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# Mapping of heavy metal pollution density and source distribution of campus soil using geographical information system

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**In this study, the pollution intensity, spatial distribution, and index-based risk distribution in campuses, which are a small prototype of cities, were mapped and the sources of heavy metals in the soil were investigated. Soil samples were taken from 9 different points from the Aksaray University Central campus, which was determined as the study area. It has been determined that the pH value in the collected soil samples varies between 8.7 and 11.0. This situation created an effect on reducing the accumulation and mobility of heavy metals in the soil. When the study area was evaluated based on the geo-accumulation index, Pb heavy metal was much denser in the places indicated as circulation areas and where students were actively present. Based on the pollution load index, it was concluded that 75% of the study area was moderately/highly polluted, and the rest consisted of unpolluted soils. Pearson correlation analysis and APCS-MLR analyses conducted to determine the source distribution showed that the contributions of natural sources, mixed sources of industrial and traffic activities, agricultural activity-based sources, and other sources were 57.49%, 21.44%, 12.67%, and 8.40%, respectively. Pb is mainly related to the mixed sources of industrial and traffic activities. Therefore, to clear up its long-term impact on the accumulation of heavy metals in the soil, it is important to conduct continuous heavy metal monitoring in the soil throughout the campus.**

**Keywords** Heavy metal, Geographical information system, Spatial distribution, Pollution indices, Soil

The soil is a basic structure that supports agricultural works and urban infrastructure. The quality of the soil significantly affects the safety of different living forms[1]. However, the soil, which is an important part of the environment and ecosystem, is highly sensitive to external pollutants[2]. Rapid industrialization, traffic intensity, increased use of chlorinated organic substances such as insecticides, antibiotics, and herbicides, and the use of organic solvents for the rapid development of agricultural activities cause soil pollution and deteriorate soil quality[3]. In addition to global warming, soil pollution has also become an increasingly important problem for societies to deal with[4].

Usually, metals with a density above 4.5 g/cm$^3$ are called heavy metals. Mercury (Hg), cadmium (Cd), lead (Pb), nickel (Ni), zinc (Zn), chromium (Cr), copper (cu) and arsenic (As) are the main heavy metals that cause environmental pollution[5]. Since heavy metals can stay in the ecosystem (soil, water, and air) for a long time and accumulate gradually, they have the characteristics of environmental persistence, toxicity, and biological accumulation. In high concentrations, they cause toxic effects on organisms living in the ecological environment[6]. The concentration of heavy metals in the soil is an important indicator in the assessment of soil quality[7]. It is estimated that worldwide, more than 50,000 areas, spanning about 200,000 hectares of land, are affected by heavy metal pollution[8]. Therefore, soils contaminated with heavy metals have become a global environmental problem that restricts the sustainable development of human society and urgently needs to be solved[9]. As a result, it can be said that conducting ecological risk assessments of heavy metals is one of the main components of environmental activities[10]. Many researchers have used enrichment factors, pollution factors, pollution load indices, and geographical accumulation indices as assessment tools to assess the pollution status of heavy metals in soil[11].

Accurate mapping of the spatial distribution of heavy metals in soil is the primary stage in risk assessment and remediation of contaminated areas[12,13]. Remote sensing is an efficient and environmentally friendly detection tool that provides long-term series and large-scale environmental monitoring with low detection costs and low

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field sampling requirements[14]. Geographical information system (GIS), one of the remote sensing methods, is a new technology used in different fields and provides important results in a short time[15]. Diaz Alarcòn et al.[16] determined that the heavy metal concentration trends were Fe > Mn > Zn > Ni > Cu > Pb > As > Cd > Hg in soil samples taken from the Boyacá industrial corridor of Colombia, and identified anthropogenic and geological sources by using GIS software and geochemical indices. Pollution characteristics, ecological risks, and source distribution of heavy metals were quantitatively identified in samples taken from the abandoned zinc smelter soil in China and mapped using the GIS database[17]. A similar study was conducted in the Al-Ahsa region of Saudi Arabia. In this study, chronic daily intake (CDI), hazard coefficient (HQ), hazard index (HI), cancer risk (CR), and total lifetime cancer risk (LCR) of heavy metals were calculated in soil samples taken, and the spatial distribution and possible sources of heavy metals were processed into the GIS database[18]. In the study in which soil samples taken from agricultural lands of Dhaka were examined, the approach of GIS, enrichment factor (EF), geo-accumulation index, and contamination factor index were used, and it was shown that more than 90% of soil samples were contaminated with higher Cr and Cd levels[19].

In order to determine the source distributions of heavy metals in the soil, multivariate statistical methods have been applied in many studies[20–23]. Principal component analysis (PCA), an important method for quality analysis, is the most preferred method for determining the source of pollution[24]. The PCA cannot clearly determine the distribution of pollution sources and their proportional effects in the environment. Therefore, Absolute Principal Component Scores (APCS) analysis along with Multivariate Linear Regression (MLR) was used to further measure the distribution of different pollution sources.

In addition to the pollution related to the natural structure of soil, anthropogenic sources such as traffic, agricultural activities, and industrial activities can also lead to pollution[25]. Because of the important environmental impacts of university campuses due to their architectural designs, layouts, population, multi-faceted activities, energy consumption, waste generation, and carbon emissions, it is necessary to conduct studies for human health, ecological welfare, and sustainable practices[26]. It has been determined that university campuses, which are characterized as small districts, are facing many environmental problems[27]. It is seen that smart and green campus studies have been included more in the literature in recent years. Despite this, studies on heavy metal research in campus soil, creation of pollution maps, and density and spatial distribution of pollution are limited in number. In this study, heavy metal pollution was detected in soil samples taken from the Central campus of Aksaray University and a pollution map was created in the GIS database. In addition, Enrichment factor (EF), Geo-accumulation index ($I_{geo}$), Contamination Factor (CF), and Pollution Load Index (PLI) calculations were performed to determine the heavy metal pollution levels. The sources of heavy metals in the campus soil were comprehensively evaluated by multiple linear regression analysis with absolute principle component score (APCS-MLR). Thus, this study helps to eliminate the deficiency by evaluating the potential risks of heavy metals in the soils on the Central campus of Aksaray University.

## Materials and methods

### Study area and sampling

Aksaray University central campus is located in Aksaray Province, Turkey, 8 km away from the city center, between latitude 38.328297 and longitude 33.988937 (Fig. 1). The desktop version of Google Earth Pro (https://www.google.com/intl/tr_ALL/earth/about/versions/), which is free for all users, was used to create the map. In the study, Fig. 1 was created using Google Earth Pro version 7.3 (GoogleData SIO, NOAA, U.S. Navy, NGA, GEBCOLandsat/CopernicusIBCAOU.S. Geological Survey). There are fertile agricultural lands, an organized industrial zone, and an intercity highway in this region. The study area is open to development on an international campus scale and anthropogenic activities are intense in the area at certain times of the day. The average altitude of the study area from the sea is 955 m, the average annual temperature of the region is 12.4 °C, and the average annual precipitation is 360 mm[28].

In the central campus area of Aksaray University (ASU), founded in 2006, there are a total of 15,500 students enrolled in different undergraduate and graduate programs. It has a circulation area of approximately 96,386 m[229]. In the context of the study, nine soil samples were taken from the circulation areas on days without precipitation (between May and June 2018) to reveal both the soil structure of the region and the pollution that may occur according to anthropogenic activities on the campus. Before the collection of samples, field survey was conducted using geographic information system (GIS). Geographic positioning system (GPS) was used to determine suitable sample locations in the survey. According to the principles of TS 9923 (Surface Soil Sampling, Transport and Storage Rules), geo-referenced samples were taken using a plastic hand trowel at a depth of 0–20 cm from the soil surface to correspond to the ideal soil zone A. Ten subsamples from each sample were combined to form one kilogram of composite soil. Then the samples were placed in plastic sample bags and brought to the Soil Laboratory of the Department of Environmental Engineering. The samples were dried in a 60 °C oven for 10 h until they reached a constant weight, and they were ground until 2 mm.

### Analytical methods

Soil pH and electrical conductivity (EC) were measured using HQ411D (Hach) equipment in 1:5 (weight/volume) soil/water suspension. The pH combination was measured using a glass electrode. Soil organic matter (OM) was oxidized with potassium dichromate in a sulfuric acid medium and determined by the Walkley-Black method[30]. The soluble total organic carbon (sTOC) and soluble total nitrogen (sTN) measurements were carried out with the TOC-TN (Shimadzu TOC-VCPN) analysis system. Total petroleum hydrocarbons (THP) were made based on the study conducted by Rauckyte et al.[31]. The oil and grease were analyzed by solid phase extraction using USEPA Method 1664 A[32]. 5 g were taken from each soil sample and allowed to dissolve in 25 mL of ultrapure water for 24 h. The solute samples were filtered through a 0.45 µm PTFE syringe filter and examined using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). All reagents used in the analyses


**Fig. 1**. Campus area and sampling points. (adapted from Google Earth Pro version 7.3)

of this study were of analytical purity (Merck, Germany). Before use, all materials were kept in 3% $HNO_3$ for 24 h and then rinsed with pure water. In order to ensure the quality of the analytical data, various laboratory quality control and quality assurance procedures were applied. All samples were analyzed three times. If the error was less than 5%, the results were used for research.

## Calculation of pollution indices

In order to evaluate the metal pollution properties of the campus soil, enrichment factor (EF), geo-accumulation index ($I_{geo}$), contamination factor (Cf), pollution load index (PLI) and ecological risk factor, which are widely used geochemical methods and pollution indices, were used. These approaches helped to assess the level of contamination and the anthropogenic impact on heavy metal levels in the soil of the study area[33–35]. Enrichment factor (EF) is recognized as a useful method for assessing pollution levels caused by human activities and environmental factors[19]. To calculate the EF, the following formula is used:

$$EF = Sample\frac{Ci}{Cref}/background\frac{Ci}{Cref} \tag{1}$$

where $C_i$ is the content of *i* heavy metal, and $C_{ref}$ is the content of the reference element (Al) for geochemical normalization[36].

The $I_{geo}$ equation is used to determine the pollution levels in soils. The equation developed by Müller[37] is calculated by the following formula:

$$I_{geo} = \log2\left[\frac{C_i}{1.5 \times\ B_i}\right] \tag{2}$$

where $B_i$ is the background value of element *i*, and $C_i$ is the content of element *i*.

The contamination factor ($C_f$) was calculated by the following equation (Eq. 3)[38].

$$C_f = C_i/C_n \tag{3}$$

In the equation, $C_i$ shows *i* heavy metal concentration and $C_n$ refers to the geochemical background concentration. In addition, two composite indices used to assess the cumulative effect of multiple heavy metals (i.e., the pollution load index (PLI)) were used. The pollution load index (PLI) was obtained by taking the *n* root of multiplication of the contamination factors ($C_f$) calculated for *n* amount metals[39]. The PLI was calculated using Eq. (4). In the equation, $C_{f1}$ is contamination factor of one heavy metal, while $C_{fn}$ is the contamination factor of n heavy metals.

$$PLI = (Cf1 \times\ Cf2 \times\ Cf3 \times\ \ldots\ . \times\ Cfn)^{1/n} \tag{4}$$

To assess the degree of pollution in the environment and the ecological risk of heavy metals in soils, the most preferred potential ecological risk index (RI), ecological risk factor ($E_r$), and $C_{deg}$, which is the sum of $C_f$ values for all evaluated heavy metals, were expressed by the Eqs. (5), (6), and (7) proposed by Hakanson[40] for the evaluation of the negative effects of heavy metals on soils.

$$RI = \Sigma\, E_r \tag{5}$$

$$C_{deg} = \Sigma\, C_f \tag{6}$$

$$Er = T_i \times\ C_f \tag{7}$$

where $C_f$ refers to the contamination factor and $T_i$ refers to the toxic reaction factor of heavy metals[40]. The calculated Igeo values were explained based on the grades described in Varol et al.[41] ve Muluye et al.[80]. The EF and PLI values are interpreted based on the categories described in Varol et al.[41] and Ferreira et al.[42]. CF, Er, RI values calculated by referring to Hakanson[40] and Müller[37] are explained according to the degrees explained by Varol et al.[41], Tiabou et al.[81], Ferreira et al.[42] and Sun et al.[5], respectively. The calculated $C_{deg}$ values were explained based on the grades described in Tiabou et al.[81]. The contamination and risk degrees of each index are shown in Table 1.

## GIS analysis

Pollution maps of the study area were obtained using the ArcGIS geographical information system (Version 10.5) and by digitizing the points. The maps created in this program were prepared based on the WGS 1984 geographical coordinate system and redesigned based on the WGS 1984 UTM Zone 36. The basic maps of the study area were created using satellite photos obtained from the Google Earth Pro program. One of the interpolation models in the ArcGIS geographic information system software is "Inverse Distance Weighted (IDW)". This model is an interpolation for the prediction of any point based on the fact that the value at a point close to that location is more effective, and the distant point is less effective[43]. Using this model, estimated heavy metal pollution maps of the study area were obtained. To determine the accuracy of IDW interpolations, the power parameters were changed from 1 to 3, and the lowest root mean squared error (RMSE) for specific power parameters was selected for each pollution index map[44].

| İndices | Degree of contamination or risk |
|---|---|
| Enrichment factor (EF)[41] | EF < 2 → Minimum enrichment |
| | 2 ≤ EF < 5 → Moderate enrichment |
| | 5 ≤ EF < 20 → Significant enrichment |
| | 20 ≤ EF < 40 → Very high |
| | EF ≥ 40 → Extremely high enrichment |
| Geographic accumulation index (Igeo)[41,80] | Igeo < 0 → Uncontaminated |
| | 0 ≤ Igeo < 1 → Unpolluted to moderately contaminated |
| | 1 ≤ Igeo < 2 → Moderately dirty |
| | 2 ≤ Igeo < 3 → Moderately to very dirty |
| | 3 ≤ Igeo < 4 → Very dirty |
| | 4 ≤ Igeo < 5 → Very to extremely dirty |
| | Igeo ≥ 5 → Extremely dirty |
| Contamination factor (CF)[41] | CF < 1 → Low pollution |
| | 1 ≤ CF < 3 → Moderate pollution |
| | 3 ≤ CF < 6 → Significant contamination |
| | CF ≥ 6 → Very high contamination |
| Ecological risk factor ($E_r$)[81] | $E_r$ < 40 → Low potential ecological risk |
| | 40 ≤ $E_r$ < 80 → Moderate potential ecological risk |
| | 80 ≤ $E_r$ < 160 → Significant potential ecological risk |
| | 160 ≤ $E_r$ < 320 → High potential ecological risk |
| | $E_r$ ≥ 320 → Very high potential ecological risk |
| $C_{deg}$ value[41] | $C_{deg}$ < 6 → Low pollution |
| | 6 ≤ $C_{deg}$ < 12 → Moderate pollution |
| | 12 ≤ $C_{deg}$ < 24 → Significant contamination |
| | $C_{deg}$ ≥ 24 → Very high contamination |
| RI value[5,42] | RI < 150 →Low risk |
| | 150 ≤ RI < 300 → Medium risk |
| | 300 ≤ RI < 600 → High risk |
| | RI ≥ 600 → Very high risk |
| Pollution load index (PLI)[42] | PLI > 1 →Polluted |
| | PLI = 1 → Baseline levels of pollution |
| | PLI < 1 → Not Polluted |

**Table 1**. Contamination and risk grading of the indices used in the study.

## Relative heavy metal source distribution

In order to determine the distribution of different pollution sources in the soil, the APCS-MLR model was used[20,21,45]. The reverse traceable APCS-MLR model derived from the Standard Principle Components Analysis (PCA) method is calculated based on multiple linear regression and standard factor analysis[22,23,46]. Predictions were made with XLSTAT statistical data analysis software (Version number: 2023.1.4, Creator: Lumivero, Denver, USA). The APCS-MLR model based on multiple linear regression can be shown as follows:

$$C_{HM} = \beta_{zero} + \sum\nolimits_{n-1}^{p} \beta_n \times APCS/MLR_n \quad (8)$$

where $C_{HM}$ is the amount of heavy metals, $\beta_{zero}$ is the intersection term of the initial regression of heavy metals, $\beta_n$ is the regression coefficient between the $n$ source and the heavy metal, and $APCS/MLR_n$ is the factor $n$ representing the absolute principle component score of the source. $\beta_n \times APCS/MLR_n$ refers to the contribution of the source factor $n$ to $C_{HM}$. In addition, in this study, the source contributions were calculated as follows.

$$Source_n = \frac{abs(Source_n) \times 100\%}{abs(Source_{ud}) + \sum\nolimits_1^p abs(Source_n)} \quad (9)$$

where $Source_n$ is the $n^{th}$ heavy metal source contribution, $Source_{ud}$ is the unidentified source contribution, and $p$ is the determined source number. Statistical analyses were performed using Excel 2024 and Origin.

# Results and discussion

## Physicochemical properties of soil samples

The physicochemical properties of the soil both contribute to the determination of heavy metal values in the soil and affect the mobility of the soil[47,48]. Table 2 shows the specific physicochemical and textural properties of nine soil samples belonging to the campus area under study.

As seen in Table 2, the pH value of the soil in the campus area varies between 8.7 and 11 and indicates a strongly alkaline type of soil. pH values can affect the mobility of heavy metals in different soils; for example, alkaline soil can reduce the accumulation and mobility of heavy metals[49]. The electrical conductivity (EC) in soil samples ranges from 20.81 to 714 µs/cm and the mean is 279.55 µs/cm. The distribution in the campus area indicates that there is a high concentration of EC at some sample points (S3, S6, and S7). OM values range from 3.59 to 20.82%. OM is necessary for soil development, soil fertility and pollution reduction[50]. The amount of organic matter can cause heavy metals to be retained in the soil. Also, the high OM content at these points may be due to discharges in the surrounding area. It was found that in terms of nutrient values in the soil samples, calcium (Ca) ranged from 29,030 to 134,300 mg/kg, magnesium (Mg) from 4796 to 101,000 mg/kg, sodium (Na) from 1258 to 140,600 mg/kg and potassium (K) from 2118 to 4544 mg/kg. The high levels of Na in the samples may be due to the natural structure of the soil. High K values indicate that excessive K fertilizer was used in agricultural activities carried out in the region in previous periods[48]. It was observed that the TPH values in the soil samples ranged from 278.85 to 1168.78 mg/kg and the mean TPH was 637.89 mg/kg. Especially at the sample points near the roadsides (at the S2, S3, and S4 points where traffic was heavy), the TPH values were at a high level. The high TPH at these points can be attributed to traffic-related emissions. It was grouped based on the soil sampling points according to the Unified Soil Classification System (USCS) (Fig. 2).

In the samples taken homogeneously from 9 points, the soil texture (clay, silt and sand distributions) was determined according to the intersection point in the Texture Triangle with mechanical analysis processes. S1, S8, and S9 are suitable for the well-graded sand (SW) class and S2, S4, and S6 are suitable for the poorly graded sand (SP) class. The S3, S5, and S7 points can be grouped under the poorly graded sand-silty sand (SP-SM) class. These soils are sandy and silty in nature, and they have a high permeability compared to clay soils; therefore, the heavy metal retention is not very high in them. However, activities and active factors other than the natural textural structure can increase the density of heavy metals.

## Distribution of heavy metals in soil

The soluble heavy metal concentrations in the soils were determined in the Aksaray campus area. In Table 3, the concentrations of heavy metals detected in the context of the study are presented.

As seen in the table, it was determined that Pb concentration ranged from 10.09 to 39.33 mg/kg, Cu from 8.35 to 35.82 mg/kg, Ni from 23.89 to 214.4 mg/kg, Cr from 11.98 to 55.63 mg/kg, Zn from 97.51 to 219.9 mg/kg. The mean Ni concentration was observed as 214.4 mg/kg at the S5 point. Compared to the international scale, this value is above the standards. The presence of geogenic activities in and around the study area explains the high level of Ni concentration. The identification of such relationships consistently in various studies strengthens the hypothesis that geological factors play an important role in shaping the elemental composition of the studied areas[51]. This collective evidence contributes to a broader understanding of the geological controls on heavy metal concentrations in Turkey[52]. Due to integrated agricultural activities and fertilizer use, the concentration of Cu and Zn in the soil is increasing[53]. In the soil of the study area, the Cu and Zn content has the potential to increase due to industrial wastes and agricultural chemicals such as fertilizers and pesticides. In general, the

| Parametre | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | – | 8.7 | 10.3 | 9.2 | 9.6 | 10.0 | 9.1 | 11.0 | 9.7 | 9.4 |
| EC | µs/cm | 20.81 | 138.3 | 714 | 161.4 | 96.45 | 505 | 506 | 90.5 | 283.5 |
| OM | % | 7.5 | 4.44 | 6.82 | 3.89 | 6.15 | 3.65 | 20.82 | 3.66 | 3.59 |
| Oil-Grease | % | 0.018 | 0.036 | 0.09 | 0.028 | 0.016 | 0.244 | 0.302 | 0.006 | 0.014 |
| sTOC | mg/kg | 1892 | 14,120 | 2979 | 795.9 | 430.1 | 7978 | 1407 | 1374 | 1411 |
| sTN | mg/kg | 72,530 | 64,090 | 34,980 | 25,600 | 1347 | 49,620 | 4528 | 44,520 | 81,860 |
| TPH | mg/kg | 394.3 | 1168.78 | 1027.74 | 986.29 | 796.07 | 256.38 | 436.8 | 395.8 | 278.8 |
| Ca | mg/kg | 83,740 | 54,770 | 134,300 | 38,140 | 60,120 | 29,030 | 119,500 | 47,490 | 38,570 |
| K | mg/kg | 4410 | 4544 | 4201 | 1962 | 3287 | 2437 | 2933 | 3339 | 2118 |
| Na | mg/kg | 3416 | 140,600 | 2968 | 1451 | 1559 | 1258 | 6731 | 2630 | 1308 |
| Mg | mg/kg | 22,660 | 12,510 | 29,720 | 4796 | 28,990 | 5082 | 101,000 | 8625 | 5701 |
| Intensity | $g/cm^3$ | 1.02 | 0.94 | 1 | 0.89 | 0.89 | 0.92 | 0.76 | 0.96 | 0.97 |
| Porosity | % | 35.9 | 35.06 | 36.71 | 37.89 | 37.5 | 34.64 | 43.66 | 39.39 | 37.11 |
| Clay/Silt | % | 9.29 | 1.07 | 10.47 | 1.74 | 6.51 | 2.00 | 14.90 | 7.08 | 4.91 |
| Sand | % | 90.71 | 98.93 | 89.53 | 98.26 | 93.49 | 97.79 | 85.10 | 92.92 | 95.09 |
| Soil Class | % | SW | SP | SP-SM | SP | SP-SM | SP | SP-SM | SW | SW |
| Moisture Capacity | mL/kg | 200 | 200 | 150 | 200 | 200 | 150 | 210 | 150 | 130 |

**Table 2.** Physicochemical properties of soil samples.

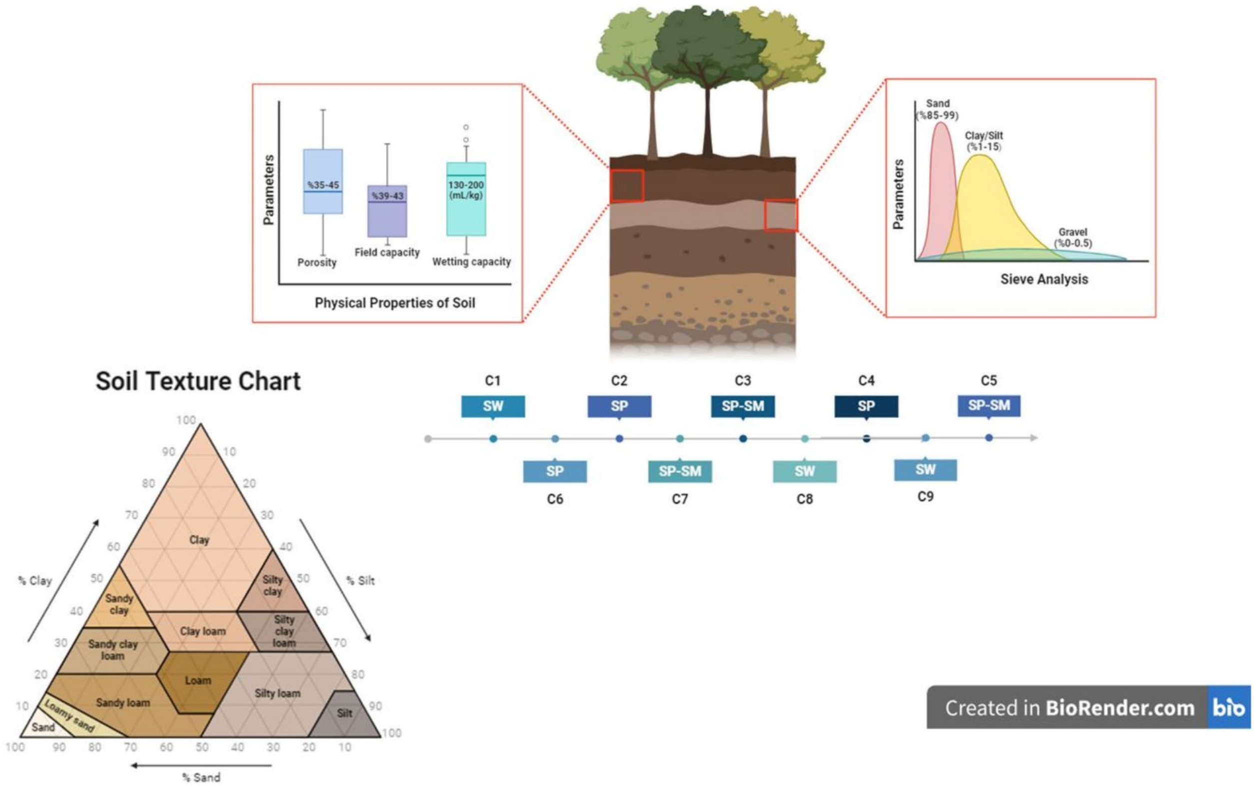


**Fig. 2**. Classification of soil samples according to USCS.

| Heavy metals (mg/kg) | Sample points | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| Cr | 29.81 | 55.63 | 31.97 | 28.29 | 34.2 | 30.09 | 0 | 26.6 | 11.98 |
| Cu | 35.82 | 14.66 | 9.655 | 11.51 | 33.18 | 10.8 | 0 | 11.87 | 8.348 |
| Ni | 25.17 | 50.23 | 46.06 | 49.87 | 214.4 | 23.89 | 0 | 30.34 | 25.26 |
| Pb | 39.33 | 14.89 | 11.58 | 13.56 | 32.79 | 11.58 | 0 | 13.3 | 10.09 |
| Zn | 181.2 | 219.9 | 137.2 | 154.6 | 99.58 | 97.51 | 0 | 108.8 | 166.4 |

**Table 3**. Heavy metal concentrations of soil samples.

high concentration of Pb at some sample points in the soil can be specifically attributed to the proximity of the campus area to highways.

## Pollution assessment of heavy metals in soil

Soil quality in terms of heavy metals was evaluated based on the permissible limits for selected parameters such as Cr, Pb, Ni, Zn, and Cu. In Table 4, the studies conducted on different soils related to heavy metal pollution indices are listed. The studies have examined the regional areas outside the campus territory, and evaluations have been made based on the basic indices in terms of certain heavy metals that create the pollution load. The indices in the literature and those used in this study show similarities.

Table 5 displays the selected power parameters, which are based on the root mean square error (RMSE) values of IDW interpolation. According to the results the lowest RMSE value was obtained from $I_{geo}$-Cu distribution. The less accurate IDW estimations were done for Ni for all indices.

## Geo-accumulation index (Igeo) values

The geo-accumulation index ($I_{geo}$) is used to measure soil pollution caused by heavy metals and classify the state of pollution at seven levels from low pollution to high pollution[63,64]. In order to assess the pollution status of heavy metals in the soil located in the campus area, $I_{geo}$ values were calculated as the pollution index for individual heavy metals[65] (Table 6).

It was found that the average $I_{geo}$ values of heavy metals in the soil throughout the campus area were as follows: Ni > Cr > Zn > Pb > Cu. The results of $I_{geo}$ values are mapped in Fig. 3. Since the average Igeo values for heavy metals (Cr, Ni, Zn, Pb, Cu) at all soil sampling points were in the range $0 \leq$ Igeo < 1, the campus soils

| Indexes | Heavy metals | Purpose of the study | References |
|---|---|---|---|
| ER | Cd, Pb, Zn, Cu | Evaluation of agricultural and urban soil quality in terms of heavy metal pollution | Askari et al.[54] |
| $I_{geo}$ | Zn, Cr, Pb, Cu, Ni, Cd | Evaluation of landfill soil quality according to ecological heavy metal risk | Ogundele et al.[55] |
| CF, $I_{geo}$, EF, PLI, RI | Cd, Co, Cr, Fe, Mn, Ni, Pb, Zn | Evaluation of soil quality according to the health risk caused by heavy metals | Adebiyi and Ayeni[56] |
| EF, CF, $I_{geo}$ | Cr, Ni, Fe, Co | Sources of heavy metal pollution in urban soil and ecological risk assessment | Moghtaderi et al.[57] |
| $I_{geo}$, CF, RI | Cu, Cr. Pb, Co | Heavy metal pollution assessment of roadside agricultural soil | Dogra et al.[58] |
| CF, $I_{geo}$, RI | As, Cd, Cr, Ni, Pb | Soil pollution assessment around Iran's Nishapur industrial zone | Mohammadi et al.[59] |
| $I_{geo}$, PLI, EF, CF, Er | Fe, Ni, Cr, Pb, Zn, As, Co, Al | Assessment of metal contamination affecting quality in surface soil | Jain et al.[60] |
| CF, PLI, $I_{geo}$ | Zn, Cr, Ni, Pb, Hg, Cd | Assessment of heavy metal pollution in some soils around Colombia | Eliana Andrea et al.[61] |
| EF, CF, RI | Zn, Cu, Fe, Mn | Assessment of ecological risk of agricultural soil quality in terms of metal pollution | Heidari et al.[62] |
| CF, $I_{geo}$, EF, PLI, RI | Cr, Cu, Pb, Ni, Zn, Fe | Mapping heavy metal source distribution in Campus soils and determining soil quality | This study |

**Table 4.** Comparison of pollution indices used for different soils.

| Index | Power level* | RMSE | Index | Power level* | RMSE |
|---|---|---|---|---|---|
| $I_{geo}$ Cr | 1 | 1.98 | EF Cr | 1 | 11.5 |
| | 2 | 1.95 | | 2 | 11.19 |
| | **3** | **1.93** | | **3** | **11** |
| $I_{geo}$ Cu | 1 | 0.039 | EF Cu | **1** | **16.09** |
| | **2** | **0.038** | | 2 | 16.53 |
| | 3 | 0.039 | | 3 | 17.2 |
| $I_{geo}$ Pb | 1 | 0.192 | EF Pb | 1 | 3.02 |
| | **2** | **0.192** | | **2** | **3** |
| | 3 | 0.194 | | 3 | 3.01 |
| $I_{geo}$ Ni | 1 | 2.19 | EF Ni | 1 | 17.04 |
| | 2 | 2.16 | | **2** | **16.78** |
| | **3** | **2.15** | | 3 | 16.79 |
| $I_{geo}$ Zn | 1 | 0.17 | EF Zn | 1 | 6.12 |
| | 2 | 0.16 | | 2 | 5.8 |
| | **3** | **0.157** | | **3** | **5.52** |
| Cf Cr | 1 | 5.14 | PLI | 1 | 1.16 |
| | 2 | 5.05 | | 2 | 1.13 |
| | **3** | **5** | | **3** | **1.12** |
| Cf Cu | **1** | **0.4** | | | |
| | 2 | 0.42 | | | |
| | 3 | 0.43 | | | |
| Cf Pb | 1 | 0.75 | | | |
| | **2** | **0.741** | | | |
| | 3 | 0.742 | | | |
| Cf Ni | 1 | 6.62 | | | |
| | 2 | 6.53 | | | |
| | **3** | **6.49** | | | |
| Cf Zn | 1 | 0.79 | | | |
| | 2 | 0.77 | | | |
| | **3** | **0.75** | | | |

**Table 5.** RMSE values of different order levels for IDW. *Bold values were selected for IDW interpolation maps.

were classified as unpolluted or moderately polluted. The results showed that the geo-accumulation index was less than 1 at many points in the campus area, which indicated that the campus site had low pollution (Table 1). In particular, the $I_{geo}$ values of Cr and Ni at point S1 were calculated as 5.98 and 6.70, respectively. These values indicate extreme pollution according to Table 1 ($I_{geo} \geq 5 \rightarrow$ extremely dirty) for both Cr and Ni. According to the $I_{geo}$ values, a change in soil quality was observed in terms of Cr and Ni at point S1. The high $I_{geo}$ values of the specified heavy metals indicate a strong spread in the soil[66]. The geo-accumulation index generally maintains a non-polluting status and can predict the impact of geogenic activity on the soil both for the past and the future[67].

| Samples | $I_{geo}$-Cr | $I_{geo}$-Cu | $I_{geo}$-Ni | $I_{geo}$-Zn | $I_{geo}$-Pb |
|---|---|---|---|---|---|
| S1 | 5.98 | 0.13 | 6.70 | 0.52 | 0.63 |
| S2 | 0.11 | 0.054 | 0.15 | 0.63 | 0.25 |
| S3 | 0.20 | 0.062 | 0.28 | 0.41 | 0.19 |
| S4 | 0.38 | 0.048 | 0.36 | 0.45 | 0.22 |
| S5 | 0.08 | 0.12 | 0.48 | 0.32 | 0.58 |
| S6 | 0.09 | 0.04 | 0.07 | 0.29 | 0.21 |
| S7 | 0.032 | 0.022 | 0.042 | 0.038 | 0.10 |
| S8 | 0.14 | 0.046 | 0.50 | 0.34 | 0.25 |
| S9 | 0.12 | 0.034 | 0.41 | 0.31 | 0.20 |
| ∑Samples | 7.13 | 0.56 | 8.99 | 3.31 | 2.63 |
| ∑Mean | 0.79 | 0.06 | 0.99 | 0.37 | 0.29 |

**Table 6**. $I_{geo}$ values of selected heavy metals in Aksaray Campus soil.

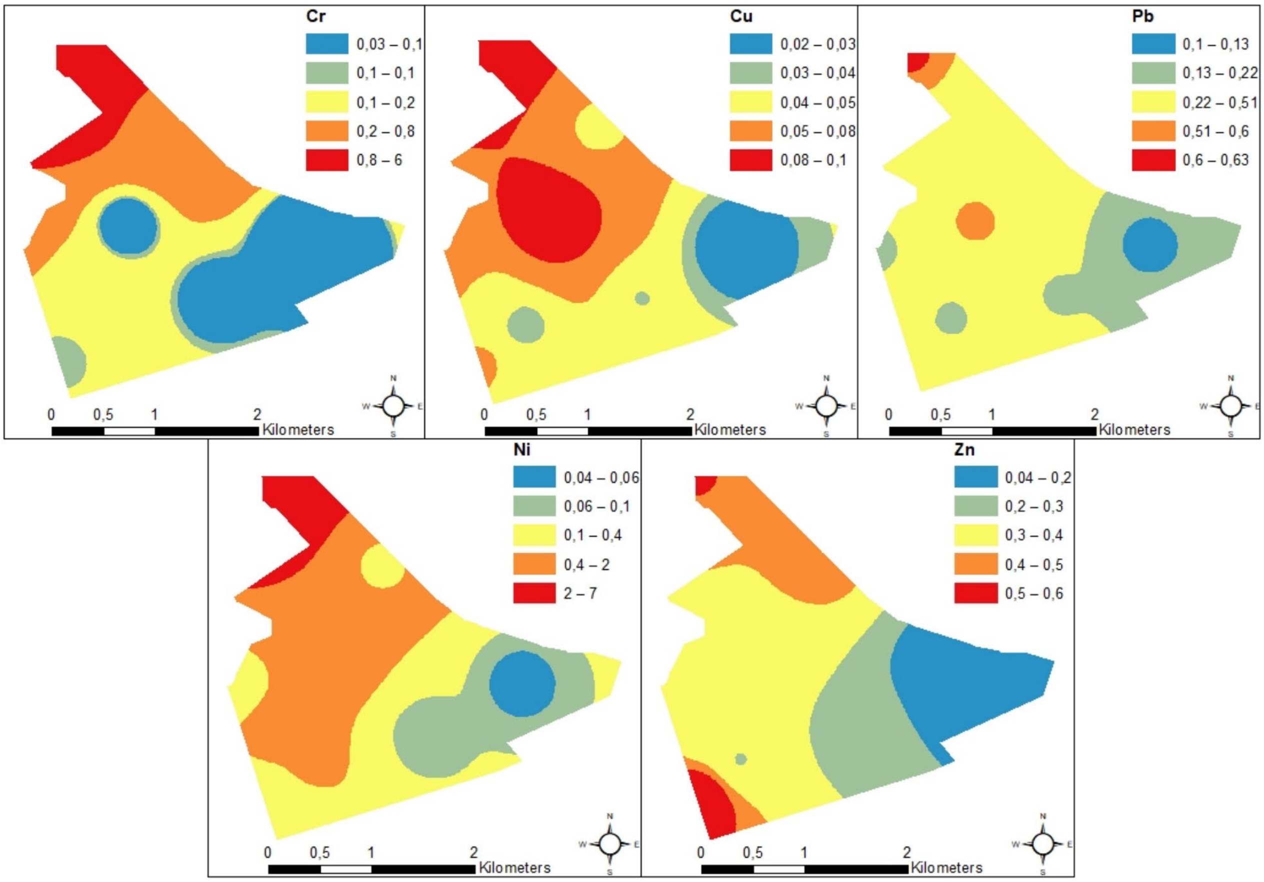


**Fig. 3**. Pollution map of the study area according to the $I_{geo}$ index.

*Enrichment factor (EF)*

In terms of determining the contamination sources of selected heavy metals, values of the Enrichment factor (EF) are more advantageous compared to the $I_{geo}$ index. If the EF index value varies between 0.5 and 1.5, this means that there is pollution caused by the natural structure of the environment (i.e., soil). If the EF value is bigger than 1.5, the cause of heavy metal-induced pollution in the soil is due to anthropogenic activity[68]. The EF approach is adopted to determine the sources contributing to the heavy metal concentration in the soils on the campus. EF is a widely used measure to determine the extent to which the concentration of pollutants has increased due to anthropogenic activities. The EF method has been used as a tool for the assessment of heavy metal pollution in various environmental media by various researchers[69,70]. The EF pollution categories generally accepted for determining the pollution source are given in Table 1. The enrichment factor (EF) values of the heavy metals selected from the soil samples in the campus area are given in Table 7. The EF values for Cr range from 0.23 (S7) to 36.48 (S1), and the mean is 6.21, which indicates a significant/meaningful enrichment. This result is in agreement with the findings of Raji et al.[71], who reported the contamination of Cr to be significant enriched. While the EF values for Cu range between 0.52 (S7: EF < 2 → Minimum enrichment) and 48.25 (S5: EF ≥ 40 → extremely high enrichment) (the mean value is 12.33), the EF values for Ni range from 1.52 (S7: EF < 2 → Minimum enrichment) to 54.06 (S1: EF ≥ 40 → extremely high enrichment) and the mean is 12.27. The average EF values for Cu (12.33) and Ni (12.27) were in the range 5 ≤ EF < 20, the campus soils were classified as significant/meaningful enrichment. These results are similar to the EF value of Ni reported by Denny et al.[69] and Cai and Li[72]. Cu is considered to be an anthropogenic derived metal which is obtained mainly from vehicle brake pads. Therefore, the EF value of Cu for high traffic areas. The EF values for Zn are between 2.1 (S7) and 23.19 (S2) (the mean is 10.18), which means that Zn is significantly enriched in soil samples. The EF values for Pb range from 1.23 (S7) to 11.83 (S5). The mean Pb value is 5.89 and shows moderate enrichment. This result is consistent with the findings of Gruszecka-Kosowska[73], which can be attributed to the fact that Pb pollution is largely caused by anthropogenic activities. The EF values of the study area are mapped in Fig. 4.

As seen in Fig. 4, Cu and Pb heavy metals are much denser in the places indicated as circulation areas where students are actively present. Numerous studies have explained that the presence of various heavy metals such as Ni in agricultural soils may be due to fertilizer application. As a result, it can be said that the contamination of agricultural soils on the campus area with heavy metals is linked to the use of fertilizers and pesticides. Therefore, while it is interpreted that the EF values of heavy metals in the soils on the campus area are primarily due to anthropogenic sources, it should not be ignored that these elements originate from the main materials of the soil. Situations where the EF value is greater than 5 indicate relative enrichment, and this can be attributed to a potential interaction between natural structure and anthropogenic sources[67]. However, significant enrichment in terms of all heavy metals in the study area points to anthropogenic sources with a strong probability.

*Degree of contamination (Cdeg) and potential ecological risk (RI) values*

The sum of the mean of the contamination factors gives the study area's degree of contamination ($C_{deg}$). The ecological risk index (RI) and $C_{deg}$ are two of the most common indices used to assess environmental risks. $C_{deg}$ and RI values are presented in Table 8. The mean of $C_{deg}$ values is 20.60 for the selected heavy metals at all points; however, $C_{deg}$ values of Cr and Ni are above the mean. At the sample points determined in the campus area, Ni indicates a high degree of contamination with a value of 39.49. Whereas Cr (32) and Zn (16.72) show significant contamination, Pb (12.3) and Cu (2.48) show moderate and low contaminations, respectively. Based on the $C_{deg}$ classification, it can be said that there is significant anthropogenic contamination at points with $C_{deg} \geq 24$. High $C_{deg}$ values indicate various degrees of contamination during periods when the transportation line and campus life are active. Changes in the distribution of pollution in the locations are affected by settlements and industrial enterprises near the campus area.

The ecological risk index (RI) is widely used to evaluate heavy metal pollution, ecological risk, bio-benefit, and toxicity in soil[74]. In the context of the study it was determined that the RI values ranged from 61.5 to 197.45 and the mean was 70.41. As a result of the analysis performed on nine soil samples, a low degree of ecological risk was observed in the campus area (except for Pb and Ni). With a value of 197.45, Ni showed medium ecological risk. The data related to the RI values were similar to the $C_{deg}$ values. The contamination factor (CF) values of the study area are mapped in Fig. 5. As shown in Fig. 5, the low CF values at nine sampling points within the study area indicate that the use of chemical fertilizers and pesticides is limited around the campus. For Ni, on the other hand, the soil structure and the impact of industrial activities around the campus may pose a risk. While CF values indicate the extent of contamination, they also help to assess the anthropogenic impact on heavy metal levels in the soils of the study area.

*Pollution load index (PLI) values*

Many researchers have investigated the distribution of pollutants in the soil structure based on PLI values. When the concentration of the elements belonging to the PLI values of the soil is above 1, it refers to the effect of anthropogenic activities[51]. The PLI values for the selected elements are given in Table 9. The mean PLI value of

| Samples | EF-Cr | EF-Cu | EF-Ni | EF-Zn | EF-Pb |
|---|---|---|---|---|---|
| S1 | 36.48 | 22.13 | 54.06 | 7.21 | 8.24 |
| S2 | 2.4 | 9.16 | 3.92 | 23.19 | 5.93 |
| S3 | 4.2 | 7.9 | 8.9 | 12 | 5.42 |
| S4 | 5.43 | 2.4 | 6.2 | 13.46 | 4.87 |
| S5 | 2.46 | 48.25 | 22 | 8.7 | 11.83 |
| S6 | 1.12 | 4.2 | 2.6 | 4.2 | 4.56 |
| S7 | 0.23 | 0.52 | 1.52 | 2.1 | 1.23 |
| S8 | 1.84 | 9.83 | 7.25 | 9.2 | 5.75 |
| S9 | 1.72 | 6.57 | 4 | 11.58 | 5.24 |
| ∑Samples | 55.88 | 110.96 | 110.45 | 91.64 | 53.07 |
| ∑Mean | 6.21 | 12.33 | 12.27 | 10.18 | 5.89 |

**Table 7.** EF values of selected heavy metals in Aksaray Campus soil.

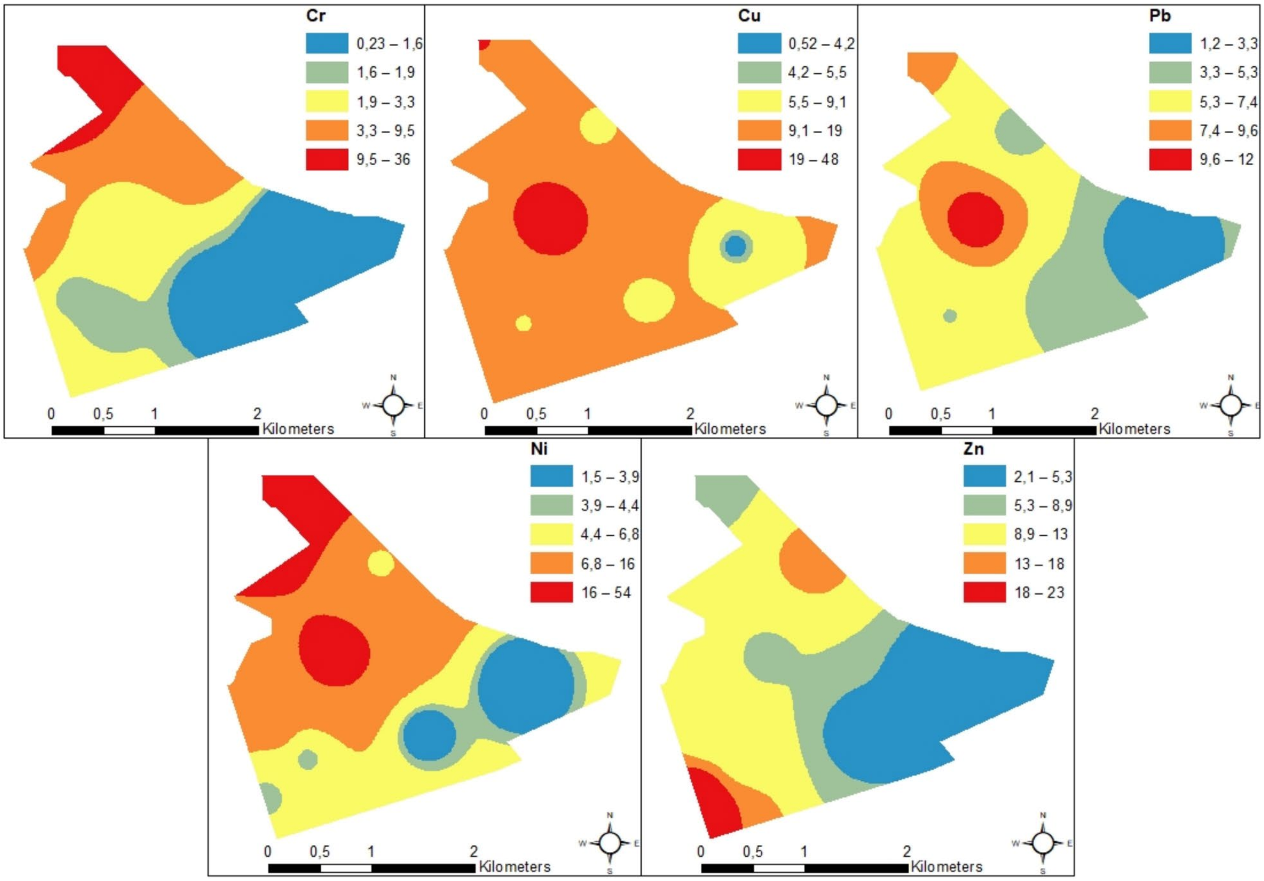


**Fig. 4**. Pollution map of the study area according to the EF index.

| Selected Heavy metals | RI | $C_{deg}$ |
|---|---|---|
| Cr | 64 | 32 |
| Cu | 12.4 | 2.48 |
| Ni | 197.45 | 39.49 |
| Zn | 16.72 | 16.72 |
| Pb | 61.5 | 12.3 |
| ∑Samples | 352.07 | 102.99 |
| ∑Mean | 70.41 | 20.60 |

**Table 8**. $C_{deg}$ and RI values for selected heavy metals in Aksaray campus soils.

the study area was 1.46 so it could be said that there was a below mediocre contamination of heavy metals in the campus area. The highest contamination was seen in the first sample location (S1) and the lowest was in S7. The PLI values of the study area are mapped in Fig. 6. As shown in Fig. 6, the PLI values for nine soil samples showed that 25% of them were polluted soils and 75% were moderately/highly polluted soils. The spatial distribution map of the PLI values is shown in Fig. 6. According to this map, the soils in the campus entrance area and areas where anthropogenic activity is intense show moderate pollution. Based on the high PLI values in these parts of the study area, the active and traffic flow times of the campus can be shown as possible sources of pollution.

## Source distribution of heavy metals

Pearson correlation analysis and APCS-MLR multivariate statistical analysis were performed to see the correlation between the 5 heavy metals examined in the study area and to determine the effect of possible sources on heavy metals in the soil. Pearson correlation coefficients are shown in Fig. 7. According to the results, the interactions between heavy metals were as follows: Cu-Ni ($R=0.921$), Ni-Pb ($R=0.937$), Ni-Cr ($R=0.878$), Cr-Ni ($R=0.948$), Cr-Zn ($R=0.867$), Zn-Cr ($R=0.756$), Zn-Cu ($R=0.905$), Pb-Cr ($R=0.779$), and Pb-Cu ($R=0.728$) ($p<0.01$). High correlation values between Pb, Cr, Cu, Zn, and Ni showed that these heavy metals

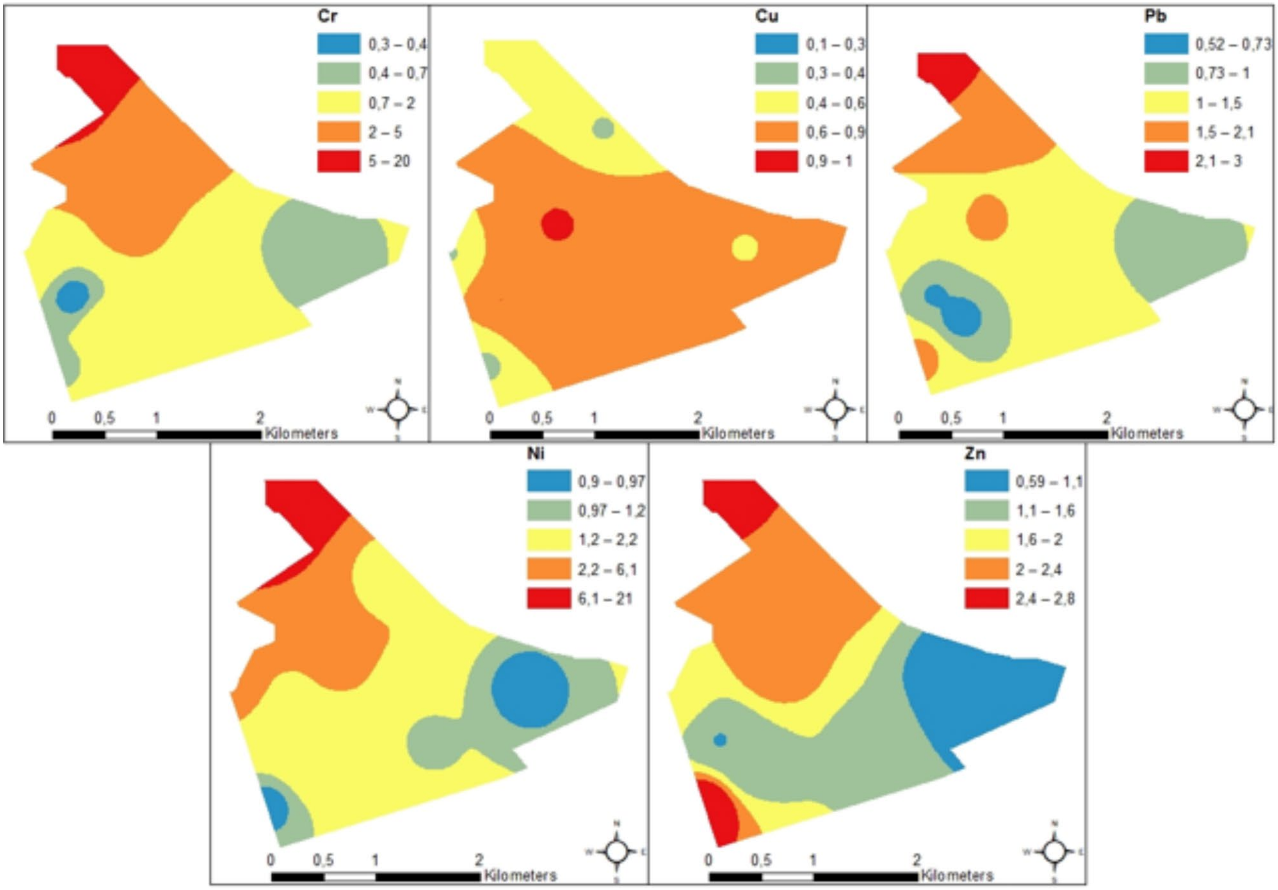


**Fig. 5**. Pollution map of the study area according to the CF index.

| Samples | PLI |
|---|---|
| S1 | 4.42 |
| S2 | 0.83 |
| S3 | 1.25 |
| S4 | 1.27 |
| S5 | 1.81 |
| S6 | 1.12 |
| S7 | 0.65 |
| S8 | 0.80 |
| S9 | 0.96 |
| ∑Samples | 13.11 |
| ∑Mean | 1.46 |

**Table 9**. PLI values for selected heavy metals in Aksaray Campus soil.

might be related to common sources available in the soil[23]. However, in addition to correlation changes, spatial variability can also increase the diversity of sources. Taking into account the processes before and after the establishment of the campus area, four main sources of pollution were selected as targets in the territory of the region. After the selection, the APCS-MLR model was applied to determine the relative contribution rate of each source[75,76]. Based on the multiple linear regression analysis, the effects of four different source types on Pb, Cr, Cu, Zn, and Ni are shown in Table 10.

The variation of the correlation coefficient ($R^2$) values between 0.832 and 0.957 showed that the APCS-MLR model used in this study was effective and the obtained results were reliable. Moreover, these results showed consistency with PCA results. Using the APCS-MLR model, four factors, which are called Source 1, Source 2, Source 3, and Source 4, respectively, were created. As shown in Fig. 7b, the cumulative contribution rates of these sources were found to be 60.6%, 25.4%, 8%, and 6%, respectively. Source 1 relatively covers Cr (75%), Ni (78%),

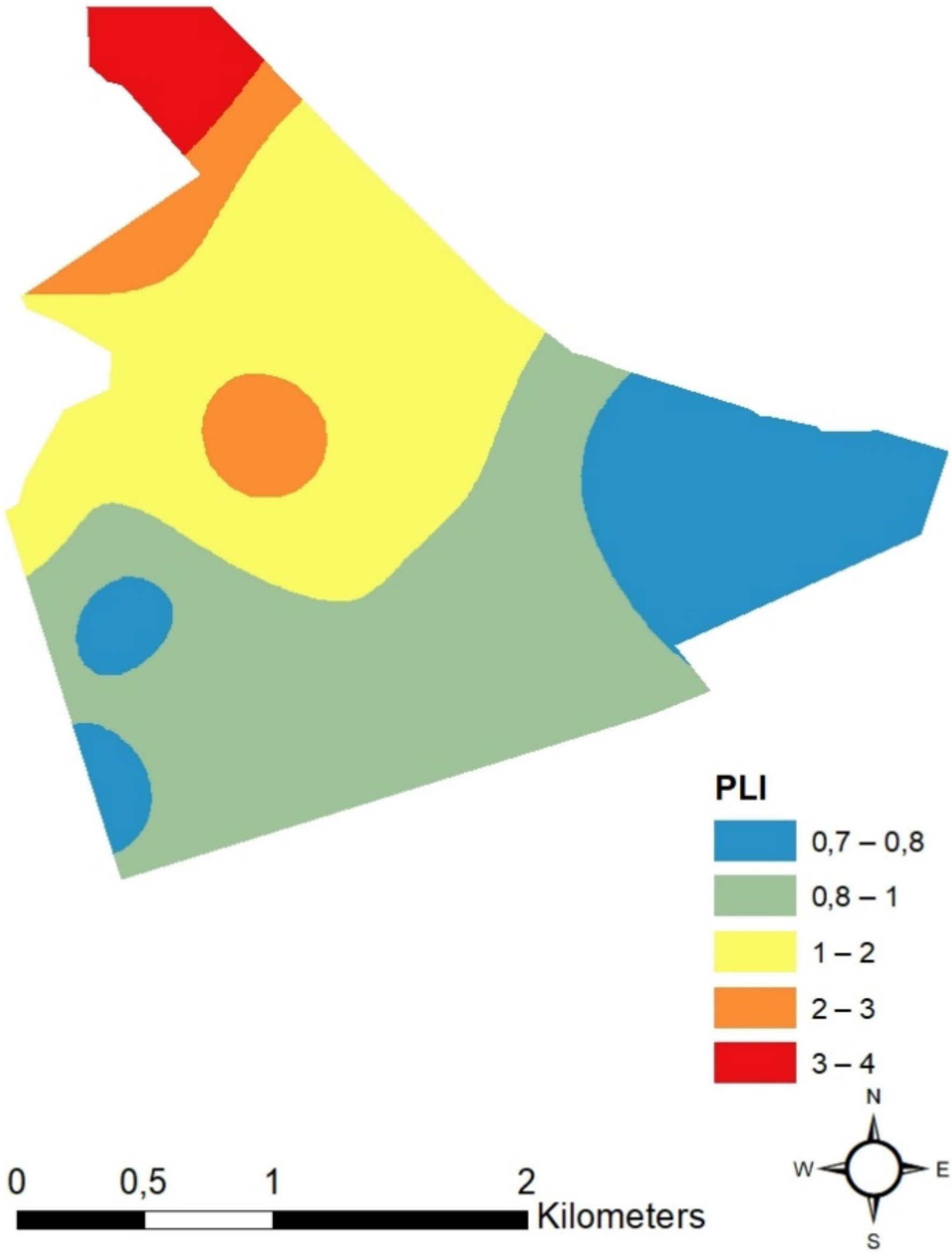


**Fig. 6**. Pollution map of the study area according to the PLI index.

Cu (70%), and Zn (65%) heavy metals. Many previous studies have revealed that Cr, Ni, Zn, and Cu originate from the main structure of the soil[25,76]. Pearson analysis also revealed that these heavy metals exhibited strong correlations. As a result, Source 1 can be interpreted as natural sources coming from the soil structure. Source 2 can only be identified by Pb (80%). The mean contents of the Pb explain in relative terms that Source 2 covers anthropogenic sources. In the literature, it has been stated that the Pb in the soil comes from anthropogenic sources, which mainly cover traffic emissions[75,77]. In addition, it has been emphasized that Cd has always been related to industrial production[78]. Therefore, Source 2 has been attributed to the mixed sources of industrial and

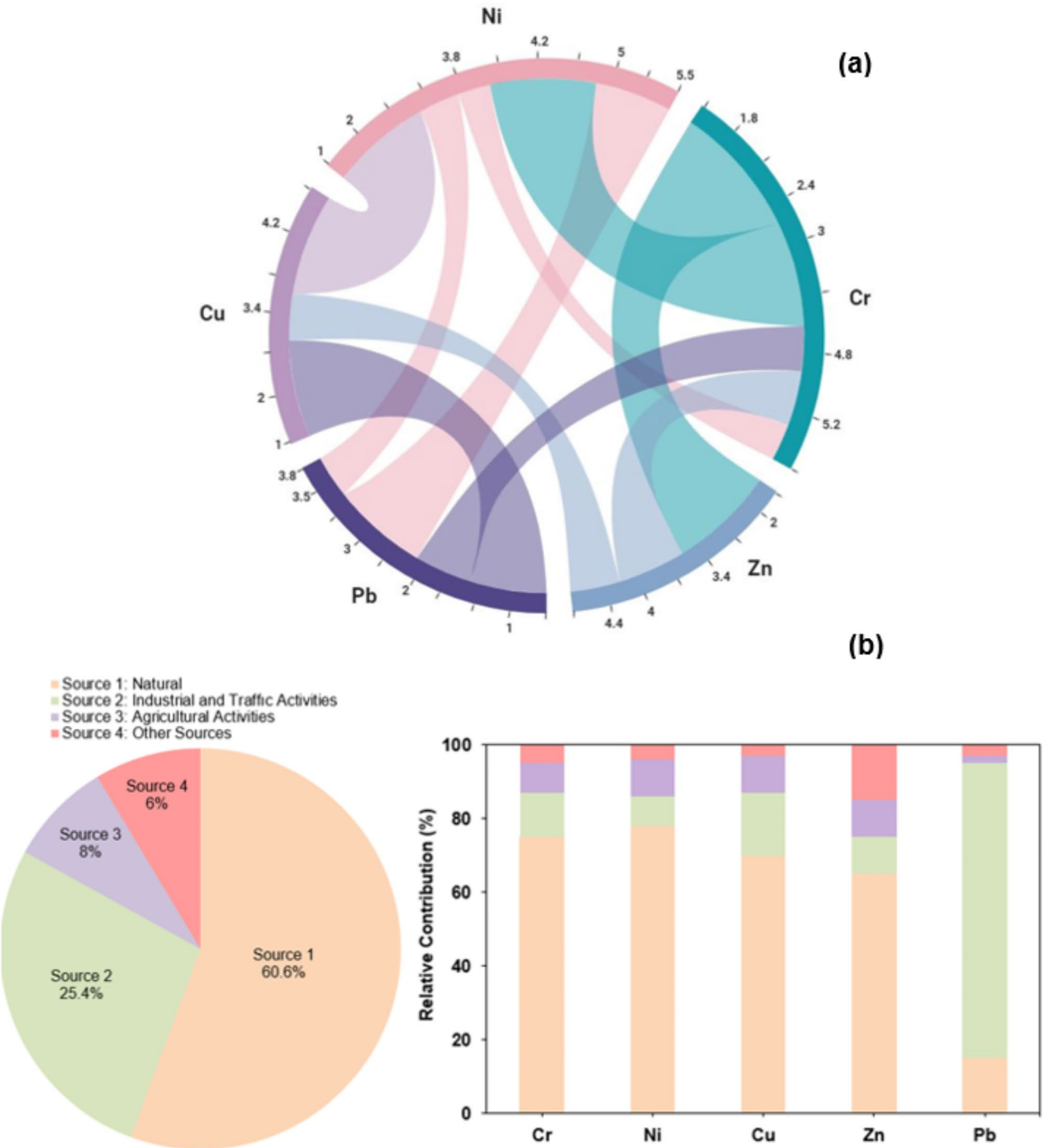


**Fig. 7**. Relative source analysis of heavy metals in soil throughout Aksaray Campus by combining Pearson correlation analysis (**a**) and APCS-MLR (**b**).

traffic activities. According to previous research, Source 3 is strongly associated with agricultural activities[25]. It can be said that in soil, Cr, Cu, Zn, and Ni enrichment, except for Pb, is partially related to agricultural activities such as irrigation and the use of fertilizers and pesticides in agricultural production. Especially for Zn, source 4 represents other sources such as atmospheric accumulation. This type of source has been expressed as other sources. In their study, Liu et al.[76] and Chen et al.[79] revealed that atmospheric accumulation always results in the accumulation of heavy metals. Pearson correlation analysis and APCS-MLR results showed that heavy metal sources in soils along intercity and urban transportation lines, such as Adana-Aksaray and Konya-Aksaray, and settlement places might consist of four main sources. The distribution of sources was sorted from the largest to the smallest as follows; natural sources (60.6%), industrial and traffic activities (25.4%), agricultural activities (8%), and other sources (6%). It was revealed that natural sources were the primary determinants of Cr, Cu,

| Parameter | Relative model | $R^2$ |
|---|---|---|
| Ni | $C_{HM} = 0.758 + 0.465APCS/MLR_{S1} + 0.246APCS/MLR_{S2} + 2.8APCS/MLR_{S3}$ | 0.957 |
| Cr | $C_{HM} = 0.937 + 1.586\ APCS/MLR_{S1} + 3.834\ APCS/MLR_{S2} + 4.296\ APCS/MLR_{S3}$ | 0.936 |
| Cu | $C_{HM} = -2.79 + 6.894\ APCS/MLR_{S1} + 1.96\ APCS/MLR_{S2} + 1.289\ APCS/MLR_{S3}$ | 0.884 |
| Zn | $C_{HM} = 7.362 + 8.314\ APCS/MLR_{S1} + 4.876\ APCS/MLR_{S2} - 5.238\ APCS/MLR_{S3}$ | 0.832 |
| Pb | $C_{HM} = 3.45 + 1.357\ APCS/MLR_{S1} + 12.584\ APCS/MLR_{S2} - 0.708\ APCS/MLR_{S3}$ | 0.934 |

**Table 10**. Parameters of APCS-MLR model based on multiple linear regression. S1: Natural sources; S2: Industrial/anthropogenic and traffic activities; S3: Agricultural activities; S4: Other sources.

Zn, and Ni, and the natural source effect was lower for Pb. Pb was mostly obtained from anthropogenic sources occurring due to industrial and traffic activities, while Cr, Cu, Zn, and Ni were affected primarily by natural sources, and then by agricultural activities.

## Conclusion

In this study, EF, CF, $I_{geo}$, PLI and other indices were used to investigate the pollution status of Cr, Ni, Zn, Cu, and Pb in the campus soil. In addition, APCS-MLR model and geochemical factors were used for the sources and distribution of these heavy metals. The mean $I_{geo}$ values of heavy metals in the soil throughout the campus area were found to be Ni > Cr > Zn > Pb > Cu. The results revealed that $I_{geo}$ values were less than 1 at many points in the campus. Analysis of $I_{geo}$ values revealed that Cr was the main pollutant in the soils on the south side with moderate pollution. EF results show that the soil has moderate or significant enrichment. The study revealed that areas with heavy traffic or vehicle movements are effective factors in terms of EF. Based on the results of APCS-MLR analyses conducted to identify heavy metal sources, the distribution of pollutant sources was determined as follows: natural sources (60.6%), industrial and traffic activities (25.4%), agricultural activities (8%), and other sources (6%). In general, this research provides important information about the heavy metal pollution in the soil along the intercity highway. Although the potential ecological and health risks in this area of study are relatively low, the accumulation of heavy metals in the soil should be constantly monitored.

## Data availability

All data generated or analysed during this study are included in this published article.

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## References

1. Zhou, F. et al. The effect of the synergistic thermal treatment and stabilization on the transformation and transportation of arsenic, chromium, and cadmium in soil. *Sci. Total Environ.* **907**, 167948 (2024).
2. Gan, Z. et al. Method of smoldering combustion for the treatment of oil sludge-contaminated soil. *Waste Manag.* **175**, 73–82 (2024).
3. Oba, B. T. et al. Application of KHSO5 for remediation of soils polluted by organochlorides: a comprehensive study on the treatment's efficacy, environmental implications, and phytotoxicity. *Sci. Total Environ.* **871**, 162023 (2023).
4. Petitjean, M., Randoux, Y., Jordens, A., Saadaoui, H. & Haemers, J. Low-complexity mapping of soil temperature for thermal treatment follow-up. *J. Contam. Hydrol.* **250**, 104056 (2022).
5. Sun, Y. et al. Application of the partial least square regression method in determining the natural background of soil heavy metals: a case study in the Songhua River basin, China. *Sci. Total Environ.* **918**, 170695 (2024).
6. Sun, Y. et al. Spatial distribution prediction of soil heavy metals based on sparse sampling and multi-source environmental data. *J. Hazard. Mater.* **465**, 133114 (2024).
7. Luo, S. et al. Urban green space area mitigates the accumulation of heavy metals in urban soils. *Chemosphere*. **352**, 141266 (2024).
8. Hu, Y. et al. Revolutionizing soil heavy metal remediation: cutting-edge innovations in plant disposal technology. *Sci. Total Environ.* **918**, 170577 (2024).
9. Mai, X. et al. Research progress on the environmental risk assessment and remediation technologies of heavy metal pollution in agricultural soil. *J. Environ. Sci.* **149**, 1–20 (2025).
10. Liu, F. et al. Impact of different industrial activities on heavy metals in floodplain soil and ecological risk assessment based on bioavailability: a case study from the Middle Yellow River Basin, northern China. *Environ. Res.* **235**, 116695 (2023).
11. Chen, D. et al. Spatial distribution, ecological risk and health risk assessment of heavy metals in agricultural soil from Ankang Basin, Shaanxi Province. *Heliyon*. **9**, e22580 (2023).
12. Ju, L., Guo, S., Ruan, X. & Wang, Y. Improving the mapping accuracy of soil heavy metals through an adaptive multi-fidelity interpolation method. *Environ. Pollut*. **330**, 121827 (2023).
13. Man, J., Zeng, L., Luo, J., Gao, W. & Yao, Y. Application of the Deep learning algorithm to identify the spatial distribution of heavy metals at contaminated sites. *ACS ES&T Eng.* **2**, 158–168 (2022).
14. Yao, L. et al. Estimating of heavy metal concentration in agricultural soils from hyperspectral satellite sensor imagery: considering the sources and migration pathways of pollutants. *Ecol. Indic.* **158**, 111416 (2024).
15. Tulun, Ş., Gürbüz, E. & Arsu, T. Developing a GIS-based landfill site suitability map for the Aksaray province, Turkey. *Environ. Earth Sci.* **80**, 310 (2021).
16. Díaz Alarcón, J. A. et al. Assessment of potentially hazardous elements in soils of the Boyacá industrial corridor (Colombia) using GIS, multivariate statistical analysis, and geochemical indexes. *Ecotoxicol. Environ. Saf.* **269**, 115725 (2024).
17. Lv, H. et al. Pollution characteristics and quantitative source apportionment of heavy metals within a zinc smelting site by GIS-based PMF and APCS-MLR models. *J. Environ. Sci.* **144**, 100–112 (2024).
18. Alharbi, T., El-Sorogy, A. S. & Al-Kahtany, K. Contamination and health risk assessment of potentially toxic elements in agricultural soil of the Al-Ahsa Oasis, Saudi Arabia using health indices and GIS. *Arab. J. Chem.* **17**, 105592 (2024).

19. Hossain Bhuiyan, M. A., Karmaker, C., Bodrud-Doza, S., Rakib, M., Saha, B. B. & M. A. & Enrichment, sources and ecological risk mapping of heavy metals in agricultural soils of Dhaka district employing SOM, PMF and GIS methods. *Chemosphere*. **263**, 128339 (2021).
20. Jin, G. et al. Source apportionment of heavy metals in farmland soil with application of APCS-MLR model: a pilot study for restoration of farmland in Shaoxing City Zhejiang, China. *Ecotoxicol. Environ. Saf.* **184**, 109495 (2019).
21. Shi, H. et al. Health Risk Assessment of Heavy Metals in Groundwater of Hainan Island using the Monte Carlo Simulation Coupled with the APCS/MLR model. *Int. J. Environ. Res. Public. Health*. **19**, 7827 (2022).
22. Wu, Q. et al. Spatial distribution, ecological risk and sources of heavy metals in soils from a typical economic development area, Southeastern China. *Sci. Total Environ.* **780**, 146557 (2021).
23. Zhang, L., Liu, Y., Wang, Y., Li, X. & Wang, Y. Investigation of phosphate removal mechanisms by a lanthanum hydroxide adsorbent using p-XRD, FTIR and XPS. *Appl. Surf. Sci.* **557**, 149838 (2021).
24. Su, C. et al. Sources and health risks of heavy metals in soils and vegetables from intensive human intervention areas in South China. *Sci. Total Environ.* **857**, 159389 (2023).
25. Duan, H. et al. Spatial distribution, risk assessment and sources of heavy metals in roadside soils exposed to the Zhengzhou-Kaifeng Intercity Railway in Huanghuai Plain, China. *Soil. Sediment. Contam. Int. J.* **33**, 1463–1484 (2024).
26. Ramakreshnan, L., Fong, C. S., Rajandra, A., Sulaiman, N. M. & Aghamohammadi, N. Addressing built environment gaps for the enhancement of campus walkability using community needs assessment approach. *Case Stud. Transp. Policy*. **15**, 101167 (2024).
27. Pakdeewanich, C., Anantavrasilp, I. & Tiyarattanachai, R. Factors influencing the usage of bicycles on university campuses: a case study of universities in Thailand. *Case Stud. Transp. Policy*. **14**, 101105 (2023).
28. Demirela, G., Yılmazer, E. & Kavurmacı, M. Aksaray Üniversitesi Kampüs Alanının Hidrojeokimyasal, Jeoteknik ve Toprak Jeokimyası Karakteristikleri, Aksaray. *Aksaray Univ. J. Sci. Eng.* **4**, 90–112 (2020).
29. Sayılarla, A. S. Ü. https://www.aksaray.edu.tr/sayilarla/?k=19&r=77
30. Nelson, D. W. & Sommers, L. E. Total Carbon, Organic Carbon, and Organic Matter. (1996).
31. Rauckyte, T., Żak, S., Pawlak, Z. & Oloyede, A. Determination of oil and grease, total petroleum hydrocarbons and volatile aromatic compounds in soil and sediment samples. *J. Environ. Eng. Landsc. Manag.* **18**, 163–169 (2010).
32. EPA, Method 1664, Revision, A. N-Hexane Extractable Material (HEM; Oil and Grease) and Silica Gel Treated N-Hexane Extractable Material (SGT HEM; Non-Polar Material) by Extraction and Gravimetry. https://www.epa.gov/sites/default/files/2015-08/documents/method_1664a_1999.pdf (1999).
33. Akbay, C., Aytop, H. & Dikici, H. Evaluation of radioactive and heavy metal pollution in agricultural soil surrounding the lignite-fired thermal power plant using pollution indices. *Int. J. Environ. Health Res.* **33**, 1490–1501 (2023).
34. Islam, M. N. et al. Effects of shipwrecks on spatiotemporal dynamics of metal/loids in sediments and seafood safety in the Bay of Bengal. *Environ. Pollut*. **315**, 120452 (2022).
35. Taşpınar, K. et al. Soil contamination assessment and potential sources of heavy metals of alpu plain Eskişehir Turkey. *Int. J. Environ. Health Res.* **32**, 1282–1290 (2022).
36. Aytop, H., Koca, Y. K. & Şenol, S. The importance of using soil series-based geochemical background values when calculating the enrichment factor in agricultural areas. *Environ. Geochem. Health*. **45**, 6215–6230 (2023).
37. Müller, G. Die Schwermetallbelastung Der Sedimente Des Neckars und seiner Nebenflüsse: Eine Bestandsaufnahme. *Chemiker-Ztg.* **105**, 157–164 (1981).
38. Wang, X. et al. Contamination, ecological and health risks of trace elements in soil of landfill and geothermal sites in Tibet. *Sci. Total Environ.* **715**, 136639 (2020).
39. Jadoon, S. et al. Spatial distribution of potentially toxic elements in urban soils of Abbottabad city, (N Pakistan): evaluation for potential risk. *Microchem. J.* **153**, 104489 (2020).
40. Hakanson, L. An ecological risk index for aquatic pollution control.a sedimentological approach. *Water Res.* **14**, 975–1001 (1980).
41. Varol, M., Deliboran, A., Aytop, H. & Ateş, Ö. Boron contamination and related health risk assessment in the soils collected from olive groves in İzmir province, Türkiye. *Chemosphere*. **343**, 140210 (2023).
42. Ferreira, S. L. C. et al. Use of pollution indices and ecological risk in the assessment of contamination from chemical elements in soils and sediments—practical aspects. *Trends Environ. Anal. Chem.* **35**, e00169 (2022).
43. Tahama, K., Baride, A., Gupta, G., Erram, V. C. & Baride, M. V. Spatial variation of sub-surface heterogenieties within the dyke swarm of Nandurbar region, Maharashtra, India, for groundwater exploration using Inverse Distance Weighted technique. *HydroResearch*. **5**, 1–12 (2022).
44. Saha, A., Gupta, B. & Sen, Patidar, S. Martínez-Villegas, N. spatial distribution based on optimal interpolation techniques and assessment of contamination risk for toxic metals in the surface soil. *J. S. Am. Earth Sci.* **115**, 103763 (2022).
45. Proshad, R. et al. Receptor model-based source apportionment and ecological risk of metals in sediments of an urban river in Bangladesh. *J. Hazard. Mater.* **423**, 127030 (2022).
46. Zhang, M. et al. Quantitative source identification and apportionment of heavy metals under two different land use types: comparison of two receptor models APCS-MLR and PMF. *Environ. Sci. Pollut. Res.* **27**, 42996–43010 (2020).
47. Bao, W., Wan, W., Sun, Z., Hong, M. & Li, H. Spatial distribution and migration of heavy metals in dry and windy area polluted by their production in the North China. *Processes* **12**, 160 (2024).
48. Yildiz, U. & Ozkul, C. Heavy metals contamination and ecological risks in agricultural soils of Uşak, western Türkiye: a geostatistical and multivariate analysis. *Environ. Geochem. Health*. **46**, 58 (2024).
49. Tian, K., Huang, B., Xing, Z. & Hu, W. Geochemical baseline establishment and ecological risk evaluation of heavy metals in greenhouse soils from Dongtai, China. *Ecol. Indic.* **72**, 510–520 (2017).
50. Ennaji, W., Barakat, A., El Baghdadi, M. & Rais, J. Heavy metal contamination in agricultural soil and ecological risk assessment in the northeast area of Tadla plain, Morocco. *J. Sediment. Environ.* **5**, 307–320 (2020).
51. Sinduja, M. et al. Evaluation and speciation of heavy metals in the soil of the Sub Urban Region of Southern India. *Soil. Sediment. Contam. Int. J.* **31**, 974–993 (2022).
52. Horasan, B. Y. The environmental impact of the abandoned mercury mines on the settlement and agricultural lands; Ladik (Konya, Turkey). *Environ. Earth Sci.* **79**, 237 (2020).
53. Magesh, N. S., Chandrasekar, N. & Elango, L. Trace element concentrations in the groundwater of the Tamiraparani river basin, South India: insights from human health risk and multivariate statistical techniques. *Chemosphere*. **185**, 468–479 (2017).
54. Askari, M. S., Alamdari, P., Chahardoli, S. & Afshari, A. Quantification of heavy metal pollution for environmental assessment of soil condition. *Environ. Monit. Assess.* **192**, 162 (2020).
55. Ogundele, L. T., Ayeku, P. O., Adebayo, A. S., Olufemi, A. P. & Adejoro, I. A. Pollution indices and potential ecological risks of heavy metals in the soil: A case study of municipal wastes site in Ondo State, Southwestern, Nigeria. *Polytechnica* **3**, 78–86 (2020).
56. Adebiyi, F. M. & Ayeni, D. A. Chemical speciation, bioavailability and risk assessment of potentially toxic metals in soils around petroleum product marketing company as environmental degradation indicators. *Pet. Res.* **7**, 286–296 (2022).
57. Moghtaderi, T., Alamdar, R., Rodríguez-Seijo, A., Naghibi, S. J. & Kumar, V. Ecological risk assessment and source apportionment of heavy metal contamination in urban soils in Shiraz, Southwest Iran. *Arab. J. Geosci.* **13**, 797 (2020).
58. Dogra, N. et al. Pollution assessment and spatial distribution of roadside agricultural soils: a case study from India. *Int. J. Environ. Health Res.* **30**, 146–159 (2020).
59. Mohammadi, A. A. et al. Assessment of Heavy Metal Pollution and Human Health Risks Assessment in Soils around an Industrial Zone in Neyshabur, Iran. *Biol. Trace Elem. Res.* **195**, 343–352 (2020).

60. Jain, C. K., Vaid, U., Sharma, S. K. & Singh, S. Assessment of potentially toxic elements' contamination in surface soils of Kulsi River Basin in North East India. *SN Appl. Sci.* **1**, 673 (2019).
61. Eliana Andrea, M. M., Carolina, A., Tito, T. E., José, C. B. & José Luis, M. N. & Luis Carlos, G.-M. Evaluation of contaminants in agricultural soils in an Irrigation District in Colombia. *Heliyon* **5**, e02217 (2019).
62. Heidari, A., Kumar, V. & Keshavarzi, A. Appraisal of metallic pollution and ecological risks in agricultural soils of Alborz Province, Iran, employing contamination indices and multivariate statistical analyses. *Int. J. Environ. Health Res.* **31**, 607–625 (2021).
63. Mirzaei, M. et al. Ecological and health risks of soil and grape heavy metals in long-term fertilized vineyards (Chaharmahal and Bakhtiari province of Iran). *Environ. Geochem. Health*. **42**, 27–43 (2020).
64. Prasad Ahirvar, B., Das, P., Srivastava, V. & Kumar, M. Perspectives of heavy metal pollution indices for soil, sediment, and water pollution evaluation: an insight. *Total Environ. Res. Themes*. **6**, 100039 (2023).
65. Jamil, M. et al. Multivariate geo-statistical perspective: evaluation of agricultural soil contaminated by industrial estate's effluents. *Environ. Geochem. Health*. **44**, 57–68 (2022).
66. Lv, Y., Kabanda, G., Chen, Y., Wu, C. & Li, W. Spatial distribution and ecological risk assessment of heavy metals in manganese (mn) contaminated site. *Front. Environ. Sci.* **10** (2022).
67. Gao, Z. et al. Characterization of soil trace metal pollution, source identification, and health risk assessment in the middle reaches of the Guihe River Basin. *Environ. Monit. Assess.* **196**, 122 (2024).
68. Mosalem, A., Redwan, M., Abdel Moneim, A. A. & Rizk, S. Distribution, speciation, and assessment of heavy metals in sediments from Wadi Asal, Red Sea, Egypt. *Environ. Monit. Assess.* **196**, 215 (2024).
69. Denny, M., Baskaran, M., Burdick, S., Tummala, C. & Dittrich, T. Investigation of pollutant metals in road dust in a post-industrial city: case study from Detroit, Michigan. *Front. Environ. Sci.* **10**, 974237 (2022).
70. Javid, A. et al. Determination and risk assessment of heavy metals in air dust fall particles. *Environ. Health Eng. Manag.* **8**, 319–327 (2021).
71. Raji, W. A., Jimoda, L. A., Ajani, A. O. & Popoola, A. O. Using enrichment factor approach for source identification of potentially toxic heavy metals along Benin-Ore-Sagamu Expressway in Nigeria. *J. Appl. Sci. Environ. Manag.* **28**, 1281–1286 (2024).
72. Cai, K. & Li, C. Street dust heavy metal pollution source apportionment and sustainable management in a typical City—Shijiazhuang, China. *Int. J. Environ. Res. Public. Health*. **16**, 2625 (2019).
73. Gruszecka-Kosowska, A. Deposited particulate matter enrichment in heavy metals and related health risk: a case study of Krakow, Poland. *Proceedings*. **44**, 230–237 (2019).
74. Amin, S., Muhammad, S. & Fatima, H. Evaluation and risks assessment of potentially toxic elements in water and sediment of the Dor River and its tributaries, Northern Pakistan. *Environ. Technol. Innov.* **21**, 101333 (2021).
75. Gorka, R., Kumar, R., Yadav, S. & Verma, A. Health implications, distribution and source apportionment of heavy metals in road deposited dust of Jammu City in northern India. *Chemosphere*. **308**, 136475 (2022).
76. Liu, H. et al. Heavy metal accumulation in the surrounding areas affected by mining in China: spatial distribution patterns, risk assessment, and influencing factors. *Sci. Total Environ.* **825**, 154004 (2022).
77. Yu, L., Zheng, T., Yuan, R. & Zheng, X. APCS-MLR model: a convenient and fast method for quantitative identification of nitrate pollution sources in groundwater. *J. Environ. Manage.* **314**, 115101 (2022).
78. Sun, J. et al. Determination of priority control factors for the management of soil trace metal(loid)s based on source-oriented health risk assessment. *J. Hazard. Mater.* **423**, 127116 (2022).
79. Chen, K., Liu, Q., Jiang, Q., Hou, X. & Gao, W. Source apportionment of surface water pollution in North Anhui Plain, Eastern China, using APCS-MLR model combined with GIS approach and socioeconomic parameters. *Ecol. Indic.* **143**, 109324 (2022).
80. Muluye, T., Mengistou, S., Hein, T. & Fetahi, T. Sediment evaluation indices point to cadmium and selenium contamination: a simultaneous analysis of potentially toxic elements in the water and sediment along the upper and middle Awash River, Ethiopia. *Environ. Adv.* **17**, 100595 (2024).
81. Tiabou, A. F., Tanyi, T. A. M., Yiika, L. P., Magdaline, M. & Ayuk, A. Spatial distribution, ecological and ecotoxicity evaluation of heavy metals in agricultural soils along Lala-Manjo Highway, Cameroon Volcanic line. *Discov. Soil.* **1**, 7 (2024).

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