Heliyon 9 (2023) e22580

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Spatial distribution, ecological risk and health risk assessment of heavy metals in agricultural soil from Ankang basin, Shaanxi Province

Daokun Chen [a,b], Shengfei Yang [a], Zhiyang Jiang [b], Zhirui Wang [a], Zhanbin Wang [a,*], Hui Tian [a,**]

[a] Xi'an Center of Mineral Resources Survey, China Geological Survey, Xi'an 710100 China
[b] School of Earth and Environment, Anhui University of Science & Technology, Huainan 232001 China

A R T I C L E I N F O

Keywords:
soil heavy metals
Ecological risk
Human health risk
Monte Carlo simulation

A B S T R A C T

In order to assess the heavy metal pollution features, ecological dangers, and health risk status posed to human beings by soils in the Ankang Basin, a study was conducted. This involved the collection of 38 surface soil samples, followed by the determination of elemental levels of arsenic, mercury, copper, cadmium, lead, chromium, nickel, and zinc. The concentrations of arsenic, mercury, copper, cadmium, lead, chromium, nickel, and zinc were quantified through the collection of 38 surface soil samples. The data obtained from the study was subjected to analysis and evaluation utilizing various academic methodologies, including the geo-accumulation index method, potential ecological risk assessment method, human health risk assessment model, and Monte Carlo simulation method. The findings indicated that the concentrations of the eight heavy metals in the soil above the background levels, with only Cadmium (Cd) marginally surpassing the threshold set for controlling soil pollution risks. The ground accumulation index revealed a higher degree of soil pollution with mercury, cadmium, copper, and zinc components. According to the possible ecological risk index, the presence of mercury and cadmium elements poses significant ecological hazards. The geographical distribution analysis suggests that these risks mostly stem from the combined impacts of human activities and the topographical and geomorphological characteristics of the river valley. The findings of the human health risk assessment indicated that the non-carcinogenic risk fell within acceptable limits. Additionally, it was observed that the carcinogenic risk associated with arsenic, mercury, cadmium, and nickel was comparatively greater for children as compared to adults. The results of the Monte Carlo simulations indicate that the non-carcinogenic hazards have a negligible effect on human health. However, it was seen that arsenic and nickel have a greater likelihood of presenting a substantial carcinogenic risk to humans, particularly in relation to the pediatric population, hence exerting a more pronounced impact on their health. In general, it is observed that conventional deterministic risk assessments tend to overstate the potential health risks associated with a given situation. Conversely, the utilization of Monte Carlo simulations has been found to effectively mitigate uncertainties in health risk assessments. It has been observed that children exhibit a higher vulnerability to both carcinogenic and non-carcinogenic health impacts resulting from exposure to heavy metals

* Corresponding author.
** Corresponding author.
E-mail addresses: solohike@163.com (Z. Wang), 359585977@qq.com (H. Tian).

https://doi.org/10.1016/j.heliyon.2023.e22580
Received 15 August 2023; Received in revised form 14 November 2023; Accepted 15 November 2023
Available online 22 November 2023

present in soil, in comparison to adults. It is recommended that residents prioritize the surveillance of soil heavy metals in relation to potential impacts on human health.

1. Introduction

Based on the findings of the 2014 National Soil Pollution Status Survey [1], the general state of the country's soil environment is not promising, particularly concerning the environmental quality of agricultural crops. This is evidenced by a significant prevalence of heavy metal points above permissible limits. The soil, serving as the uppermost layer of surface material, holds significant importance within the ecosystem. Particularly, farming soil stands as a crucial resource for the sustenance and progress of human existence [2,3]. The pollution of land resources occurs as a consequence of the soil heavy metal surpassing the self-purification capacity of the soil environmental system, which is attributed to the rapid socio-economic growth and ongoing disturbance of land resources by human activities. The issue of land resource pollution is increasingly becoming a matter of great concern in numerous countries and areas, resulting in substantial detrimental effects on both the ecological environment and human well-being [4–6]. Soil heavy metal pollution is persistent, toxic, and has other characteristics, the accumulation of heavy metals in agricultural soil may not only lead to crop yield and quality reduction, but also damage the original ecological quality, and through the soil, plants, and other pathways to enter the human body to cause adverse effects on sensitive populations [7,8]. Hence, the assessment of the present condition and ecological implications of heavy metal contamination in agricultural soils holds immense importance in ensuring the mitigation of health risks to humans, ensuring food security, and promoting the sustainable development of agricultural systems.

Presently, numerous scientists have employed enrichment factors, pollution factors, pollution load indexes, and geo-accumulation indexes as assessment tools to evaluate the pollution status of heavy metals in soil [9–12]. Furthermore, the researchers employed the prospective ecological risk index model [13] and the human health risk model [14] to conduct a quantitative assessment of the impacts of heavy metals on the ecological environment. Additionally, they evaluated the potential damage to human health by examining hazard indices and carcinogenic risk [15]. Nevertheless, it is important to acknowledge that every evaluation method has its own set of limitations [16]. Therefore, it becomes imperative to integrate multiple evaluation indicators in order to conduct a comprehensive analysis that can enhance the assessment of pollution levels in the study area [17]. This approach can also offer theoretical insights for mitigating human health risks and implementing effective environmental governance [18]. The primary approach utilized in human health risk assessment involves the quantitative evaluation of soil heavy metal concentrations and exposure parameters across many channels, including ingestion, dermal intrusion, and pulmonary inhalation [19]. Nevertheless, it is important to note that even among individuals within the same population, the likelihood of exposure to certain risks might vary. This variability can be attributed to factors such as age, health condition, sensitivity to pollutants, metabolic variations, and other relevant factors [20]. Consequently, it is crucial to acknowledge that the outcomes of risk assessments conducted based on these criteria may not accurately reflect the actual circumstances [21,22]. However, Monte Carlo simulation can well compensate for the inadequacies of the classic technique, which effectively executes probabilistic health risk analysis by estimating the probability that a pollutant exceeds a danger threshold and prioritizing parts of health risk control [23]. Hence, the utilization of Monte Carlo simulation in probabilistic health risk assessment may offer greater flexibility in the evaluation of health risks, mitigate uncertainties associated with the assessment process, and enhance the precision of health risk assessment outcomes [24].

Ankang City, located in Shaanxi Province, is situated within the Hanjiang River Basin. This basin serves as a crucial water conservation area for the Central Line Project of South-to-North Water Diversion. Additionally, it is recognized as a highly productive agricultural region. Consequently, the significance of maintaining optimal soil environmental quality within the Ankang Basin is readily apparent. Nevertheless, historical research on the pollution levels and associated ecological and human health hazards posed by heavy metals in agricultural soils within the Ankang Basin has been limited. Furthermore, there has been a dearth of studies focusing on the evaluation and assessment of these risks using a standardized index. Additionally, investigations pertaining to the potential human health concerns have been lacking. Mengchu Wei conducted an analysis of agricultural soils and various crops in Shiquan County, located in Shaanxi Province. Based on the utilization of traditional health risk assessment methods, the study determined that the region exhibits a discernible risk of carcinogenicity [25]. The utilization of Monte Carlo simulation surpasses conventional evaluation approaches in the context of health risk assessment. This study examines the impact of soil on the health risk of both adults and children. Multiple evaluation indicators and Monte Carlo simulation are employed to compare the results with those obtained using traditional health risk assessment methods. The geo-accumulation index lacks the ability to comprehensively assess soil heavy metal pollution in a systematic manner. On the other hand, the prospective ecological risk assessment method effectively elucidates the relationship between heavy metal concentration and biotoxicity. However, it does not fully capture the biological impacts induced by heavy metals. Traditional health assessment approaches fail to account for variations in risk caused by individual differences. However, by integrating Monte Carlo simulation with health risk analysis, the issue of imprecise health risk assessment resulting from fixed parameters can be resolved [26].

Hence, the primary objective of this study is to assess the extent of heavy metal contamination in agricultural soils within the Ankang Basin and examine the associated health hazards to human populations. The findings of this research endeavor will serve as valuable scientific evidence for policymakers in formulating effective management strategies. The primary aims of this research are as follows: (1) to comprehend the extent of contamination in agricultural soils within the designated study region and analyze their spatial distribution; (2) to evaluate the ecological hazards posed by heavy metal; (3) to assess the probabilistic health risks associated with heavy metals for adults and children by employing Monte Carlo simulation as a means of risk assessment.

2. Materials and methods

2.1. Study area and sample collection

The Ankang Basin is situated in the geographical region between the Qinling Mountains and the Ba Mountains. It is bounded by the Xixiang Basin and the Hanzhong Basin to the west, while to the north it is bordered by the Shangdan Basin in Shangluo City. The geographical feature under consideration spans a distance beyond 100 km in an east-west direction, exhibiting variable widths in a north-south orientation. It is comprised of a series of five diminutive basins. The region is characterized by a subtropical continental monsoon climate, exhibiting four distinct seasons. The climate is characterized by mild and humid conditions, with an average temperature ranging from 15 °C to 17 °C over many years. Precipitation is abundant, with an average annual rainfall of 1050 mm and an average of 94 days of rainfall per year. The frost-free period in this region is lengthy, averaging 253 days annually, with the longest period lasting up to 280 days and the shortest period lasting 210 days.

The study area under investigation is located in the northwestern region of Hanbin District, Ankang City. The selection of sample points followed the guidelines outlined in the "Specification for land quality geochemical assessment" (DZ/T 0295–2016). A total of 38 sampling points were established, as depicted in Fig. 1. Each sample was collected at a depth of 0–20 cm. Sampling was performed using GPS coordinates as the central reference point. A composite sample was created by collecting samples in a five-point aliquot pattern, forming a "X" shape, at the central location of each sample. These individual samples were then combined into a single composite sample. The data collection process involves recording pertinent information such as sample point details, GPS coordinates, sampling media, and labeling records during the sample handover verification process. Once the samples were collected without any errors, they were allowed to undergo natural drying. To prevent the large soil pieces from adhering to each other, a wooden stick was used to crack them. Additionally, any branches, roots, stones, insects, or other impurities were carefully eliminated. The samples were then mixed thoroughly and stored in sample bottles using the quadratic method. Each bottle was appropriately labeled for preservation purposes. Subsequently, the samples were dispatched to the laboratory for further analysis.

2.2. Chemical analysis

The collection of soil samples The determination of elemental content, specifically Cu, Cd, Pb, Cr, Ni, and Zn, was conducted using the Haiguang manufacturing (AFS-9561) atomic fluorescence spectrophotometer for the Hg element. For the Cu, Cd, Pb, Cr, Ni, and Zn elements, the Japanese Shimadzu manufacturing (AA-7000) atomic absorption spectrophotometer was employed. The determination of As and Hg elements was carried out in accordance with the specifications outlined in the "Soil Quality of Total Mercury, Arsenic, Lead Determination of Atomic Fluorescence Method" (GB/T22105-2008). The remaining elements were analyzed and tested in accordance with the technical provisions specified in the series of documents titled "Detailed Investigation of Sample Analysis and Test Method for National Soil Pollution Situation" as outlined in the environmental protection soil letter [2017] 1625, annex 1 part 1 2-1. The experimental results were subjected to quality control measures by employing national soil-level reference samples for testing at every stage of the analytical process.

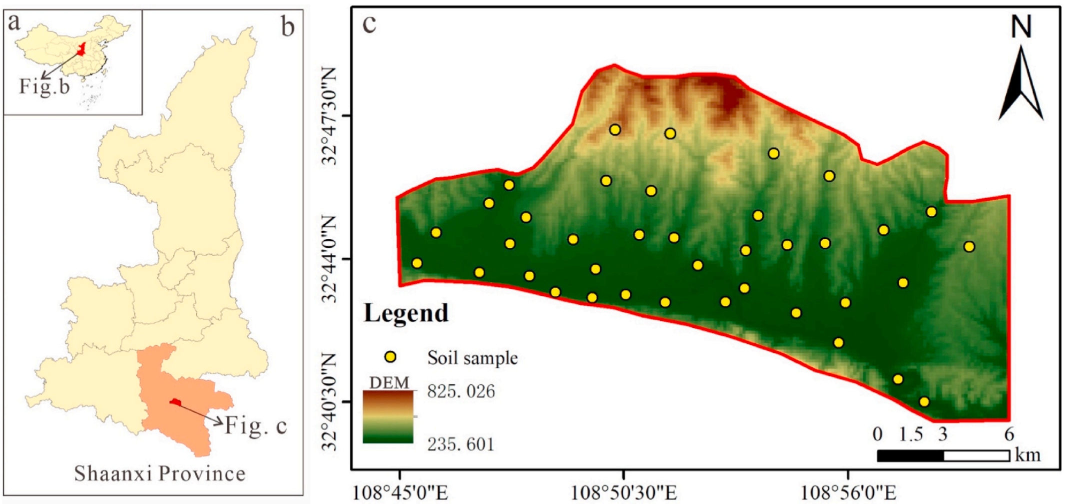

Fig. 1. Location and sampling map of the study area.
Note: a. National geographic boundaries of China, with the red area showing the geo-administrative geographic boundaries of Shaanxi Province; b. Shaanxi administrative and geographic boundaries, light red is Ankang City of which the positive red boundary range is the study area; c. Map of the study area with DEM data where yellow dots are soil sampling points.

2.3. Assessment methods

Various pollution index models were employed in this study to assess diverse contamination scenarios pertaining to soil heavy metals. Various methods were employed to assess the pollution levels of heavy metals in the soil environment and to evaluate the associated ecological and health risks. These methods included the geo-accumulation index method (Igeo), the potential ecological risk index method (RI), the human health risk assessment method (HHRA), and the Monte Carlo simulation.

2.3.1. Geo-accumulation index

The geo-accumulation index (Igeo) is a quantitative method used to assess the enrichment of trace elements in soil. It achieves this by comparing the ratio of measured values to background values in the soil environment [27,28]. The formula used to calculate it is as follows:

$$I_{geo} = log_2 \frac{C_n}{1.5B_n} \tag{1}$$

The details of the Igeo are presented in the supporting data file Table S1.

2.3.2. Potential ecological risk index

The approach proposed by Ref. [29],known as the potential ecological risk index (RI) method, provides a quantitative assessment of the extent to which soil heavy metal elements are enriched. This method enables the determination of the level of potential ecological risk associated with heavy pollution in the soil environment. The formula used for the calculation of this evaluation is as follows:

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times C_f^i = \sum_{i=1}^{n} T_r^i \times \frac{C_i}{C_n^i} \tag{2}$$

The details of the RI are presented in the supporting data file Table S2.

2.3.3. Human health risk assessment

The health risk assessment model, as suggested by the United States Environmental Protection Agency (USEPA), was employed to quantify the potential health risks associated with soil heavy metal contamination. These risks were evaluated based on three pathways: ingestion, inhalation, and dermal intrusion [30]. Furthermore, the levels of heavy metals ingested by two distinct populations, namely adults and children, were assessed using these aforementioned pathways [31,32].The assessment of the carcinogenic and non-carcinogenic risks posed by heavy metals to human beings involves the evaluation of the hazards associated with three different pathways of exposure [33].The formula used for the calculation of this evaluation is as follows:

$$ADD_{ing} = C_s \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{3}$$

$$ADD_{inh} = C_s \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \tag{4}$$

$$ADD_{der} = C_s \times \frac{AF \times SA \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{5}$$

The details of the HHRA are presented in the supporting data file Table S3.

The hazards of heavy metals to the human body through different routes of intake can be categorized into carcinogenic risk (CR) and non-carcinogenic risk (NCR), and NCR is measured by calculating the hazard coefficients (HQ) for different routes of each element to obtain the overall hazard index (HI). The formula used for the calculation of this evaluation is as follows:

$$HI = \sum HQ_i = \sum \frac{ADD_{ing} + ADD_{inh} + ADD_{der}}{RfD_i} \tag{6}$$

$$CR = \sum CR_i = \sum \left(ADD_{ing} + ADD_{inh} + ADD_{der}\right) \times SF_i \tag{7}$$

The SF and RfD for different pathways of soil heavy metal intake are shown in Table S4.

2.3.4. Monte Carlo simulation

The researchers employed the Monte Carlo simulation technique to analyze the inherent uncertainty and variability present in the probability distribution of health risks. To obtain the risk values, they established assumptions and developed a probabilistic model based on the chosen parameters. The stochastic simulation was conducted with a total of 10,000 iterations, and the predicted values were utilized as an approximate solution [34].

The supporting data file Table S5 provides the specifics on the settings of the Probability density function parameters in the context of probabilistic human health risk assessment.

2.4. Statistical analyses

This study employed mathematical and statistical analyses, including heavy metal concentration statistics and correlation, utilizing IBM SPSS 26 and Excel 2021. Spatial analyses, such as Kriging interpolation of elemental distributions, were conducted using ArcGIS 10.8. Monte Carlo algorithm simulations were performed using Crystal Ball software, and mapping was executed in OriginPro 2021.

3. Results and discussion

3.1. Descriptive statistics of heavy metal content in soils

Table 1 presents the descriptive attributes of soil physicochemical parameters and heavy metal concentrations within the designated study region. The mean soil pH was determined to be 6.40, with the observed low pH levels in agricultural areas mostly attributed to the deliberate use of fertilizers by human activities [35,36]. The mean concentration of eight heavy metal elements (Arsenic, Mercury, Copper, Cadmium, Lead, Chromium, Nickel, Zinc) in the soil of Shaanxi Province surpassed the background level of the soil environment. This observation suggests that all eight heavy metals exhibited varying degrees of enrichment within the investigated region. This outcome aligns with the discovery made by Xiao Ran, indicating that the concentrations of heavy metals in the soils of the Hanzhong Basin in Shaanxi Province surpassed the established background levels [37]. With the exception of copper (Cu) and cadmium (Cd), which exhibited exceedance rates of 13.2 % and 36.8 % respectively, the remaining six elements did not surpass the risk screening levels.

The coefficient of variation (CV) is a measure that quantifies the extent of variation and dispersion of heavy metals in soil [38]. Based on the classification criteria for CV as stated in Ref. [39], it was observed that Cd exhibited a significant degree of variability. On the other hand, As, Cu, and Pb displayed a moderate level of variability, while Ni, Zn, Cr, and Hg exhibited a relatively low level of variability. It is worth noting that higher CV values were indicative of greater impacts resulting from anthropogenic activities, whereas lower CV values were associated with lesser impacts from such activities, as discussed in Ref. [40]. The data suggests that Cd is more susceptible to external influences, and the notable skewness and kurtosis of Hg and Cd imply that certain soil samples originate from regions with elevated heavy metal concentrations and significant rates of heavy metal enrichment.

4. Spatial distribution and physicochemical properties of heavy metals

Based on the results of the Shapiro-Wilk (S–W) normalcy distribution test, it is evident that only the variables Hg and Cd required logarithmic adjustment, while all other variables exhibited conformity to a normal distribution. The process of ordinary kriging interpolation analysis was conducted using ArcGIS 10.8 software. Fig. 2 displays the distribution anomalies of eight soil heavy metals within the designated study region. The study area exhibited distinct patterns in the distribution of soil heavy metals. Notably, there were evident anomalies of heavy metal enrichment in the southeastern region, followed by a similar enrichment in the southwestern part of the area. The spatial distribution of elements such as As, Pb, Cd, Ni, and Cr displayed a high degree of similarity. These findings indicate that the presence of soil heavy metals in the study area can be primarily attributed to factors such as soil-forming matrices, industrial activities, transportation, agricultural production methods, and residents' lifestyles [41].

Based on the Pearson correlation coefficient presented in Fig. 3, it is evident that soil pH exhibited a statistically significant negative correlation (−0.34) with Hg, while its association with other components was found to be statistically negligible. The activity and transport of soil heavy metals can be influenced by soil pH, hence resulting in the enrichment of heavy metals [42]. The investigation revealed a statistically significant link among the elements, indicating a potential common origin. The observed robust association between the elements As and Cd, Pb, Cr, Ni, and Zn implies that these elements could potentially be influenced by both the soil-forming parent material and anthropogenic activities. The observed significant association between mercury (Hg) and lead (Pb) as well as zinc (Zn) indicates that the primary source of mercury is predominantly influenced by transportation activities. This finding aligns with the

Table 1
Descriptive statistics of soil heavy metals in the study area (mg/kg).

Elements	pH	As	Hg	Cu	Cd	Pb	Cr	Ni	Zn
Min	4.21	7.18	0.015	24.3	0.02	12.7	52.6	25.4	76.4
Max	8.29	25.5	0.508	67.0	1.15	34.9	104.0	58.5	153.0
Mean	6.40	14.03	0.867	40.07	0.31	24.74	77.16	40.64	109.18
SD	1.17	3.64	0.085	9.57	0.27	5.19	11.1	7.52	18.25
CV(%)	18.3	25.9	9.8	23.9	87.1	21.0	14.4	18.5	16.7
Skewness	0.77	0.527	3.635	0.93	1.587	0.015	−0.067	0.2	0.607
Kurtosis	−1.251	1.29	16.547	1.08	2.511	−0.359	−0.10	0.093	0.149
Exceedance rate (%)	–	74.7	92.1	100	78.9	73.7	89.5	94.7	100
Standard a	–	11.1	0.03	21.4	0.094	21.4	62.5	28.8	69.4
Exceedance rate (%)	–	0.0	0.0	13.2	36.8	0.0	0.0	0.0	0.0
Standard b	–	40	1.8	50	0.3	90	150	70	200

Note: a. Background value of Shaanxi Province; b. The value of 5.5 < pH ≤ 6.5 in the standard for control of soil pollution risk of agricultural land (Trial) (GB 15618–2018) shall be adopted.

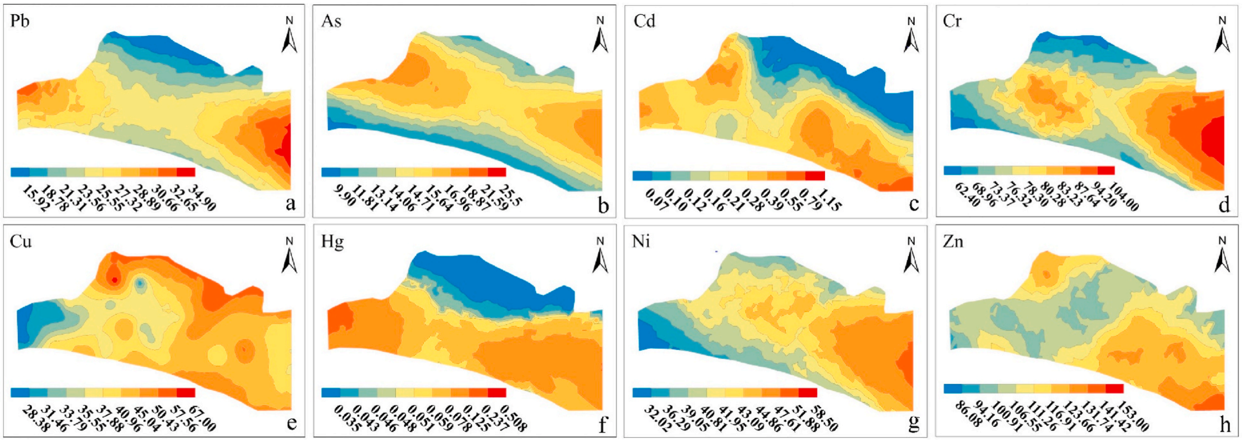

Fig. 2. Distribution of soil heavy metals in the study area.

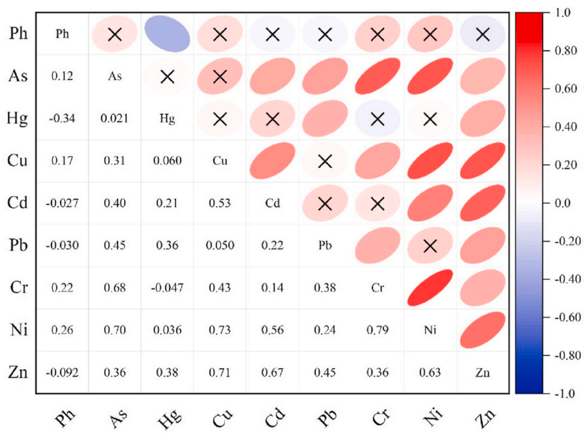

Fig. 3. Pearson correlation analysis.

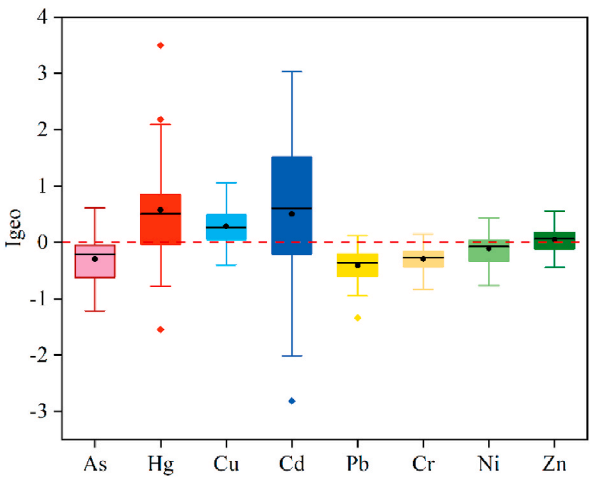

Fig. 4. Box plots of geo-accumulation pollution index.

empirical findings obtained within the study region.

4.1. Evaluation of heavy metal pollution

4.1.1. Evaluation of the geo-accumulation index

The Igeo evaluation method primarily focuses on investigating the impact of soil heavy metals on human activities. The present study utilizes the ground accumulation index to assess the extent of soil heavy metal contamination in the study area, taking into consideration the background value of the soil environment in Shaanxi Province. The results obtained according to Eq. (1) are shown in Fig. 4, it is evident that the elements Hg, Cd, Cu, and Zn are significantly impacted by anthropogenic activities. Furthermore, based on the land accumulation index grading criteria, these four elements are classified as experiencing light to moderate pollution, falling within level 1 of the grading standard. The Igeo values of Ni, As, Cr, and Pb are found to be below zero, suggesting minimal influence from anthropogenic activities and indicating a state of non-pollution. The Igeo values of the four soil heavy metal elements are all below 0, suggesting that these elements exhibit minimal anthropogenic influence and are in a non-polluted condition. In summary, the presence of Hg, Cd, Cu, and Zn in agricultural soils can be attributed to many anthropogenic activities, including agricultural practices, transportation, industrial processes, and residential activities.

4.1.2. Assessment of potential ecological risks

The present investigation involved the calculation of the potential ecological risk coefficient (Er) and the potential ecological risk index (RI) for heavy metals in the soils of the designated study region. The quantification of ecological risk based on soil background values and toxicity coefficients using Eq. (2). Based on the data shown in Fig. 5a, it is evident that the Er values of the Hg and Cd elements fell between the 80–160 range. This observation suggests that both Hg and Cd provide significant ecological threats to the soils within the research area. The six remaining elements exhibit Er values exceeding 40, suggesting minimal to negligible ecological danger to the soil within the designated study area. The research area has a mean RI score of 252, indicating a moderate level of ecological risk. The elevated value of the potential ecological risk index (RI) seen in Fig. 5b aligns with the spatial distribution of high concentrations of soil heavy metals within the examined region. Furthermore, the prominent RI value in soil mostly stems from the elevated levels of mercury (Hg) and cadmium (Cd) present in the soil [43]. Hence, the primary contaminants that contribute to ecological hazards in the agricultural land within the designated research region are mercury (Hg) and cadmium (Cd). This phenomenon can be primarily linked to the process of urbanization, which has led to a growth in the number of residential dwellings and industrial establishments in close proximity to agricultural lands. The southern-eastern region of the country exhibits notably higher RI values, whilst the northern-eastern region has comparatively lower RI values in agricultural soils. The primary factor contributing to the observed variety in RI values is the geographical distribution, which is influenced by densely inhabited regions, intensive traffic, concentrated agricultural and industrial activities, as well as the terrain of rivers. Hence, it is crucial to prioritize the allocation of industrial companies that engage in production activities leading to localized heavy metal contamination.

4.1.3. Health risk assessment

This study examines the carcinogenic and non-carcinogenic risks associated with eight soil heavy metals in the Ankang Basin, focusing on three specific pathways. According to the data presented in Table 2, the hazard index (HI) values for each soil heavy metal were found to be below 1 for both adult and pediatric populations. This suggests that the non-carcinogenic risk associated with these heavy metals is within acceptable limits, indicating a safe level of exposure. The HI values of children were found to be significantly higher compared to those of adults, suggesting that youngsters exhibit greater vulnerability to health risks associated with soil heavy metals and have heightened sensitivity to environmental contaminants in comparison to adults [44].

The absence of slope variables pertaining to Cr and Zn soil heavy metals necessitated the calculation of the overall carcinogenic risk just for the three pathways associated with As, Hg, Cd, and Ni. Additionally, the carcinogenic risk was assessed specifically for the

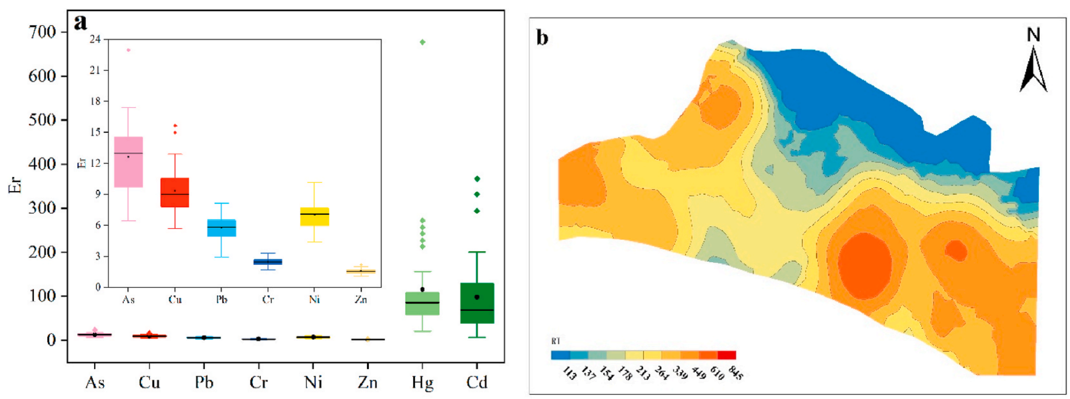

Fig. 5. Box plot of potential ecological risk factors (a) and spatial distribution of potential ecological risk indices (b).

Table 2
Non-carcinogenic risk results of HMs in adults and children.

Elements	Adults				Children			
	HQ_{ing}	HQ_{inh}	HQ_{der}	HI	HQ_{ing}	HQ_{inh}	HQ_{der}	HI
As	7.26E-02	5.41E-04	2.90E-04	7.34E-02	4.67E-01	9.01E-04	1.11E-03	4.69E-01
Hg	4.48E-03	2.04E-06	2.56E-04	4.74E-03	2.89E-02	3.39E-06	9.79E-04	2.98E-02
Cu	1.55E-03	1.65E-07	2.07E-05	1.58E-03	1.00E-02	2.75E-07	7.91E-05	1.01E-02
Cd	4.81E-04	1.79E-05	7.68E-05	5.76E-04	3.10E-03	2.99E-05	2.94E-04	3.42E-03
Pb	1.10E-02	1.16E-06	2.92E-04	1.13E-02	7.06E-02	1.94E-06	1.12E-03	7.17E-02
Cr	3.99E-02	4.46E-04	6.37E-03	4.67E-02	2.57E-01	7.43E-04	2.44E-02	2.82E-01
Ni	3.15E-03	7.47E-05	3.15E-04	3.54E-03	2.03E-02	1.24E-04	1.20E-03	2.16E-02
Zn	5.65E-04	6.02E-08	1.13E-05	5.76E-04	3.64E-03	1.00E-07	4.31E-05	3.68E-03

Table 3
Carcinogenic risk results of HMs in adults and children.

Elements	Adults				Children			
	CR_{ing}	CR_{inh}	CR_{der}	CR	CR_{ing}	CR_{inh}	CR_{der}	CR
As	3.27E-05	3.5E-08	3.18E-07	3.3E-05	2.10E-04	5.83E-08	1.22E-06	2.11E-04
Hg	2.02E-06	2.17E-09	8.05E-09	2.03E-06	1.30E-05	3.61E-09	3.08E-08	1.30E-05
Cu	–	5.57E-09	–	–	–	9.27E-09	–	–
Cd	2.93E-06	3.23E-10	1.17E-08	2.95E-06	1.89E-05	5.38E-10	4.48E-08	1.89E-05
Pb	–	2.58E-08	–	–	–	4.29E-08	–	–
Ni	3.15E-05	2.82E-07	3.15E-09	3.18E-05	2.03E-04	4.7E-07	1.2E-08	2.03E-04

respiratory intake pathway of Cu and Pb. Based on the findings presented in Table 3, it can be observed that the cumulative carcinogenic risks for adults and children followed the order of As > Ni > Cd > Hg. Furthermore, the carcinogenic risks associated with various exposure pathways and the overall cumulative carcinogenic risks were found to be higher in children compared to adults. Specifically, the risks associated with ingestion were higher than those associated with respiratory and dermal exposure pathways, which aligns with the calculated Hazard Index (HI) values. The cumulative carcinogenic risk (CR) values for arsenic (As) and nickel (Ni) in children were found to be greater than 10^{-4}, suggesting that the cumulative carcinogenic risk of As and Ni was higher in children compared to adults. Similarly, within the children group, the CR values exceeded 10^{-4}, indicating that the cumulative carcinogenic risk of As and Ni was higher in children compared to the adult group. The elements Hg, Cd, and Ni exhibit CR values over 10^{-6} in adults, so suggesting that these four elements likewise present a carcinogenic hazard to adult individuals.

4.1.4. Health risk assessment based on Monte Carlo simulation

The researchers employed the Monte Carlo simulation to conduct a simulation and evaluation of the potential risk posed by heavy metals to human health. This assessment was predicated on an analysis of the prevailing environmental pollution levels, as well as the assessment parameters specific to various populations. By utilizing this approach, the researchers were able to significantly mitigate the inherent inaccuracies associated with the assessment outcomes [45]. The resulting probability of health risks associated with heavy metals is visually represented in Figs. 6 and 7. The findings indicated that the non-carcinogenic risk associated with the ingestion of each heavy metal through the three different routes was within the established safety thresholds for both adult and pediatric populations. The probabilistic evaluation of carcinogenic risk revealed that youngsters have a higher susceptibility to the carcinogenic effects of four heavy metals, namely Arsenic (As), Cadmium (Cd), Mercury (Hg), and Nickel (Ni), compared to adults. The average cancer risk for both demographic cohorts, comprising adults and children, surpassed a threshold of 10^{-6} by 100 %. This finding suggests that these four heavy metals present a discernible carcinogenic danger to the human population. The likelihood of a substantial carcinogenic risk among the pediatric population surpasses the maximum carcinogenic risk threshold for both arsenic (As) and nickel (Ni) ($CR > 10^{-4}$). The findings indicated a statistically significant elevation in the combined risk of arsenic (As) and nickel (Ni) exposure among youngsters. The observed mean values of the carcinogenic risk associated with heavy metals, specifically arsenic (As), nickel (Ni), cadmium (Cd), and mercury (Hg), indicate a consistent trend across both the adult and child groups. The outcomes derived from the Monte Carlo simulation for probabilistic risk analysis shown a broad consensus with the outcomes obtained through the human health risk assessment approach. Hence, it is crucial to prioritize the enhancement of awareness regarding the potential risks associated with soil heavy metal exposure on children within the designated research region.

5. Conclusion

The findings of this study can be summarized as follows: In comparison to the background values of soils in Shaanxi Province, the study area exhibits higher exceedance rates of heavy metals in farmland soils. This suggests varying degrees of enrichment of heavy metal elements in the soils of the study area. However, it is important to note that only two elements, namely Cu and Cd, exceeded the soil environmental quality standards. The presence of regional variation in soil heavy metals suggests that they are influenced by

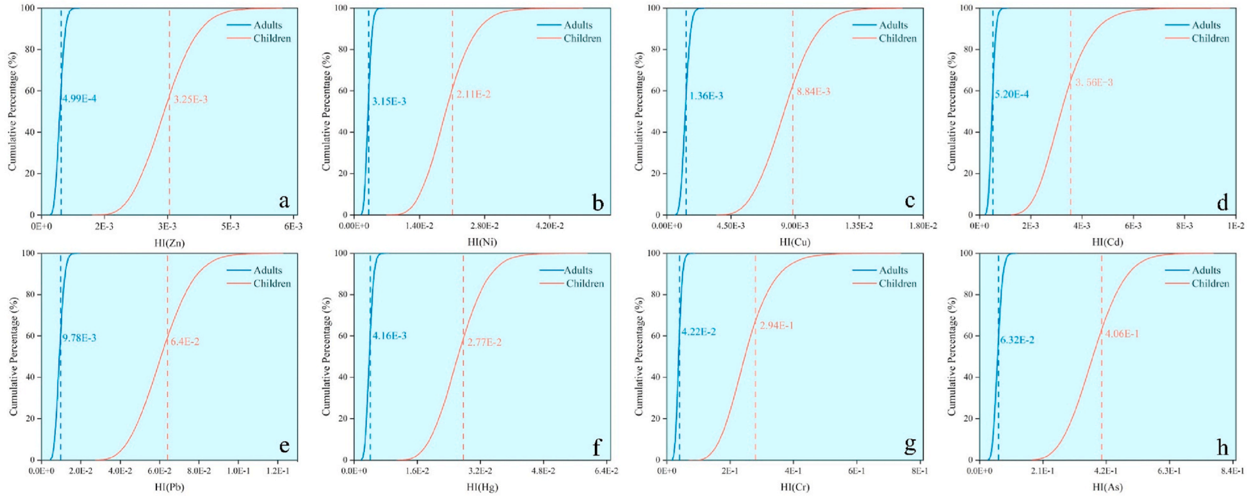

Fig. 6. Non-carcinogenic probabilistic health risk assessment for HMs.
Note: The blue and red background areas in the figure represent negligible and warning risks, respectively.

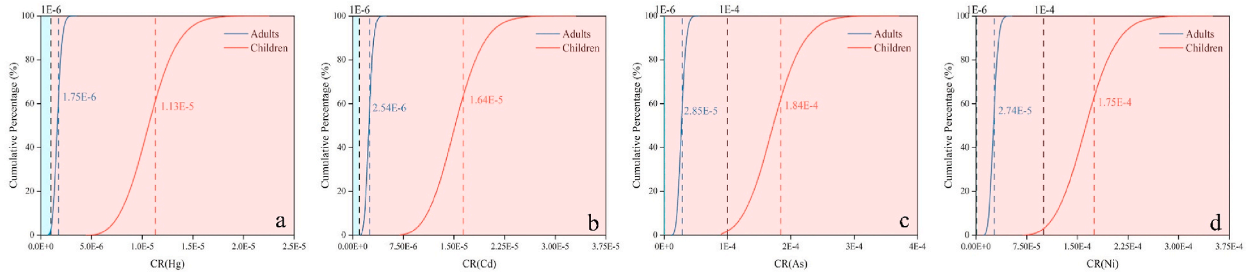

Fig. 7. Carcinogenic probabilistic health risk assessment for HMs
Note: The blue and red background areas in the figure represent negligible and warning risks, respectively.

anthropogenic activities, including the use of fertilizers and pesticides, transportation, industrial manufacturing, and household practices. According to the findings obtained by the geo-accumulation index approach, it has been determined that the soil has been subjected to contamination by four heavy metal elements, namely mercury, cadmium, copper, and zinc, as a result of human activities. The soil environment within the designated study region exhibits a moderate level of ecological risk, mostly attributed to the presence of cadmium and mercury, which contribute significantly to the overall ecological risk assessment. The concentration of ecological risk within the study area is primarily observed in the north-eastern and south-western regions. This distribution can be attributed to the cumulative impacts of human activities and the notable topographical characteristics of the river valleys. It is important to highlight the significance of these factors in understanding the ecological risk within the study area. The findings of the study indicate that the presence of heavy metals in the study region poses specific carcinogenic risks to the populations residing there. Particularly, the elements arsenic (As) and nickel (Ni) exhibit cumulative carcinogenic hazards, particularly among the children population. The findings derived from health risk modeling utilizing Monte Carlo simulation suggest that conventional approaches of assessing sexuality may potentially overstate the health hazards associated with heavy metal exposure in humans. However, the overall patterns of health risks pertaining to heavy metal components remained largely consistent across both evaluation methodologies. The non-carcinogenic risk probabilities for both substances fell within acceptable ranges, whereas the levels of As and Ni above the maximum permissible threshold for carcinogenic risk in children. This finding further underscores the need for heightened concern over the risk posed to the pediatric population. Children exhibit increased non-carcinogenic and carcinogenic risks through various routes of intake compared to adults. Notably, oral intake serves as the primary mode of exposure in the general population. The elevated risk observed in children can be attributed to their lower body weight and higher rate of oral consumption. Therefore, it is imperative to explore potential methodologies that might be employed to further mitigate heavy metal contamination and associated health hazards.

CRediT authorship contribution statement

Daokun Chen: Investigation, Methodology, Writing – original draft. **Shengfei Yang:** Formal analysis. **Zhiyang Jiang:** Investigation. **Zhirui Wang:** Investigation. **Zhanbin Wang:** Methodology. **Hui Tian:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Xinbin Li from Xi'an Center of Mineral Resources Survey, China Geological Survey for their assistance with the final editing of the paper. This study was supported by China Geological Survey (DD20230481, DD20220868).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22580.

References

[1] N.C. Chen, Y.J. Zheng, X.F. He, X.F. Li, X.X. Zhang, Analysis of the Report on the national general survey of soil contamination, Journal of Agro-Environment Science 36 (2017) 1689–1692.
[2] H.B. Cao, J.J. Chen, J. Zhang, H. Zhang, L. Qiao, Y. Men, Heavy metals in rice and garden vegetables and their potential health risks to inhabitants in the vicinity of an industrial zone in Jiangsu, China, J. Environ. Sci. 22 (2010) 1792–1799.
[3] D.M. Xu, R.B. Fu, H.Q. Liu, X.P. Guo, Current knowledge from heavy metal pollution in Chinese smelter contaminated soils, health risk implications and associated remediation progress in recent decades: a critical review, J. Clean. Prod. 286 (2021), 124989.
[4] G. Nziguheba, E. Smolders, Inputs of trace elements in agricultural soils via phosphate fertilizers in European countries, Sci. Total Environ. 390 (2008) 53–57.
[5] B. Hu, S. Shao, H. Ni, Z. Fu, L.S. Hu, Y. Zhou, X.X. Min, S.F. She, et al., Current status, spatial features, health risks, and potential driving factors of soil heavy metal pollution in China at province level, Environ. Pollut. 266 (2020), 114961.
[6] N.A. Bhat, P. Ghosh, W. Ahmed, F. Naaz, A.P. Darshinee, Heavy metal contamination in soils and stream water in Tungabhadra basin, Karnataka: environmental and health risk assessment | SpringerLink, Int. J. Environ. Sci. Technol. 20 (2023) 3071–3084.
[7] W.Q. Xing, H. Liu, T. Banet, H.S. Wang, J.A. Ippolito, L.P. Li, Cadmium, copper, lead and zinc accumulation in wild plant species near a lead smelter, Ecotoxicol. Environ. Saf. 198 (2020), 110683.
[8] Z.M. Lian, X.M. Zhao, X. Gu, X.R. Li, M.M. Luan, M. Yu, Presence, sources, and risk assessment of heavy metals in the upland soils of northern China using Monte Carlo simulation, Ecotoxicol. Environ. Saf. 230 (2022), 113154.
[9] X.D. Guo, Y.S. Zhao, H.Y. He, X.G. Wang, Potential ecological risk assessment of soil heavy metals in Hunchun basin, Northeast China, Arabian J. Geosci. 13 (2020) 56.
[10] F.F. Wang, Q.Y. Guan, J. Tian, J.K. Lin, Y.Y. Yang, L.Q. Yang, N.H. Pan, Contamination characteristics, source apportionment, and health risk assessment of heavy metals in agricultural soil in the Hexi Corridor, Catena 191 (2020), 104573.
[11] Y.F. Wang, H.F. Cheng, Soil heavy metal(loid) pollution and health risk assessment of farmlands developed on two different terrains on the Tibetan Plateau, China, Chemosphere 335 (2023), 139148.
[12] B. Cheng, Z. Wang, X. Yan, Y. Yu, L. Liu, Y. Gao, H. Zhang, X. Yang, Characteristics and pollution risks of Cu, Ni, Cd, Pb, Hg and as in farmland soil near coal mines, Soil & Environmental Health 1 (2023), 100035.
[13] Y. Sheng, Z. Wang, X. Feng, Potential ecological risk and zoning control strategies for heavy metals in soils surrounding core water sources: a case study from Danjiangkou Reservoir, China, Ecotoxicol. Environ. Saf. 252 (2023), 114610.
[14] A. Kharazi, M. Leili, M. Khazaei, M.Y. Alikhani, R. Shokoohi, Human health risk assessment of heavy metals in agricultural soil and food crops in Hamadan, Iran, J. Food Compos. Anal. 100 (2021), 103890.
[15] Z. Wang, P.P. Luo, X.B. Zha, C.Y. Xu, S. Kang, M.M. Zhou, D. Nover, Y.H. Wang, Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil, J. Clean. Prod. 379 (2022), 134043.
[16] B.G. Wei, L.S. Yang, A review of heavy metal contaminations in urban soils, urban road dust, and agricultural soils from China, Microchem. J. 94 (2010) 99–107.
[17] Z.J. Jiang, S.Z. Yang, S. Luo, Source analysis and health risk assessment of heavy metals in agricultural land of multi-mineral mining and smelting area in the Karst region – a case study of Jichangpo Town, Southwest China, Heliyon 9 (2023), e17246.
[18] P. Liu, W. Hu, K. Tian, B. Huang, Y.C. Zhao, X.K. Wang, Y.Q. Zhou, B. Shi, et al., Accumulation and ecological risk of heavy metals in soils along the coastal areas of the Bohai Sea and the Yellow Sea: a comparative study of China and South Korea, Environ. Int. 137 (2020), 105519.
[19] N. Adimalla, J. Chen, H. Qian, Spatial characteristics of heavy metal contamination and potential human health risk assessment of urban soils: a case study from an urban region of South India, Ecotoxicol. Environ. Saf. 194 (2020), 110406.
[20] L. Chen, M.X. Zhou, J.Z. Wang, Z.Q. Zhang, C.J. Duan, X.X. Wang, S.L. Zhao, X.H. Bai, et al., A global meta-analysis of heavy metal(loid)s pollution in soils near copper mines: evaluation of pollution level and probabilistic health risks, Sci. Total Environ. 835 (2022), 155441.
[21] J.H. Huang, S.Y. Peng, X. Mao, F. Li, S.T. Guo, L.X. Shi, Y.H. Shi, H.B. Yu, G.M. Zeng, Source apportionment and spatial and quantitative ecological risk assessment of heavy metals in soils from a typical Chinese agricultural county, Process Saf. Environ. Protect. 126 (2019) 339–347.
[22] S.Y. Yang, S.B. Gu, M.J. He, X.J. Tang, L.Q. Ma, J.M. Xu, X.M. Liu, Policy adjustment impacts Cd, Cu, Ni, Pb and Zn contamination in soils around e-waste area: concentrations, sources and health risks, Sci. Total Environ. 741 (2020), 140442.
[23] D. Ding, L. Kong, D. Jiang, J. Wei, S. Cao, X. Li, L. Zheng, S. Deng, Source apportionment and health risk assessment of chemicals of concern in soil, water, and sediment at a large strontium slag pile area, J. Environ. Manag. 304 (2022), 114228.
[24] I. Mukherjee, U.K. Singh, R.P. Singh, Kumari D. Anshumali, P.K. Jha, P. Mehta, Characterization of heavy metal pollution in an anthropogenically and geologically influenced semi-arid region of east India and assessment of ecological and human health risks, Sci. Total Environ. 705 (2020), 135801.
[25] M.C. Wei, A.F. Pan, R.Y. Ma, H. Wang, Distribution characteristics, source analysis and health risk assessment of heavy metals in farmland soil in Shiquan County, Shaanxi Province, Process Saf. Environ. Protect. 171 (2023) 225–237.
[26] Y. Panqing, A. Abliz, S. Xiaoli, H. Aisaiduli, Human health risk assessment of heavy metal–contaminated soil based on Monte Carlo simulation, Sci. Rep. 13 (2023) 7033.
[27] K. Loska, D. Wiechuła, I. Korus, Metal contamination of farming soils affected by industry, Environ. Int. 30 (2004) 159–165.
[28] M. Chen, X.Y. Chen, Y.Z. Xing, Y. Liu, S.W. Zhang, D. Zhang, J.M. Zhu, Arsenic and cadmium in soils from a typical mining city in Huainan, China: spatial distribution, ecological risk assessment and health risk assessment, Bull. Environ. Contam. Toxicol. 107 (2021) 1080–1086.
[29] L. Hakanson, An ecological risk index for aquatic pollution control.a sedimentological approach, Water Res. 14 (1980) 975–1001.
[30] US EPA National Center for Environmental Assessment WD, Moya J Exposure Factors Handbook, 1997. Final Report).

[31] Q.Y. Guan, Z. Liu, W.Y. Shao, J. Tian, H.P. Luo, F. Ni, Y.X. Shan, Probabilistic risk assessment of heavy metals in urban farmland soils of a typical oasis city in northwest China, Sci. Total Environ. 833 (2022), 155096.

[32] H. Gui, Q.C. Yang, X.Y. Lu, H.L. Wang, Q.B. Gu, J.D. Martín, Spatial distribution, contamination characteristics and ecological-health risk assessment of toxic heavy metals in soils near a smelting area, Environ. Res. 222 (2023), 115328.

[33] Z. Wang, L.L. Bai, Y. Zhang, K.L. Zhao, J. Wu, W. Fu, Spatial variation, sources identification and risk assessment of soil heavy metals in a typical Torreya grandis cv. Merrillii plantation region of southeastern China, Sci. Total Environ. 849 (2022), 157832.

[34] R. Ramesh, M. Subramanian, E. Lakshmanan, A. Subramaniyan, G. Ganesan, Human health risk assessment using Monte Carlo simulations for groundwater with uranium in southern India, Ecotoxicol. Environ. Saf. 226 (2021), 112781.

[35] W. Zhao, Y Tong Cui, X.P. Sun, H.Y. Wang, X.H. Teng, Corn stover biochar increased the edible safety of spinach by reducing the migration of mercury from soil to spinach, Sci. Total Environ. 758 (2021), 143883.

[36] Q.M. Wu, W.Y. Hu, H.F. Wang, P. Liu, X.K. Wang, B. Huang, Spatial distribution, ecological risk and sources of heavy metals in soils from a typical economic development area, Southeastern China, Sci. Total Environ. 780 (2021), 146557.

[37] R. Xiao, D. Guo, A. Ali, S. Mi, T. Liu, C.Y. Ren, R.H. Li, Z.Q. Zhang, Accumulation, ecological-health risks assessment, and source apportionment of heavy metals in paddy soils: a case study in Hanzhong, Shaanxi, China, Environ. Pollut. 248 (2019) 349–357.

[38] A. Gallardo, R. Paramá, Spatial variability of soil elements in two plant communities of NW Spain, Geoderma 139 (2007) 199–208.

[39] M.M. Orosun, K.J. Oyewumi, M.R. Usikalu, C.A. Onumejor, Dataset on radioactivity measurement of Beryllium mining field in Ifelodun and gold mining field in Moro, Kwara State, North-central Nigeria, Data Brief 31 (2020), 105888.

[40] H. Baltas, M. Sirin, E. Gökbayrak, A.E. Ozcelik, A case study on pollution and a human health risk assessment of heavy metals in agricultural soils around Sinop province, Turkey, Chemosphere 241 (2020), 125015.

[41] S. Wang, L.M. Cai, H.H. Wen, J. Luo, Q.S. Wang, X. Liu, Spatial distribution and source apportionment of heavy metals in soil from a typical county-level city of Guangdong Province, China, Sci. Total Environ. 655 (2019) 92–101.

[42] L. Chai, Y.H. Wang, X. Wang, L. Ma, Z.X. Cheng, L.M. Su, Pollution characteristics, spatial distributions, and source apportionment of heavy metals in cultivated soil in Lanzhou, China, Ecol. Indicat. 125 (2021), 107507.

[43] W.X. Chen, Q. Li, Z. Wang, Z.J. Sun, Spatial distribution characteristics and pollution evaluation of heavy metals in arable land soil of China, Environmental Science 41 (2020) 2822–2833.

[44] Z.Y. Li, Z.W. Ma, T.J. van der Kuijp, Z.W. Yuan, L. Huang, A review of soil heavy metal pollution from mines in China: pollution and health risk assessment, Sci. Total Environ. 468–469 (2014) 843–853.

[45] X.P. Chen, S. Liu, Y. Luo, Spatiotemporal distribution and probabilistic health risk assessment of arsenic in drinking water and wheat in Northwest China, Ecotoxicol. Environ. Saf. 256 (2023), 114880.