Low) | 0.6(Low) | 0.35(Low) | 1.45(Low) | 0.73(Low) | 0.83(Low) |
| 28 | 3.71(Moderate) | 0.51(Low) | 0.44(Low) | 0.99(Low) | 1.64(Low) | 2.27(Moderate) |
| 29 | 1.92(Low) | 0.59(Low) | 0.24(Low) | 0.52(Low) | 1.34(Low) | 1.59(Low) |
| 30 | 2.68(Moderate) | 0.99(Low) | 0.42(Low) | 0.72(Low) | 2.17(Moderate) | 1.32(Low) |
| 31 | 0.19(Low) | 0.24(Low) | 0.25(Low) | 0.1(Low) | 2.53(Moderate) | 0.47(Low) |
| 32 | 0.84(Low) | 2.93(Moderate) | 1.76(Low) | 1.45(Low) | 4.27(Moderate) | 1.98(Low) |
| 33 | 0.96(Low) | 1.4(Low) | 1.62(Low) | 0.55(Low) | 2.74(Moderate) | 1.32(Low) |
| 34 | 0.36(Low) | 1.31(Low) | 0.89(Low) | 3.26(Moderate) | 5.62(High) | 1.7(Low) |
| 35 | 1.09(Low) | 1.97(Low) | 1.18(Low) | 1.69(Low) | 8.45(High) | 1.42(Low) |
| 36 | 0.48(Low) | 0.4(Low) | 0.27(Low) | 0.47(Low) | 1.46(Low) | 0.6(Low) |
| 37 | 0.84(Low) | 0.57(Low) | 0.3(Low) | 0.49(Low) | 3.08(Moderate) | 1.33(Low) |
| 38 | 4.67(Moderate) | 3.82(Moderate) | 1.48(Low) | 3.22(Moderate) | 6.59(High) | 12.02(High) |
| 39 | 1.87(Low) | 1.36(Low) | 0.3(Low) | 0.81(Low) | 3.5(Moderate) | 3.54(Moderate) |
| 40 | 2.56(Moderate) | 0.61(Low) | 0.23(Low) | 0.43(Low) | 1(Low) | 0.36(Low) |
| **Mean** | **1.30(Low)** | **1.36(Low)** | **0.77(Low)** | **1.03(Low)** | **5.53(High)** | **4.7(Moderate)** |

Based on the results of the analysis, we found that the average values of the EF for the heavy metals in the study area exhibit a clear hierarchy based on their pollution levels. Specifically, the EF values for Zinc (Zn) are recorded at 5.53, followed by Manganese (Mn) at 4.73, Cadmium (Cd) at 1.36, Arsenic (As) at 1.30, Lead (Pb) at 1.03, and finally Copper (Cu) at 0.77, indicating a downward trend in pollution levels. In light of these findings, it can be concluded that Zn demonstrates a significantly high level of pollution, categorizing it as a pollutant of great concern. In contrast, Mn is identified as having a medium pollution level, thus requiring attention but not as urgent as that for Zinc. On the other hand, Cadmium, Arsenic, Lead, and Copper metals are classified under a low pollution category, which is illustrated in Table 7, highlighting their comparatively lesser impact on the overall pollution level in the area.

The spatial changes of pollution based on the enrichment factor are shown in the figure (3) that shows a predominance of low to moderate levels of arsenic across most areas, with a few spots indicating higher concentrations. The presence of agricultural land and urban areas suggests that these regions may be contributing to arsenic levels. Cadmium levels are mostly low, with some moderate concentrations scattered throughout the map. Similar to arsenic, agricultural and urban areas are present, indicating potential sources of cadmium pollution. The figure indicates predominantly low levels of copper, with only a few areas showing moderate levels. The presence of industrial areas may suggest localized sources of copper pollution. Manganese shows a more varied distribution, with several areas indicating high levels, particularly in the central part of the map. The presence of industrial areas and urban zones correlates with higher manganese levels, suggesting industrial activities may be a significant source. Lead levels are mostly low, with some moderate concentrations in specific areas. Urban areas and roads are present, which may contribute to lead pollution. Zinc shows a significant range, with several areas indicating very high levels, particularly in the southern part of the map. Industrial areas are prominently associated with high zinc levels, indicating potential pollution sources.

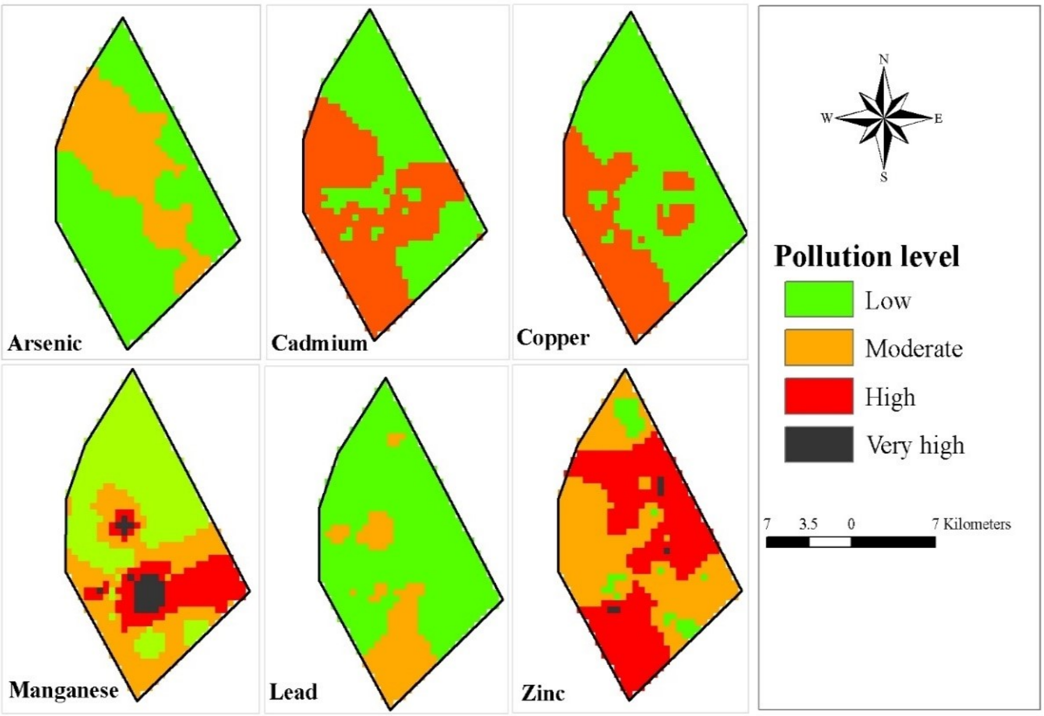


**Figure 3.** Heavy metal pollution levels in the study area based on enrichment factors.

***Pollution assessment using MSPF***

We used the multi-element index MSPF to assess soil pollution levels across all sites. This index was derived from the Cf values of all heavy metals at each sampling location, with results presented in Table 8. The table consists of 40 samples, each containing measurements of various heavy metals (Fe, As, Cd, Cu, Pb, Zn, MN) along with a corresponding pollution level classification. The pollution levels range from "Very low" to "Extremely high". Sample 40 has the lowest concentrations across all metals, indicating minimal environmental impact. Sample 22 shows low concentrations, suggesting limited pollution risk. Samples like 2, 8, and 29 have moderate levels of metals, indicating a potential for environmental concern but not immediate danger. Samples such as 10, 11, and 19 exhibit higher concentrations, which could pose significant risks to health and the environment. Samples like 1, 5, and 9 show very high concentrations of multiple metals, indicating severe pollution levels. Sample 5 stands out with extremely high levels of Cd and Zn, which are particularly concerning. Sample 1 Contains high levels of multiple metals, particularly Fe (4.7), Zn (87.9), and MSPF (12.6), leading to a classification of "Very high". Sample 5 Exhibits extremely high levels of Cd (111.9) and Zn (165.2), which are critical pollutants, resulting in an "Extremely high" classification. Sample 9 Shows high concentrations of Zn (66.2) and MSPF (9.5), contributing to its "Very high" pollution level. Sample 22 With low concentrations across all metals, it is classified as "Low", indicating minimal environmental impact.

**Table 6.** Pollution levels at sampling sites throughout Jiroft city based on MSPF values.

| Samples | Pollution Factor | | | | | | | | MSPF | Pollution level |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fe | As | Cd | Cu | Pb | Zn | MN | Cd | | |
| 1 | 8.4 | 2.2 | 4 | 2.3 | 8 | 12.1 | 43 | 80 | 11.4 | Very high |
| 2 | 1.2 | 1.5 | 3.1 | 2.5 | 3.4 | 1.9 | 7.2 | 20.9 | 3 | Moderate |
| 3 | 4.7 | 2.6 | 2.3 | 1.3 | 2.7 | 46.7 | 27.5 | 87.9 | 12.6 | Very high |
| 4 | 1.7 | 1.3 | 3.7 | 2.3 | 1.5 | 1.2 | 10.1 | 21.8 | 3.1 | Moderate |
| 5 | 3.8 | 1.2 | 7.4 | 3.6 | 2.2 | 111.9 | 35.1 | 165.2 | 23.6 | Extremely high |
| 6 | 1.9 | 1.6 | 3.4 | 4.4 | 1.3 | 13.3 | 2.7 | 28.7 | 4.1 | High |
| 7 | 25.8 | 1.4 | 4.3 | 1.7 | 3.1 | 8.7 | 2.2 | 47.1 | 6.7 | High |
| 8 | 2.3 | 1.8 | 2.6 | 0.8 | 1.1 | 2.7 | 2.5 | 13.7 | 2 | Moderate |
| 9 | 4.5 | 4.1 | 4.9 | 2.9 | 4.2 | 7.6 | 37.9 | 66.2 | 9.5 | Very high |
| 10 | 2.5 | 1.6 | 4 | 2.3 | 3.6 | 6.6 | 7.4 | 28 | 4 | High |
| 11 | 1 | 1.7 | 2.6 | 2.2 | 1.5 | 4.6 | 17.1 | 30.7 | 4.4 | High |
| 12 | 2.2 | 1.7 | 11.7 | 0.9 | 3.6 | 2.8 | 27.6 | 50.5 | 7.2 | High |
| 13 | 9.6 | 2.9 | 4.9 | 1.8 | 4.9 | 31.1 | 62.4 | 117.6 | 16.8 | Extremely high |
| 14 | 2.6 | 1.6 | 4.9 | 2.1 | 6.5 | 22.9 | 65.3 | 105.9 | 15.1 | Very high |
| 15 | 2.1 | 3.3 | 5.1 | 1.1 | 3.1 | 10 | 29.2 | 53.9 | 7.7 | High |
| 16 | 1.1 | 4.9 | 3.7 | 2 | 1.9 | 2.8 | 4.5 | 20.9 | 3 | Moderate |
| 17 | 3.8 | 4.6 | 2.9 | 2 | 2.2 | 1.8 | 35.3 | 52.5 | 7.5 | High |
| 18 | 1.5 | 4.5 | 4.9 | 1.3 | 1.7 | 6.9 | 5.8 | 26.7 | 3.8 | Moderate |
| 19 | 4.6 | 3.7 | 2.3 | 3.3 | 3.5 | 13.6 | 15.7 | 46.7 | 6.7 | High |
| 20 | 3 | 2.9 | 3.4 | 1.8 | 1.5 | 98.2 | 19.3 | 130.1 | 18.6 | Extremely high |
| 21 | 3.1 | 3.5 | 9.7 | 4.3 | 1.8 | 6.8 | 2.9 | 32 | 4.6 | High |
| 22 | 1.5 | 2.3 | 1.4 | 0.7 | 1 | 2.7 | 2.9 | 12.6 | 1.8 | Low |
| 23 | 1.6 | 2.8 | 1.1 | 0.5 | 0.8 | 60.7 | 2.8 | 70.3 | 10 | Very high |
| 24 | 8.2 | 3 | 6 | 3 | 1.4 | 1.9 | 3.9 | 27.4 | 3.9 | Moderate |
| 25 | 2.2 | 1.9 | 2.3 | 1.2 | 2.2 | 18.4 | 6.1 | 34.2 | 4.9 | High |
| 26 | 2.7 | 3 | 1.7 | 0.4 | 1.2 | 2.7 | 7.3 | 19.1 | 2.7 | Moderate |
| 27 | 3.3 | 5.1 | 2.3 | 1.1 | 4.8 | 2.4 | 2.7 | 21.8 | 3.1 | Moderate |
| 28 | 1 | 3.6 | 0.6 | 0.4 | 1 | 1.6 | 2.2 | 10.4 | 1.5 | Low |
| 29 | 2.1 | 4.1 | 1.4 | 0.5 | 1.1 | 2.8 | 3.4 | 15.5 | 2.2 | Moderate |
| 30 | 1.5 | 4.1 | 1.7 | 0.6 | 1.1 | 3.3 | 2 | 14.3 | 2 | Moderate |
| 31 | 8.4 | 1.6 | 2.3 | 2.1 | 0.8 | 21.1 | 3.9 | 40.3 | 5.8 | High |
| 32 | 1.2 | 1 | 4 | 2.1 | 1.7 | 5.1 | 2.4 | 17.4 | 2.5 | Moderate |
| 33 | 1.6 | 1.5 | 2.6 | 2.6 | 0.9 | 4.4 | 2.1 | 15.7 | 2.2 | Moderate |
| 34 | 3.4 | 1.2 | 5.1 | 3 | 11.2 | 19.1 | 5.9 | 49.1 | 7 | High |
| 35 | 1.4 | 1.5 | 3.1 | 1.6 | 2.4 | 11.7 | 2 | 23.8 | 3.4 | Moderate |
| 36 | 2.5 | 1.2 | 1.1 | 0.7 | 1.2 | 3.6 | 1.5 | 11.7 | 1.7 | Low |
| 37 | 2.2 | 1.9 | 1.4 | 0.7 | 1.1 | 6.7 | 2.9 | 16.9 | 2.4 | Moderate |
| 38 | 0.4 | 1.8 | 1.7 | 0.6 | 1.3 | 2.6 | 4.7 | 13.1 | 1.9 | Low |
| 39 | 1.3 | 2.4 | 2 | 0.4 | 1 | 4.5 | 4.6 | 16.2 | 2.3 | Moderate |
| 40 | 1.2 | 3.2 | 0.9 | 0.3 | 0.5 | 1.2 | 0.4 | 7.7 | 1.1 | Very low |
| **Mean** | **3.5** | **2.5** | **3.5** | **1.7** | **2.5** | **14.8** | **13.1** | **41.6** | **5.9** | **High** |

Figure (4) illustrates the distribution of soil samples across different pollution classes in the study area. A minimal percentage of samples fall into very low category (2%), indicating very little pollution. Slightly more samples (7%) are classified as low pollution, but still a small proportion overall. A moderate level of pollution is observed in a small segment of the samples (12%). High pollution category represents a significant portion (32%), suggesting that a considerable amount of soil is affected by high pollution levels. More than a third of the samples (37%) are in very high category, pointing to serious pollution concerns. A notable percentage of samples (10%) are classified as extremely high, highlighting critical pollution issues.

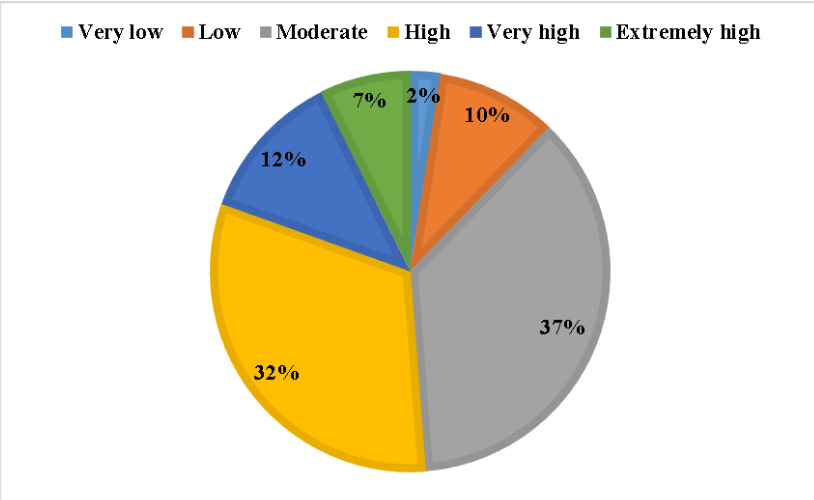


**Figure 4.** Proportions of soil samples across different pollution classes in the study area.

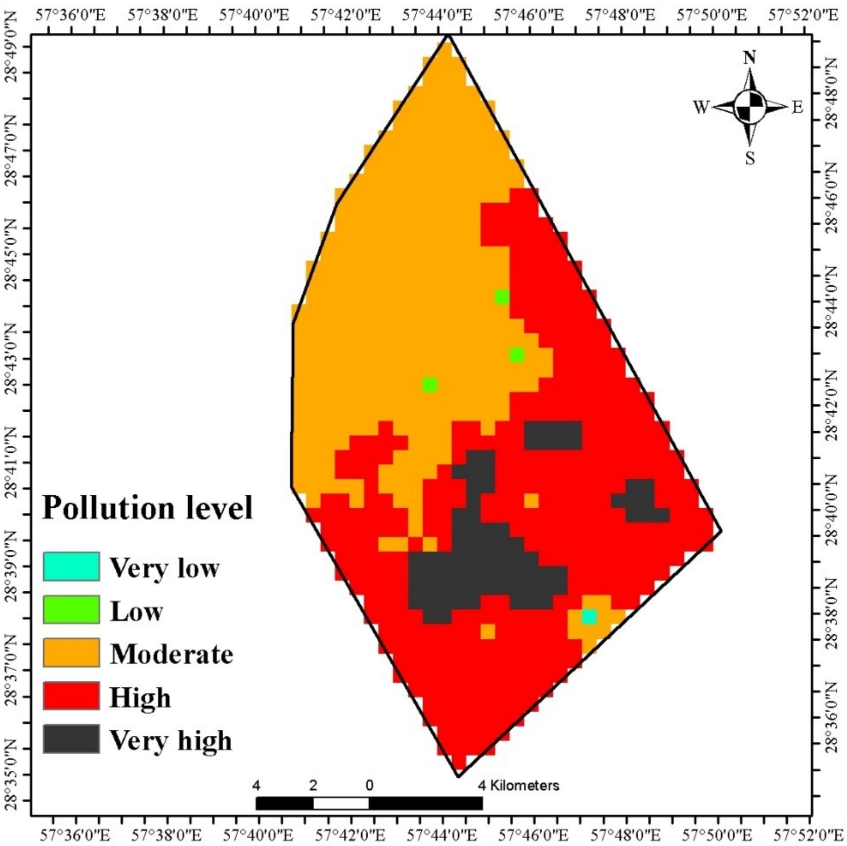


**Figure 5.** Soil pollution levels in the study area based on the mean soil pollution factor.

The spatial changes of pollution based on the MSPF are shown in the figure (5). Very low pollution regions are characterized by minimal pollution, suggesting a healthy environmental condition. They may serve as reference points for assessing pollution impacts in surrounding areas. Low pollution regions are scattered throughout the map, primarily in the northern and northeastern sections. These regions exhibit low pollution levels, indicating relatively good soil quality. Continued monitoring is advisable to ensure these areas do not degrade. Moderate pollution areas are more prevalent in the central part of the study area. These regions are experiencing moderate pollution levels, which may pose some risks to health and the environment.

High pollution regions are primarily located in the southern and southwestern parts of the map. The presence of high pollution levels in these areas raises concerns about environmental health and sustainability. These areas with high pollution levels may pose health risks to nearby populations, necessitating monitoring and potential remediation efforts. Very high pollution regions are concentrated in specific zones, particularly in the southernmost part of the map. These regions are critically polluted and require urgent intervention.

***Potential ecological risk in the study area***

Potential ecological risk for each element separately (Ei) and also for each soil sample are presented in Table 9. Each sample consists of measurements for five heavy metals (As, Cd, Cu, Pb, Zn), with a calculated exposure index (Ei) and a potential risk classification that ranges from "Very low risk" to "Very high risk."

In terms of risk level, sample 5 shows the highest Ei of Cadmium (Cd) at 222.9, contributing to the very high-risk status with a total exposure index of 376.1. Sample 21 also presents high exposure levels, particularly with As at 34.8 and Cd at 291.4. Sample 34 has elevated Ei of Pb (56.2) and an overall exposure index of 257, indicating severe pollution. Multiple samples are classified as high risk due to significant Ei of Cd and Pb. Sample 1 has an overall exposure index of 205.5, primarily driven by high levels of As (21.9) and Cd (120). Samples 3 and 9 also highlight concerning levels, with sample 3 showing As levels at 26.3 and sample 9 having a total index of 230.2, further emphasizing the high pollution risk. A few samples fall into moderate risk category, indicating relatively lower metal concentrations. Sample 22, for example, has an Ei of 77.1 with moderate levels of metals. Other samples are placed in the class with considerable risk. These samples present lower but still significant levels of potential risk. For example, sample 4, with an exposure index of 144.6, shows elevated levels of Cd (111.4).

Percentage of soil samples in various ecological risk classes in the study area is shown in Figure (6). It suggests that a considerable portion of the samples (45%) falls into considerable risk level. High risk is the second largest, with a total of 32.5%. It indicates a substantial number of samples that are classified as high risk, though fewer than those in the considerable risk category. Moderate risk category has a smaller area, representing 12.5%. It shows that moderate risk is less prevalent compared to the higher risk categories. Very High Risk is the smallest section, with a total of 10%. It indicates that very high risk is the least common among the categories presented. Overall, the chart illustrates a gradient of risk levels, with considerable risk being the most common and very high risk being the least common.

The PERI map illustrates the distribution of heavy metal contamination risk levels across Jiroft city (Fig. 7a). Based on the provided map, moderate risk areas are primarily located in the northeastern part of the map. The moderate risk suggests that these regions may experience occasional issues, but they are generally stable. Monitoring and preventive measures can be less intensive here. Considerable risk areas are scattered throughout the central part of the study area and may be need more attention. High risk areas dominate the southern and southwestern parts of the map and they are likely to face significant challenges. Very high-risk areas are concentrated in specific zones, particularly in the southernmost part of the Jirof city. These areas are critically at risk and require urgent intervention.

**Table 7.** PER values and potential risk levels in soil samples across the study area.

| Samples | Ei | | | | | PER | Potential Risk level |
|---|---|---|---|---|---|---|---|
| | As | Cd | Cu | Pb | Zn | | |
| 1 | 21.9 | 120 | 11.3 | 40.2 | 12.1 | 205.5 | High risk |
| 2 | 14.6 | 94.3 | 12.6 | 17.2 | 1.9 | 140.6 | Considerable risk |
| 3 | 26.3 | 68.6 | 6.7 | 13.7 | 46.7 | 162 | High risk |
| 4 | 13.3 | 111.4 | 11.4 | 7.3 | 1.2 | 144.6 | Considerable risk |
| 5 | 12.4 | 222.9 | 18.2 | 10.8 | 111.9 | 376.1 | Very high risk |
| 6 | 15.5 | 102.9 | 22.1 | 6.5 | 13.3 | 160.3 | High risk |
| 7 | 13.7 | 128.6 | 8.4 | 15.7 | 8.7 | 175 | High risk |
| 8 | 17.7 | 77.1 | 3.8 | 5.6 | 2.7 | 106.9 | Considerable risk |
| 9 | 41.2 | 145.7 | 14.5 | 21.2 | 7.6 | 230.2 | High risk |
| 10 | 16.4 | 120 | 11.3 | 17.8 | 6.6 | 172.2 | High risk |
| 11 | 16.7 | 77.1 | 11.1 | 7.4 | 4.6 | 116.9 | Considerable risk |
| 12 | 17.3 | 351.4 | 4.3 | 18.1 | 2.8 | 393.9 | Very high risk |
| 13 | 29.5 | 145.7 | 8.9 | 24.3 | 31.1 | 239.5 | High risk |
| 14 | 16.2 | 145.7 | 10.7 | 32.6 | 22.9 | 228.2 | High risk |
| 15 | 32.8 | 154.3 | 5.3 | 15.4 | 10 | 217.8 | High risk |
| 16 | 49 | 111.4 | 10.2 | 9.5 | 2.8 | 182.8 | High risk |
| 17 | 45.6 | 85.7 | 9.8 | 11.2 | 1.8 | 154.1 | Considerable risk |
| 18 | 45.5 | 145.7 | 6.6 | 8.6 | 6.9 | 213.2 | High risk |
| 19 | 36.7 | 68.6 | 16.4 | 17.7 | 13.6 | 153 | Considerable risk |
| 20 | 28.5 | 102.9 | 9.2 | 7.3 | 98.2 | 246.1 | High risk |
| 21 | 34.8 | 291.4 | 21.6 | 8.8 | 6.8 | 363.3 | Very high risk |
| 22 | 22.8 | 42.9 | 3.6 | 5.1 | 2.7 | 77.1 | Moderate risk |
| 23 | 27.6 | 34.3 | 2.3 | 4.2 | 60.7 | 129.1 | Considerable risk |
| 24 | 30.1 | 180 | 14.8 | 7 | 1.9 | 233.8 | High risk |
| 25 | 19.2 | 68.6 | 5.8 | 10.9 | 18.4 | 122.9 | Considerable risk |
| 26 | 30.1 | 51.4 | 2.2 | 6.1 | 2.7 | 92.4 | Considerable risk |
| 27 | 51.1 | 68.6 | 5.7 | 24 | 2.4 | 151.8 | Considerable risk |
| 28 | 36.4 | 17.1 | 2.1 | 4.8 | 1.6 | 62.1 | Moderate risk |
| 29 | 41.1 | 42.9 | 2.5 | 5.6 | 2.8 | 94.9 | Considerable risk |
| 30 | 40.8 | 51.4 | 3.1 | 5.4 | 3.3 | 104.1 | Considerable risk |
| 31 | 16.1 | 68.6 | 10.4 | 4.1 | 21.1 | 120.3 | Considerable risk |
| 32 | 10 | 120 | 10.4 | 8.7 | 5.1 | 154.1 | Considerable risk |
| 33 | 15.4 | 77.1 | 12.9 | 4.4 | 4.4 | 114.2 | Considerable risk |
| 34 | 12.2 | 154.3 | 15.1 | 56.2 | 19.1 | 257 | Very high risk |
| 35 | 15.3 | 94.3 | 8.2 | 11.8 | 11.7 | 141.3 | Considerable risk |
| 36 | 11.9 | 34.3 | 3.3 | 5.9 | 3.6 | 58.9 | Moderate risk |
| 37 | 18.7 | 42.9 | 3.3 | 5.4 | 6.7 | 77 | Moderate risk |
| 38 | 18.4 | 51.4 | 2.9 | 6.3 | 2.6 | 81.5 | Considerable risk |
| 39 | 24.2 | 60 | 1.9 | 5.2 | 4.5 | 95.8 | Considerable risk |
| 40 | 31.6 | 25.7 | 1.4 | 2.6 | 1.2 | 62.5 | Moderate risk |
| Mean | 25.5 | 103.9 | 8.7 | 12.5 | 14.8 | 165.3 | High risk |

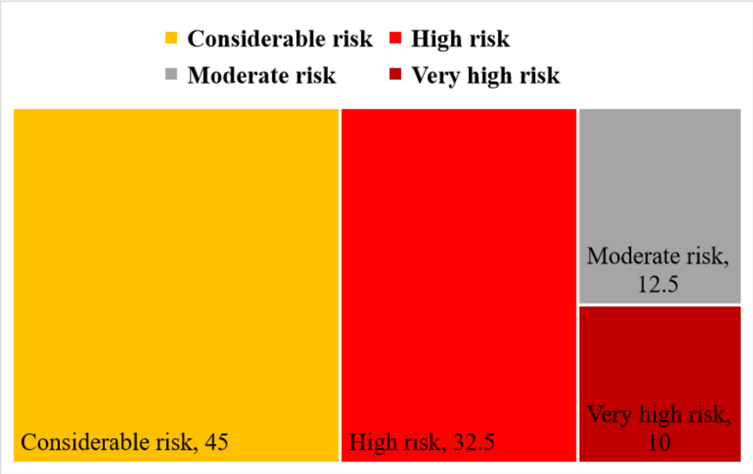


**Figure 5.** Proportions of soil samples in various ecological risk classes in the study area.

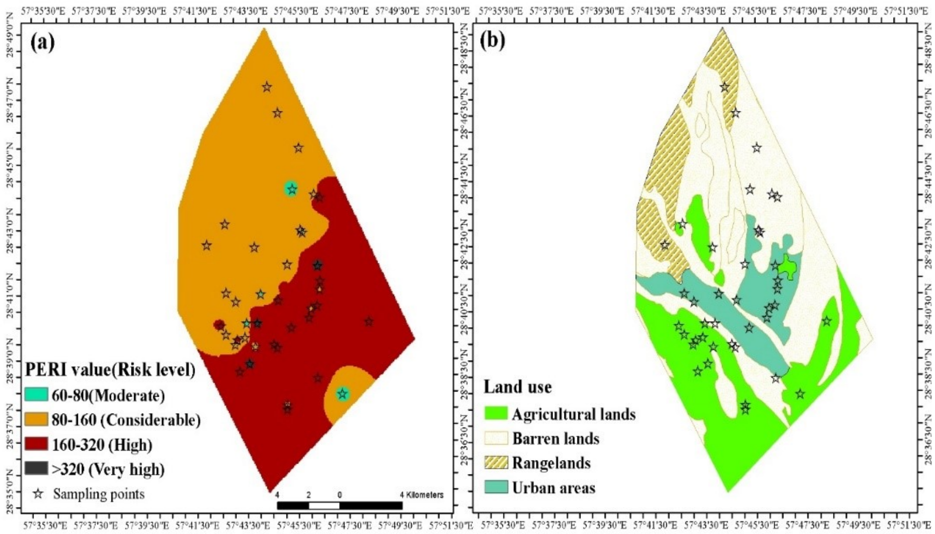


**Figure 6.** Potential ecological risk in the study area

Many agricultural areas are situated in high to very high-risk zones. This indicates that farming practices could be adversely affected by ecological risks, necessitating sustainable practices and risk mitigation strategies. Rangelands are also found in considerable to very high-risk areas. The ecological health of these lands is crucial for livestock grazing, and management practices must be implemented to prevent degradation. Urban regions, while less extensive, are located in areas of considerable to high risk. Urban planning must consider ecological risks to ensure sustainable development and minimize environmental impacts. Although barren lands are less affected by ecological risks, their proximity to high-risk areas can influence their ecological stability. Management strategies should consider the interconnectedness of these areas (Fig. 7b).

***Heavy metals source identification***

We determined heavy metal sources using the Pearson correlation coefficient (r) and principal component analysis (PCA). These methods also helped explore the associations among heavy metals and identify their potential origins in the study area. Stronger correlations were found between Cu-Cd ($r = 0.51$) and Pb-Mn ($r = 0.50$) at a confidence level exceeding 95% (Table 10). In contrast, the weakest correlations were observed for Fe-Zn, As-Cd, As-Pb, As-Mn, and Zn-Pb ($r < \pm 0.1$).

**Table 8.** Pearson correlation coefficients between heavy metals in the study area.

| Heavy metal | Fe | As | Cd | Cu | Pb | Zn | Mn |
|---|---|---|---|---|---|---|---|
| Fe | 1.000 | | | | | | |
| AS | -0.107 | 1.000 | | | | | |
| Cd | 0.170 | -0.096 | 1.000 | | | | |
| Cu | 0.161 | -0.160 | 0.511 | 1.000 | | | |
| Pb | 0.232 | -0.092 | 0.340 | 0.312 | 1.000 | | |
| Zn | 0.067 | -0.145 | 0.154 | 0.204 | 0.042 | 1.000 | |
| Mn | 0.164 | 0.035 | 0.368 | 0.207 | 0.500 | 0.327 | 1.000 |

In the PCA method, the varimax rotation identified the key heavy metals (HMs) in the study area. The first three components, with eigenvalues exceeding one, accounted for 63.59% of the total variance: 33.75% from the first component, 15.51% from the second, and 14.33% from the third (Table 11). PC1 was primarily associated with Pb and Cd (loading factor > 0.3), PC2 with Zn and Cd, and PC3 with As (loading factor > 0.3) (Fig.8). The highest negative loading factors were observed for Fe in PC2 (r = -0.36) and Cu in PC3 (r = -0.27).

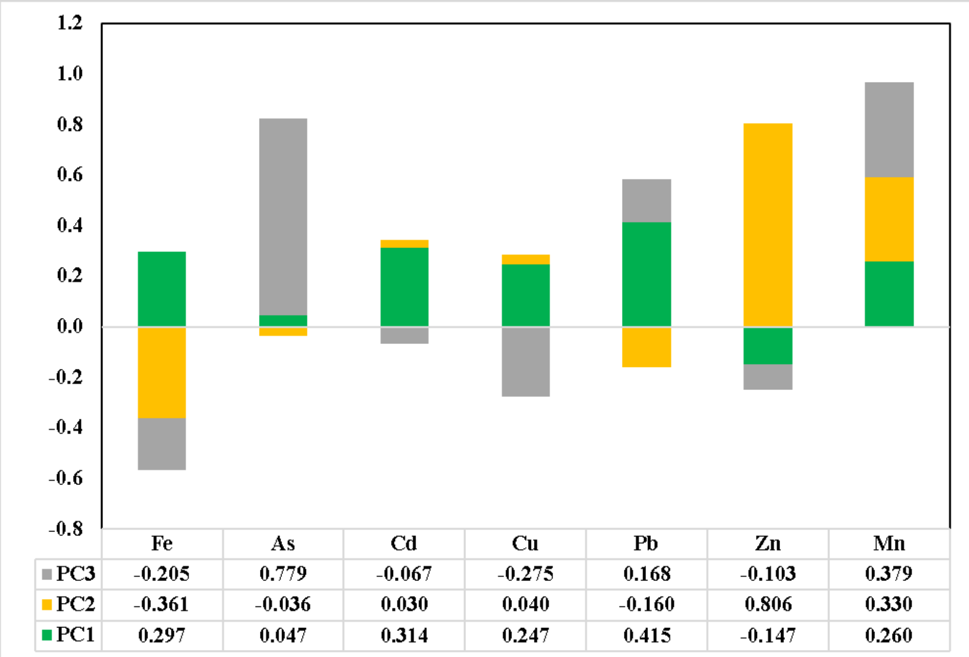


**Figure 7.** Factor loads from rotated principal components using the varimax rotation method in the study area.

**Table 9.** Eigenvalues from principal component analysis (PCA) for the study area.

| Component | Initial Eigenvalues | | |
|---|---|---|---|
| | Total | % of Variance | Cumulative % |
| **PC1** | 2.363 | 33.750 | 33.750 |
| **PC2** | 1.086 | 15.514 | 49.264 |
| **PC3** | 1.003 | 14.334 | 63.598 |
| **PC4** | 0.915 | 13.071 | 76.669 |
| **PC5** | 0.775 | 11.072 | 87.741 |
| **PC6** | 0.508 | 7.263 | 95.004 |
| **PC7** | 0.350 | 4.996 | 100.000 |

## Discussion

### *Heavy metals concentration*

Assessing heavy metal risk is crucial for public health, environmental protection, and sustainable development (Huang et al., 2020). This study focused on Jiroft, a city in southeastern Iran. The results from the heavy metal analysis in the study area indicate varying levels of contamination, with significant implications for environmental health. Zn, with the reported average concentration of 0.66 mg/kg and maximum of 4.98 mg/kg, indicates that Zn levels are relatively low in the studied area. The coefficient of variation (Cv = 61%) suggests moderate variability in Zn concentrations across samples. Mn, with the average level of 3.61 mg/kg and maximum of 17.98 mg/kg and a Cv of 79%, indicates substantial variability. The presence of Mn could be linked to both geological factors and anthropogenic activities in the area. Fe concentrations range from 0.46 to 30.18 mg/kg, with an average of 4.08 mg/kg and a high Cv (82%). This variability suggests that Fe levels may be influenced by local soil type, organic matter, and potential contamination sources. Cd concentrations are notably low, with a maximum of 0.04 mg/kg and an average of 0.01 mg/kg. The high Cv (151%) indicates limited consistency across samples, but overall, Cd levels remain well below concerning thresholds. Cu, with the average concentration of 0.65 mg/kg and a maximum of 1.66 mg/kg, along with a high Cv (158%), highlights the variability in Cu levels that may result from agricultural runoff and urbanization. Pb with the average concentration of 0.48 mg/kg, a maximum of 2.17 mg/kg, and a Cv of 116%, show moderate levels of variability. Pb is a concerning contaminant due to its toxicity, especially in urban areas. As with the average concentration of 0.51 mg/kg and a maximum of 1.02 mg/kg, accompanied by an extremely high Cv (218%), indicate considerable variability, emphasizing the need for monitoring due to As's hazardous nature. The results indicated elevated heavy metal concentrations in Jiroft's soil compared to natural background levels, suggesting anthropogenic influence (McLennan, 2001; Sohrabizadeh et al., 2023).In a study, Soltani-Gerdefaramarzi et al. (2021) focused on heavy metal contamination in urban soils of Yazd, reporting Zn, Mn, Fe, Cd, Cu, Pb, and As concentrations significantly higher than those observed in our findings. In another study, Mohseni-Bandpei et al. (2017) found Zn, Cd, Cu, and Pb levels considerably higher than in our study. Such findings illustrate that urban areas in central Iran may experience greater environmental pressures compared to the study area, where the maximum concentration is just 4.9, 17.9, 30.1, 0.04, 1.6, 2.1, and 1.02 mg/kg for the Zn, Mn, Fe, Cd, Cu, Pb, and As, respectively.

### *Pollution assessment using EF and MSPF*

In the study area, the EF for As ranges from 0.05 to 4.67, with a mean of 1.3, indicating a low pollution level. This suggests that As concentrations are relatively close to natural background levels, with minimal anthropogenic influence. The EF for Cd ranges from 0.15 to 4.62, with a mean of 1.36, also classified as low pollution. This indicates that while there is some enrichment, it remains within acceptable limits. The enrichment factor for Cu shows a range of 0.07 to 2.33, with a mean of 0.77, indicating low pollution levels. This suggests that Cu levels are not significantly elevated compared to natural background levels. The Pb enrichment factor ranges from 0.1 to 3.26, with a mean of 1.03, classified as low pollution. This indicates that Pb levels are relatively stable and not significantly impacted by anthropogenic activities. The enrichment factor for Zn is notably higher, ranging from 0.24 to 38.59, with a mean of 5.53, indicating high pollution levels. This suggests significant anthropogenic contributions to Zn concentrations in the area. The enrichment factor for Mn ranges from 0.08 to 25.16, with a mean of 4.74, indicating moderate pollution levels. This suggests that Mn levels may be influenced by both natural sources and human activities. The analysis of enrichment factors for heavy metals in the study area indicates generally low levels of pollution for As, Cd, Cu, and Pb, while Zn shows significant enrichment, suggesting anthropogenic influence. The moderate levels of Mn also indicate some degree of human impact. Ebadi and Hisoriev (2018)demonstrated that the enrichment index for copper, zinc, and manganese in the Farah Abad region of Iran is below one, indicating low pollution levels, which aligns with this study's findings. In contrast, Moghtaderi et al. (2020) reported a medium to high pollution level for nickel, chromium, and cobalt in Shiraz, southwest Iran, but their results for other heavy metals were almost consistent with this study, showing low pollution levels for those elements.

In terms of MSPF, the majority of soil samples (79%) fall into the high, very high, and extremely high categories, indicating significant pollution in the study area. Only a small fraction of samples is in the very low and low categories, suggesting that pollution is a prevalent issue. In summary, the comparison reveals that while both Enrichment Factors and Pollution Factors indicate significant levels of heavy metals in the soil, the enrichment factors provide insight into how these metals are accumulating relative to natural levels. Notably, Zinc and Mn appear to be major pollutants, reflecting both high pollution and enrichment levels, warranting further investigation and remediation efforts to address soil contamination. Similar findings regarding heavy metal contamination are reported by Ebrahimi-Khusfi et al. (2023), indicating that the other regions of southeastern Iran also faces serious pollution issues, particularly from heavy metals.

***Potential ecological risk in the study area***

According to Ei values, Cd is the most concerning heavy metal across several samples, contributing to high and very high-risk classifications. Elevated Cd levels may indicate industrial contamination or agricultural runoff. As concentrations are also significant, particularly in samples classified as high risk, suggesting potential groundwater contamination or health hazards associated with soil. The distribution of samples indicating high risk is not uniform, suggesting localized sources of pollution, likely from industrial activities or urban runoff. The study area with considerable risk encompasses the largest region, with over 45% of soil samples categorized in this class. The PERI map clearly illustrated that the majority of the area falls within high to very high-risk categories, particularly in the southern regions. This highlights the need for targeted risk management strategies and resource allocation to address the challenges faced in these critical zones. The moderate and considerable risk areas, while less urgent, still require monitoring to prevent escalation into higher risk levels. The combination of ecological risk levels with land use types reveals the need for integrated management approaches. Agricultural and rangelands within high-risk zones require targeted interventions to safeguard both environmental health and local livelihoods. Sustainable practices and proactive risk management are essential to mitigate ecological threats across all land use types. Recent studies have also reported significant ecological risks in southeastern Iran (Soleimani-Sardo et al., 2023) and notable risks in Kurdistan(Karimyan et al., 2020) and Hamedan (Kharazi et al., 2021) which align with our findings.

***Heavy metal source identification***

In the study area, the strongest correlations were observed between Cu and Cd ($r = 0.51$) and between Lead Pb and Mn ($r = 0.50$), both exceeding the 95% confidence level. These correlations suggest that Cu and Cd may originate from similar anthropogenic sources, possibly related to industrial activities or agricultural practices that utilize fertilizers containing these metals (Mirzaei Aminiyan et al., 2018; Shi et al., 2019). Conversely, the weakest correlations were found among Fe and Zn, As, and Cd, and other combinations, indicating that these metals may have distinct sources or pathways of contamination. The PCA results, with three components accounting for 63.59% of the total variance, further elucidate the sources of heavy metals in the study area. The first component (PC1) is primarily associated with Pb and Cd, indicating that these metals may share a common source, likely linked to industrial emissions or urban runoff. The second component (PC2) shows a strong association with Zn and Cd, suggesting that these metals may also be influenced by similar anthropogenic activities. The third component (PC3) is associated with As, indicating that this metal may have different sources, potentially related to geological factors or specific industrial processes. The negative loading factors for Fe in PC2 (r = -0.36) and Cu in PC3 (r = -0.27) suggest that these metals may be inversely related to the other metals in their respective components, indicating distinct sources or behaviors in the environment. In general, the findings demonstrate that natural activities have contributed more to the contamination of the region with Pb, Zn, Cd, and As than human activities. This trend has also been observed in other regions of Iran(Ghaneei-Bafghi et al., 2024). However, human activities have significantly increased contamination levels for Fe and Cu in the study area. The impact of anthropogenic activities on pollution in other parts of Iran has also been confirmed (Hani and Pazira, 2011; Taghavi et al., 2024), aligning with this study's results.

## Conclusion

The heavy metal concentrations map indicated that arsenic levels are particularly elevated in the eastern parts, while zinc concentrations are notably higher in the central regions. The assessment of pollution using the enrichment factor (EF) and multi-element index (MSPF) demonstrated that zinc and manganese are of particular concern, with several samples classified as having high to very high pollution levels. Moreover, the potential ecological risk assessment indicated that certain samples pose a very high risk, particularly those with elevated cadmium and arsenic levels. This underscores the urgent need for targeted monitoring and remediation efforts in high-risk areas to mitigate the adverse effects of heavy metal pollution on both the environment and public health. In conclusion, this study not only highlights the current state of heavy metal contamination in Jiroft but also serves as a critical foundation for future studies aimed at understanding the long-term impacts of such pollution. The results emphasize the importance of implementing effective management strategies to address heavy metal pollution and protect local communities. By identifying and controlling anthropogenic sources of heavy metal pollution, developing and implementing effective remediation techniques, monitoring heavy metal concentrations and promoting public awareness, Jiroft city can significantly reduce its ecological risk and create a healthier environment for its residents and ecosystems.

## Acknowledgements

The authors would like to thank the vice-chancellor of education and research in the University of Jiroft for his support.

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