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*Original Research*

# Environmental Risk Assessment of Heavy Metals in Cultivated Soils Around Industrial Area and Source Identification under APCS-MLR Model: a Case of Suzhou in Northern China

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**Abstract**

To investigate the impact of industrial activities on the environmental accumulation and the health risks to humans of heavy metals in urban soils, the cultivated soil samples around different industrial areas were collected and analyzed. The heavy metal concentrations in the soil samples were in the decreasing order Mn>Zn>Cr>Ni>Cu>Pb>As>Sn>Cd>Hg, and the average concentrations of all heavy metals exceeding the corresponding background values. In addition to Cd and Hg, all the other eight metals were classified as low ecological risk; Cd had low, moderate, and considerable ecological risk and Hg were in low, high, and very high ecological risk. The proportion of RI in the four ecological risk levels of low risk, moderate risk, considerable risk and high risk were 69.6%, 13%, 8.7% and 8.7%, respectively. All Mn and some Cr pose non-carcinogenic risk to children primarily through inhalation exposure. Carcinogenic risk is Cr>Ni>As>Pb>Cd, and the exposure route is mainly by ingestion. For children, Cr, Ni and As were high carcinogenic risk and Pb, Cd were acceptable carcinogenic risk; for adults, Cr and Ni were high risk, As was acceptable risk, and Pb and Cd were no risk. The results of the APCS-MLR receptor model showed that the percentages of vehicle emission sources, coal transport industrial sources, coal-fired power plant sources and natural sources were 27.8%, 25.2%, 8.7% and 38.3%, respectively.

**Keywords**: heavy metals, potential ecological risk, human health risk assessment, source identification, APCS-MLR receptor model

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## Introduction

The past decades have witnessed the rapid development of population, urbanization and industrialization, and the urban environment is facing enormous challenges, especially the problem of heavy metal pollution and accumulation brought by industrial activities and other human activities on the arable soil on which human beings depend for survival [1, 2]. For instance, coal mining activities [3], Ore slag accumulation [4], smelting waste deposits [5] and other industrial emissions [6, 7] will have an impact on surrounding soils. In view of the high toxicological characteristics, persistence, difficult biodegradability and higher public health risks of soil heavy metals, the United Nations Environment Programme (UNEP) has identified eight heavy metals i.e. Pb, Cu, Cd, Hg, Cr, Ni, Zn and As as priority pollutants for control [2, 4].

According to previous studies, numerous properties of heavy metals in arable soils have been revealed. Li et al. [8] developed an innovative methodology of the risk distribution pattern by studying pollution risk of China's cultivated land from industrial production on a larger spatial scale, and revealed results with a risk percentage of 18.77%. Wei et al. [9] found geogenic and anthropogenic sources are spatial-dependent when studying geochemical accumulation and source tracing of heavy metals in arable soils. Also, sources assessment, ecological and health risk assessment of heavy metals in surface soils from an industrial area in India appeared in the report of Pobi et al. [10]. Similarly, the pollution and ecological risk of heavy metals in urban agricultural soils of Yaoundé from Cameroon were studied by Aboubakar et al. [11]. In summary, pollution evaluation, spatial distribution, risk assessment and source analysis have received much attention. Li et al. [12] used index methods such as geological accumulation index ($I_{geo}$) and potential ecological risk index (PERI) for pollution evaluation analysis. Risk assessment includes potential ecological risk assessment, health risk assessment, non-carcinogenic risk assessment, etc [13]. Additionally, there are qualitative and quantitative analysis for pollution source analysis, and the former includes correlation analysis, cluster analysis, principal component analysis, etc, while the latter can be achieved through chemical mass balance (CMB), positive matrix factorization (PMF), edge analysis (UNMIX), GeogDetector Model (GDM) and absolute principal component analysis-multivariate linear regression (APCS-MLR) model [14, 15].

Considering risk impacts and pollution sources, this study aims (1) to investigate heavy metal concentration characteristics in soils; (2) to evaluate the levels of potential ecological risk, non-carcinogenic risk and carcinogenic risk of heavy metals; and (3) to identify the qualitative and quantitative sources via APCS-MLR model. The results of this study will provide detailed information for environment protection and agriculture soil management.

## Materials and Methods

### Study Site

Suzhou (115°53′-118°10′E, 32°43′-34°38′N) is located in the north of Anhui Province, and the climate belongs to warm temperate zone and the semi-humid monsoon section, with an average annual temperature of 14.7ºC, and annual rainfall around 774-896 mm [16]. The terrain is mainly plain, which belongs to the southern part of Huanghe-Huaihe Plain and the main agricultural crops include wheat, corn, soybean and cotton, etc [17]. The area is rich in coal resources and is an important part of the Huainan and Huaibei coalfields, which is one of the large coal industry bases in China, with large coal mines such as Zhuxianzhuang, Luling, Qinan, Qidong, Taoyuan and Qianyingzi [18]. Suzhou is also a city in the Yangtze River Economic Belt, and is the closest city to the port in Anhui province, with a number of industrial parks integrating industry, agriculture, electronics and logistics, such as Suzhou-Maanshan modern industrial park, Suzhou youth e-commerce industrial park, food processing and circulation industry park. To sum up, Suzhou is a city with diversified development of coal resources, modern agriculture and modern industry.

The cultivated soils with crops around the coal-fired power station and coal gangue accumulation site were selected as research object of this study. The sampling point of gangue accumulation is around the biomass power plant, which is not in production and during the preparatory construction period when sampling. Some sampling points have also been set up on the other side of the river near Suzhou Modern Grain Logistics Industrial Park. The rest of sampling sites were set up near coal-fired power plant in northern of Suzhou city. The sampling sites are located in Fig. 1.

### Sampling and Analysis

Total 23 topsoil samples (0-20 cm) near industrial zero of Suzhou, northern China, were collected with recording of specific sampling locations through GPS positioning system. After clearing sundries such as branches, weeds and gravel from the soil surface with a surface paint shovel, five-point method was applied to form one mixed soil sample of more than 1 kg at each sampling site, which was then placed in a clean zip-lock bag and brought back to laboratory. The soil samples were air dried under natural conditions, and finally ground into powders that can pass through a 200 mesh wooden nylon sieve using an agate–mortar and pestle, and then stored in clean zip-lock bags for further testing and analysis. Then the samples were pre-treated into flakes by using a tablet press and boric acid and analyzed by High Definition X-fluorescence spectrometer [19-21]. Liu et al.[21] compared the differences between X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) for the measurement of heavy metals Cu, Zn, As, Ni, Pb and

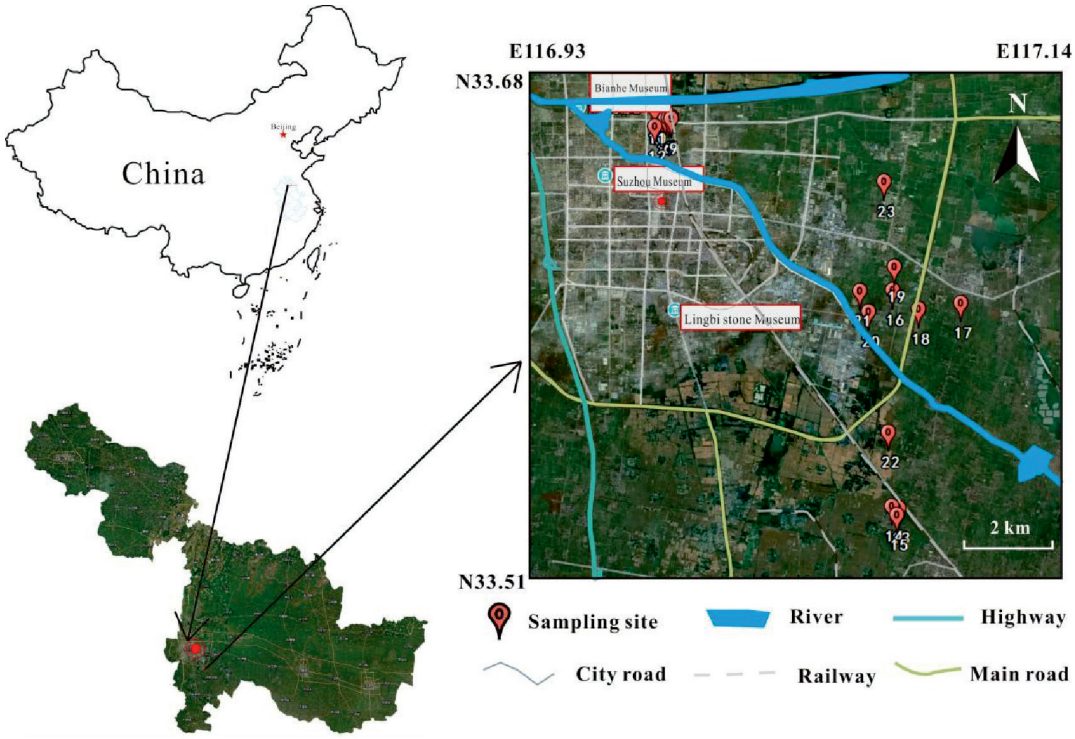


Fig. 1. Location of study area and the sampling sites in Suzhou.

Cr in soil samples, and showed that the relative standard deviations (RSDs) were consistently less than 5%. Also, our soil samples were measured parallel 3 times with RSD less than 5%, and the soil component analysis standard material (GBW07430, GSS-16) was analyzed simultaneously for calibration (once per five samples). The concentrations of ten kinds of heavy metals (Cr, Mn, Ni, Cu, Zn, As, Cd, Sn, Hg, Pb) have been measured, and their average recovery rates were 105%, 101%, 100%, 114%, 100%, 99%, 87%, 98%, 77% and 103%, respectively.

## Potential Ecological Risk Index

Hakanson [22] in 1980 recommend the potential ecological risk index (RI) method evaluating the effects of heavy metal contamination on human health and environment in sediments, which has since been widely applied to the evaluation of pollution in water bodies and environmental soils [23-25, 3]. The calculation formulas of single factor pollution index ($P_i$), potential ecological risk index ($E_r$) and comprehensive potential ecological risk index (RI) are exhibited in Eqs. (1)-(3).

$$P_i = \frac{C_i}{B_i} \tag{1}$$

$$E_{\mathrm{r}}^i = T_{\mathrm{r}}^i \quad P_i \tag{2}$$

$$RI = \sum_{i=1}^{\mathrm{n}} E_r^i \tag{3}$$

Where $P_i$ values are obtained by the ratio of the measured values of heavy metals to the background values, and the toxic-response coefficients $T_r^i$ of each heavy metal are Cr = 2, Mn = Zn = Sn = 1, Ni = Cu = Pb = 5, As = 10, Cd = 30, Hg = 40, respectively [25]. The $E_r^i$ and RI can be classified into five and four risk levels respectively: when $E_r^i$<40 and RI < 150, it represents a low ecological risk; when 40≤$E_r^i$<80 and 150≤RI<300, it shows moderate ecological risk; Considerable ecological risk is displayed when 80≤$E_r^i$<160 and 300≤RI<600; 160≤$E_r^i$<320 and RI>600 exhibits high ecological risk; when $E_r^i \geq 320$, it implies very high ecological risk.

## Human Health Risk Assessment

The human health risk assessment model recommended by the U.S. Environmental Protection Agency [26] was used to evaluate the non-carcinogenic and carcinogenic health risks of soil heavy metals to children and adults. The main exposure pathways are ingestion (*ing*), dermal contact (*der*), and inhalation (*inh*) and formulas for calculating the average daily intake (ADI) of heavy metals are respectively shown in (4), (5), and (6).

$$\mathrm{ADI}_{ing} = \frac{C_i \times \mathrm{R}_{ing} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \tag{4}$$

$$\mathrm{ADI}_{der} = \frac{C_i \times \mathrm{AF} \times \mathrm{SA} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \tag{5}$$

$$\mathrm{ADI}_{inh} = \frac{C_i \times \mathrm{R}_{inh} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \tag{6}$$

Where $C_i$ indicates the concentration of heavy metals (mg/kg), $R_{ing}$ and $R_{inh}$ separately mean ingestion rate and inhalation rate, EF is exposure frequency and ED is exposure duration, AF is skin adherence factor, SA means exposed skin area, ABS represents dermal absorption factor, PEF stands particle emission factor, BW is average body weight, and AT is average exposure time. The units and values of the above parameters are shown in Table 1 [27-29].

The non-carcinogenic risk can be characterized by the hazard quotient (HQ) and hazard index (HI) calculated as presented in Equation (7). Similarly, the carcinogenic risk can be expressed by Equation (8), CR is the carcinogenic risk of heavy metals, and TCR is the total carcinogenic risk index.

$$HI = \sum HQ_i = \sum \frac{ADI_i}{R_fD_i} \quad (7)$$

$$TCR = \sum CR_i = \sum ADI_i \times SF_i \quad (8)$$

Where $R_fD_i$ is the reference dose of each heavy metal, $SF_i$ indicates the carcinogenic slope factor of heavy metals under different exposure pathways, with detailed values are listed in Table 1. Where HI or HQ<1, it means there is no non-carcinogenic risk, and HI or HQ>1, it indicates the possible existence of non-carcinogenic risk. When CR or TCR<$10^{-6}$, it is no carcinogenic risk level; when CR or TCR>$10^{-4}$, it is high carcinogenic risk level; and when $10^{-6}$<CR or TCR<$10^{-4}$, there is an acceptable level of carcinogenic risk [30, 31].

## APCS-MLR Receptor Model

The absolute principal component analysis-multiple linear regression (APCS-MLR) receptor model was performed on the basis of principal component analysis to quantify the contribution of each factor to the environment.

Thurston and Spengler [32] in 1985, Gholizadeh et al. [33] in 2016 proposed the calculation method and steps of APCS-MLR model as shown in Eqs. (9)-(13). The factor standardization score was first calculated; then one anthropogenic sample with zero content was introduced and then standardized; the elemental concentration was used as the dependent variable and the absolute principal component factor score (APCS) was used as the independent variable for multiple linear regression analysis, and the obtained regression coefficients could be transformed into the contribution of each source to the content of each sample by APCS.

$$Z_{ij} = \frac{C_{ij} - \overline{C_i}}{\sigma_i} \quad (9)$$

$$Z_{ij} = \frac{0 - \overline{C_i}}{\sigma_i} = -\frac{\overline{C_i}}{\sigma_i} \quad (10)$$

$$C_i = b_{i0} + \sum_{p=1}^{n} (b_{pi} \times APCS_p) \quad (11)$$

$$RC_{pi} = \frac{|b_{pi} \times APCS_{pave}|}{|b_{i0}| + \sum_{p=1}^{n} |b_{pi} \times APCS_{pave}|} \times 100\% \quad (12)$$

$$RC_{i0} = \frac{|b_{i0}|}{|b_{i0}| + \sum_{p=1}^{n} |b_{pi} \times APCS_{pave}|} \times 100\% \quad (13)$$

Where $Z_{ij}$ is the standardized factor score, $C_{ij}$ is the measured value of heavy metal $i$ (mg/kg), $\overline{C_i}$ and $\sigma_i$ are

Table 1. Parameter values of average daily intake (ADI), reference dose ($R_fD$) and slope factor (SF) for heavy metals under different exposure routes.

| Parameters | Unit | Children | Adults | | $R_fD_{ing}$ | $R_fD_{der}$ | $R_fD_{inh}$ | $SF_{ing}$ | $SF_{der}$ | $SF_{inh}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | mg/(kg·d) | | | kg·d / mg | | |
| $R_{ing}$ | mg/d | 200 | 100 | Cr | 3.00E-03 | 6.00E-05 | 2.86E-05 | 5.00E-01 | 2.00E+00 | 4.20E+01 |
| $R_{inh}$ | $m^3$/d | 10 | 20 | Mn | 4.60E-02 | 2.30E-02 | 1.43E-05 | - | - | - |
| EF | d/a | 350 | 350 | Ni | 2.00E-02 | 5.40E-03 | 2.06E-02 | 1.70E+00 | 4.25E+01 | 8.40E-01 |
| ED | a | 6 | 24 | Cu | 4.00E-02 | 1.20E-02 | 4.00E-02 | - | - | - |
| BW | kg | 16 | 60 | Zn | 3.00E-01 | 6.00E-02 | 3.00E-01 | - | - | - |
| AT | d | 365*ED | 365*ED | As | 3.00E-04 | 1.23E-04 | 3.00E-04 | 1.50E+00 | 3.66E+00 | 1.51E+01 |
| PEF | $m^3$/kg | 1.36E+09 | 1.36E+09 | Cd | 1.00E-03 | 1.00E-05 | 1.00E-03 | 3.80E-01 | 3.80E-01 | 6.30E+00 |
| SA | $cm^2$ | 2800 | 5700 | Hg | 3.00E-04 | 2.10E-05 | 8.57E-05 | | | |
| ABS | dimension-less | 0.001 (As:0.03) | 0.001 (As:0.03) | Pb | 3.50E-03 | 5.25E-04 | 3.52E-03 | 8.50E-03 | - | 4.20E-02 |
| AF | mg/cm *day | 0.2 | 0.07 | Sn | - | - | - | - | - | - |

Table 2. Descriptive statistics of heavy metal concentrations (mg/kg).

| | Cr | Mn | Ni | Cu | Zn | As | Cd | Sn | Hg | Pb |
|---|---|---|---|---|---|---|---|---|---|---|
| Minimum | 55.8 | 227.4 | 22.2 | 18.9 | 58.5 | 8.93 | 0.098 | 2.79 | 0.03 | 17.1 |
| Maximum | 163.4 | 936.5 | 89.3 | 133.4 | 237 | 22.3 | 0.35 | 16.2 | 0.89 | 75 |
| Mean | 80.00 | 578.84 | 38.22 | 37.64 | 91.78 | 13.82 | 0.193 | 4.60 | 0.11 | 28.58 |
| Median | 76.3 | 539 | 36.7 | 27.5 | 71.8 | 13.4 | 0.19 | 3.51 | 0.03 | 24 |
| Standard Deviation | 21.10 | 148.67 | 12.73 | 24.94 | 47.72 | 3.71 | 0.06 | 3.35 | 0.20 | 15.67 |
| Coefficient of Variation/ % | 26 | 26 | 33 | 66 | 52 | 27 | 33 | 73 | 191 | 55 |
| Background(CNEMC1990) | 66.5 | 530 | 29.8 | 20.4 | 62 | 9 | 0.097 | 1.4 | 0.033 | 26.6 |

the averages and standard deviation of heavy metal $i$ (mg/kg), respectively. The $b_{i0}$ denotes the constant obtained by multiple linear regression of heavy metal $i$, and $b_{pi}$ indicates the regression coefficient of pollution source p on $i$. The values $b_{pi}\times\mathrm{APCS}_{\mathrm{p}}$ represent p contributions to $C_i$, and $b_{pi}\times\mathrm{APCS}_{pave}$ average values of all samples expresses the average absolute contribution of pollution source p [34, 35].

## Results and Discussion

### Heavy Metals Concentrations

The statistical characteristics of ten heavy metals of soil samples in the study areas are presented in Table 2, and the box plots and column stacking diagram of heavy metal concentration at the samples points are presented in Fig. 2 and Fig. 3. The concentration ranges of heavy metals Cr, Mn, Ni, Cu, Zn, As, Cd, Sn, Hg, and Pb are respectively 55.8-163.4, 227.4-936.5, 22.2-89.3, 18.9-133.4, 58.5-237, 8.93-22.3, 0.098-0.35, 2.79-16.2, 0.03-0.89 and 17.1-75 and the average values are 80, 578.84, 38.22, 37.64, 91.78, 13.82, 0.193, 4.60, 0.11 and 28.58 mg/kg with the decreasing order Mn>Zn>Cr>Ni>Cu>Pb>As>Sn>Cd>Hg.

As can be seen from the box graph and table, the mean value of each element is greater than the median, indicating high values of outliers. According to the background values of heavy metals in Anhui Province soils [36] listed in Table 2, the average values of all heavy metals are higher than the corresponding background values, and the ratios of both are 1.20, 1.09, 1.28, 1.85, 1.48, 1.54, 1.98, 3.28, 3.21 and 1.07 times, respectively. For the analysis of pollution at the sampling points, the exceedance rates are 73.9%, 56.5%, 87.0%, 91.3%, 82.6%, 95.7%, 100%, 100%, 17.4% and 30.4%, respectively.

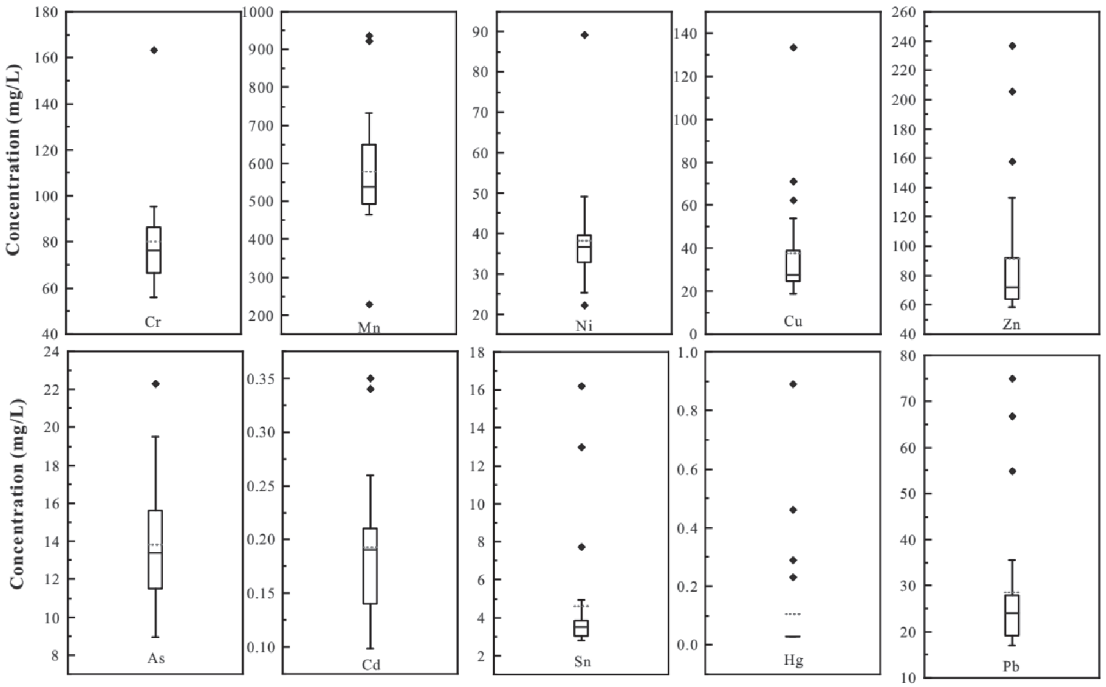


Fig. 2. Box plots of heavy metal concentrations in soil samples.

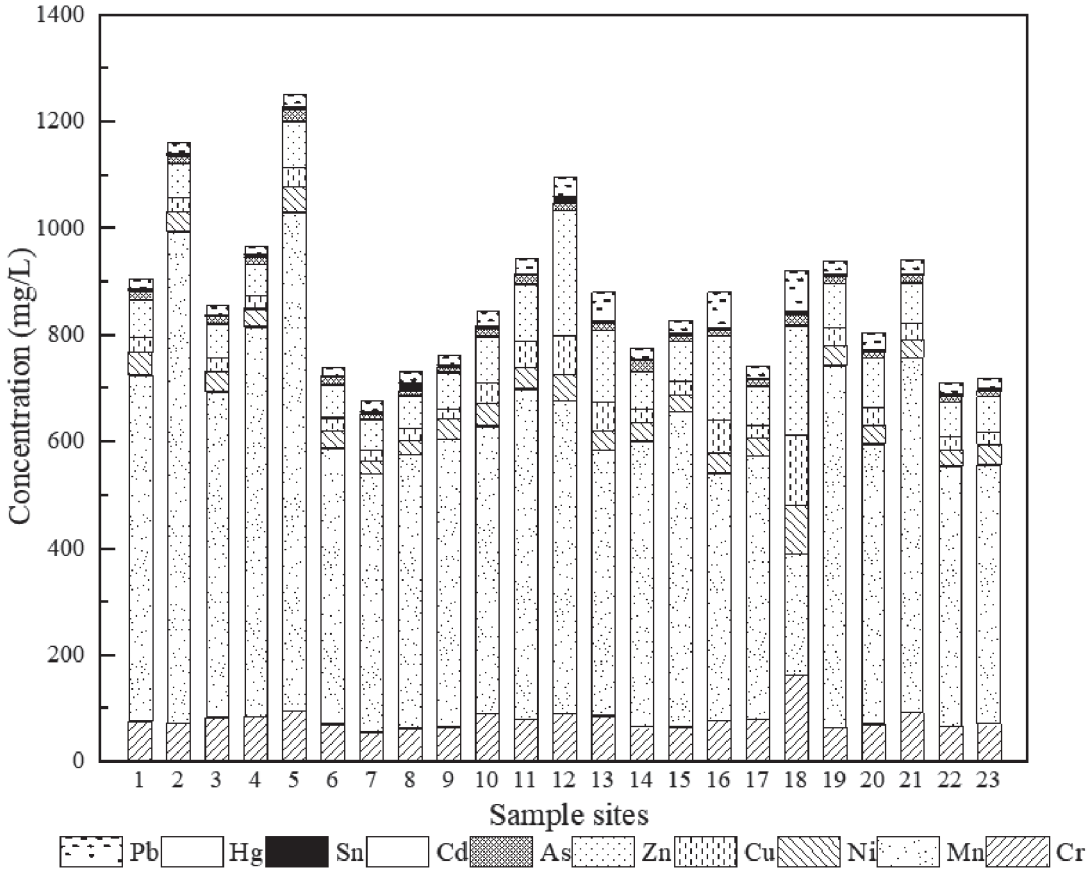


Fig. 3. Column stacking diagram of heavy metal concentrations at sampling sites.

On the studies revealing CV<10%, 10%<CV<100% and CV>100% indicate respectively low, moderate and strong anthropogenic contributions from Ashayeri and Keshavarzi [35] and Mamat et al. [37], in this paper, except for Hg (CV = 191%) being highly impacted by human activities, all other elements are moderate anthropogenic contributions with CV ranging from 26% to 73%, representing relatively large fluctuations in the concentration amounts of each heavy metal can be seen from Fig. 3. The highest heavy metal amounts are observed at sampling sites 2, 5 and 12 for the high concentrations of Mn and Zn.

## Potential Ecological Risk Assessment

The $E_r$ and RI are calculated according to Eqs. (1)-(3), and the box diagrams and pie charts are drawn respectively as shown in Fig. 4. With the exception of the heavy metals Cd and Hg, all the other eight metals are classified as low ecological risk, and the average $E_r$ values in descending order are Hg>Cd>As>Cu>Ni>Pb>Sn>Cr>Zn>Mn. This order is in general accordance with the ecological risk values ranking of heavy metals in Turkey by Fural [38]. The range of $E_r$ values for Cd is 30-108, spanning three classes of low ecological risk, moderate ecological risk and considerable ecological risk, with respective percentages of 8.7%, 78.3% and 13.0%. Faraji et al. [39] also found a high potential ecological risk in Fars Province for Cd when investigating the health and ecological risks attributed to the soil heavy metals in Iran from 2000 to August 2021. The four sites with relatively high concentration values of Hg directly influenced the results of the potential ecological risk evaluation, and all sites except these four were in the low ecological risk class. The points exceeding the standard were in the high and very high ecological risk classes, each accounting for 4.3% and 13.0% respectively. These two elements play an important role in the results of the ecological risk assessment because of their high toxic-response coefficients $T_r^i$ (Cd = 30, Hg = 40). As can be seen from the results of the comprehensive potential ecological risk assessment in Fig. 4, all four risk levels are observed, with the proportions being 69.6% low risk, 13% moderate risk, 8.7% considerable risk and 8.7% high risk.

## Human Health Risk Assessment

In this study, the non-carcinogenic and carcinogenic risks of heavy metals to children and adults are evaluated at three routes of exposure: ingestion, dermal contact and inhalation, calculated according to Eqs. (4)-(8), and the results are shown in Table 3.

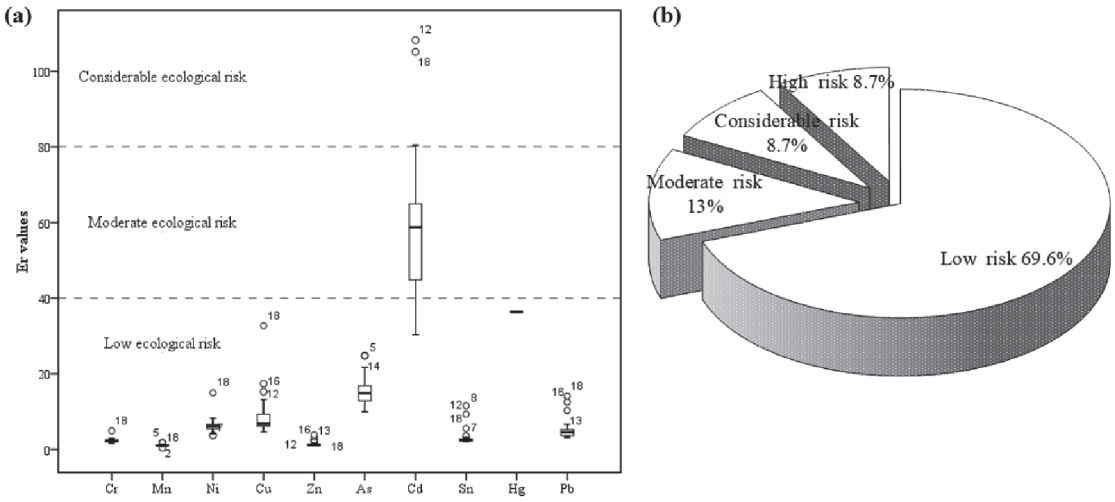


Fig. 4. Box plots of Er and pie charts of RI on soil heavy metals.

The magnitude order of average HI values of all heavy metals for children is consistent with adults', and the order is Mn>Cr>As>Pb>Ni>Cu>Hg>Zn>Cd. With the exception of Mn, the average HI values of all elements for children and adults are less than 1, meaning there are no non-carcinogenic risks. The non-carcinogenic risk values of Mn at all sampling sites exceeded 1, including the environmental background of Mn, with HI of 6.66 and 3.49 for children and adults, respectively. For Mn, the high non-carcinogenic risk from the inhalation route leads to a high total risk, while the other two routes of exposure do not cause risk. For Cr, although the average HI value is less than 1, the single HI value 1.66 for children exceeds 1 at site 18, and single HI values of the other four points 5, 10, 12 and 21 are 0.97, 0.92, 0.92 and 0.94, respectively. This means that attention needs to be paid to the non-carcinogenic risk of the heavy metal Cr, especially under inhalation and ingestion

Table 3. Non-carcinogenic and carcinogenic risks of heavy metals to children and adults.

| | | $HQ_{ing}$ | $HQ_{der}$ | $HQ_{inh}$ | HI | $CR_{ing}$ | $CR_{der}$ | $CR_{inh}$ | CR |
|---|---|---|---|---|---|---|---|---|---|
| Cr | Children | 3.20E-01 | 4.48E-02 | 4.50E-01 | 8.14E-01 | 4.79E-04 | 5.37E-06 | 5.40E-04 | 1.03E-03 |
| | Adults | 4.26E-02 | 8.50E-03 | 2.40E-01 | 2.91E-01 | 6.39E-05 | 1.02E-06 | 2.88E-04 | 3.53E-04 |
| Mn | Children | 1.51E-01 | 8.45E-04 | 6.51E+00 | 6.66E+00 | - | - | - | - |
| | Adults | 2.01E-02 | 1.60E-04 | 3.47E+00 | 3.49E+00 | - | - | - | - |
| Ni | Children | 2.29E-02 | 2.38E-04 | 2.98E-04 | 2.34E-02 | 7.79E-04 | 5.45E-05 | 5.16E-06 | 8.38E-04 |
| | Adults | 3.05E-03 | 4.51E-05 | 1.59E-04 | 3.26E-03 | 1.04E-04 | 1.04E-05 | 2.75E-06 | 1.17E-04 |
| Cu | Children | 1.13E-02 | 1.05E-04 | 1.51E-04 | 1.15E-02 | - | - | - | - |
| | Adults | 1.50E-03 | 2.00E-05 | 8.07E-05 | 1.60E-03 | - | - | - | - |
| Zn | Children | 3.67E-03 | 5.13E-05 | 4.92E-05 | 3.77E-03 | - | - | - | - |
| | Adults | 4.89E-04 | 9.75E-06 | 2.62E-05 | 5.25E-04 | - | - | - | - |
| As | Children | 5.52E-01 | 1.13E-01 | 7.41E-03 | 6.73E-01 | 2.48E-04 | 5.09E-05 | 3.36E-05 | 3.33E-04 |
| | Adults | 7.36E-02 | 2.15E-02 | 3.95E-03 | 9.90E-02 | 3.31E-05 | 9.67E-06 | 1.79E-05 | 6.07E-05 |
| Cd | Children | 2.31E-03 | 6.46E-04 | 3.10E-05 | 2.98E-03 | 8.77E-07 | 2.46E-09 | 1.95E-07 | 1.07E-06 |
| | Adults | 3.08E-04 | 1.23E-04 | 1.65E-05 | 4.47E-04 | 1.17E-07 | 4.67E-10 | 1.04E-07 | 2.21E-07 |
| Hg | Children | 4.24E-03 | 1.70E-04 | 1.99E-04 | 4.61E-03 | - | - | - | - |
| | Adults | 5.65E-04 | 3.22E-05 | 1.06E-04 | 7.04E-04 | - | - | - | - |
| Pb | Children | 9.79E-02 | 1.83E-03 | 1.31E-03 | 1.01E-01 | 2.91E-06 | - | 1.93E-07 | 3.11E-06 |
| | Adults | 1.31E-02 | 3.47E-04 | 6.97E-04 | 1.41E-02 | 3.88E-07 | - | 1.03E-07 | 4.91E-07 |

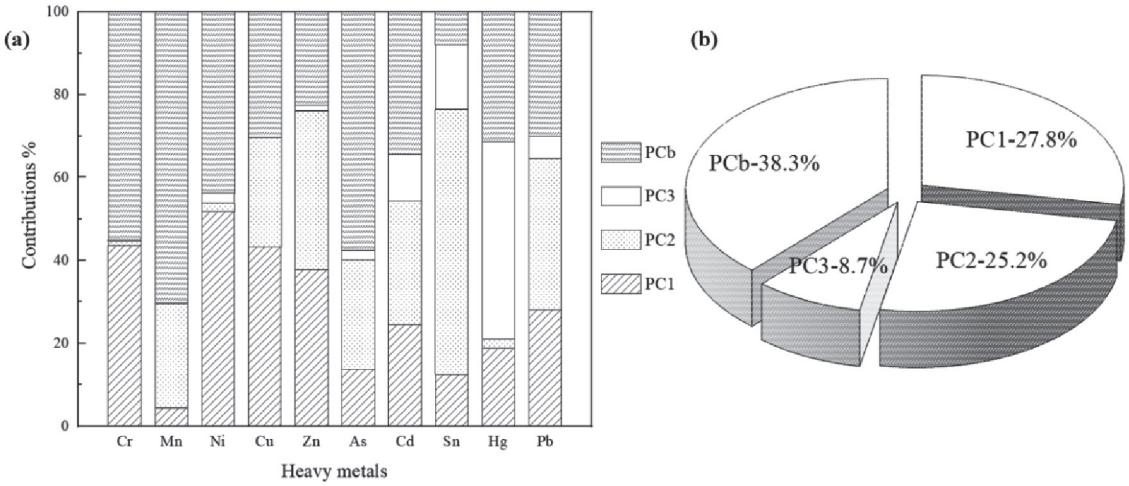


Fig. 5. Source contributions of heavy metals in surface soils for APCS-MLR model.

exposure routes. There is also a risk in the carcinogenic risk assessment of Cr and a potential carcinogenic risk for both children and adults, the same results were also found in the studies of Shi et al. [28], Song et al. [30] and Wang et al. [31]. In terms of the magnitude of the carcinogenic risk index, the following order of Cr>Ni>As>Pb>Cd is followed, which was the same for children and adults. Children are at risk of carcinogenesis for the above five metals through three exposure modes, with Cr, Ni and As being in the high carcinogenic risk dominated by the risk of ingestion, followed by the risk of inhalation and finally the risk of dermal contact, and Cd and Pb in the acceptable carcinogenic risk range based on the risk of ingestion. For adults, the metals with a high carcinogenic risk are Cr and Ni, while As has an acceptable carcinogenic risk, and Cd and Pb are not at the carcinogenic risk level. This indicates the need to focus on the carcinogenic risk of several toxic heavy metals, especially the risk of ingestion and inhalation for children. The similar conclusion that heavy metals pose a higher carcinogenic risk for children than adults is also reflected in the studies of many scholars [27, 28, 30].

## APCS-MLR Receptor Model

The APCS-MLR receptor model was introduced for further quantitative analysis of contamination sources and the results are depicted in Fig. 5. With the exception of Mn ($R^2$ = 0.548) and Sn ($R^2$ = 0.468) for which the regression coefficients are lower, the $R^2$ values of the other elements range from 0.642 to 0.965 (mean $R^2$ = 0.81), along with the ratios of measured to predicted concentration are 1, demonstrating that the source apportionment of heavy metals in the collected soil samples was reasonable dopting the APCS-MLR method.

PCb is a constant value of multiple linear regression calculations, commonly defined as an unidentified source, which here is partially consistent with the natural source [35, 40] and predominance of Mn, As, Cr and Ni with contributions of 70.23%, 57.54%, 55.09% and 43.87%, respectively. PC3 is dominated by Hg with contributions of 47.65%. Combined with the concentration characteristic of Hg hotspots around coal-fired thermal power plants in the north of the city, it is assumed that PC3 is influenced by coal combustion in power plants and produces Hg enrichment and ecological hazards to surrounding soils through atmospheric deposition, which is consistent with the findings of Shi et al. [3] and Xu et al. [24]. The difference here from the principal component analysis (PCA) is the subdivision of the human impact sources in the PCA into two categories based on $E_r$, RI and concentration characteristic at sampling points, i.e., one category of vehicular emission source PC1 dominated by Cu, Zn and Pb [3], and the other type of industrial source PC2 associated with coal transport led by Cd and Sn. In summary, PC1, PC2, PC3 and PCb represent 27.8%, 25.2%, 8.7% and 38.3% of vehicle emission sources, coal transport industrial sources, coal-fired power plant sources and natural source.

## Conclusions

A total of 23 surface soils with crops growth around various industrial area in Suzhou were collected and evaluated for heavy metal pollution and source analysis, using $E_r$ and RI pollution assessment methods, and APCS-MLR receptor model for source identification and quantification. The concentrations of 10 heavy metals were presented in the following decreasing order Mn>Zn>Cr>Ni>Cu>Pb>As>Sn>Cd>Hg, and their average concentrations exceeded the corresponding background values.

According to $E_r$ and RI, the environmental risk assessment results revealed that except for Cd and Hg, all the other eight metals were classified as low ecological risk; Cd had low, moderate, and considerable ecological risk, with respective percentages of 8.7%, 78.3% and

13.0%; Hg were in low, high, and very high ecological risk with 82.6%, 4.3% and 13.0%. The RI proportion of four ecological risk levels (low risk, moderate risk, considerable risk and high risk) were 69.6%, 13%, 8.7% and 8.7%, respectively.

According to the non-carcinogenic risk index, there is non-carcinogenic risk exposure to Mn dominated by inhalation risk for children and adults. At some sampling sites, there is non-carcinogenic risk only for children exposed to Cr, predominantly by inhalation and ingestion. The order of carcinogenic risk is Cr>Ni>As>Pb>Cd, all of which are carcinogenic to children and the exposure route is mainly by ingestion, with the first three being high carcinogenic risk and the last two being acceptable carcinogenic risk for children; and for adults the first two are high carcinogenic risk, As is acceptable carcinogenic risk, and the last two are no carcinogenic risk.

For APCS-MLR model, the vehicular emission source PC1 accounting for 27.8% dominated by Cu, Zn and Pb, the other type of industrial source PC2 accounting for 25.2% associated with coal transport led by Cd and Sn. PC3 was dominated by Hg with contributions of 47.65%. PCb was natural source and explained by Mn, As, Cr and Ni with contribution of 38.3%.

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## Conflict of Interest

The authors declare no competing interests.

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