Assessment of Soil-Heavy Metal Pollution and the Health Risks in a Mining Area from Southern Shaanxi Province, China

Rui Chen, Lei Han, Zhao Liu, Yonghua Zhao, Risheng Li, Longfei Xia, and Yamin Fan

Abstract: Soil-heavy metal pollution in mining areas is one of the problems in the comprehensive treatment of soil environmental pollution. To explore the degree of soil-heavy metal pollution and the human health risk in mining areas, the contents of soil As, Cd, Cu, Cr, Hg, Ni, Pb, and Cr(VI) in an abandoned gold mining area were determined. The geoaccumulation index (I_{geo}), single-factor pollution index (SPI), Nemerow comprehensive pollution index (NCPI), potential ecological risk index (PERI), and the human health risk assessment model were used to assess the pollution degree and the risk of soil-heavy metal pollution. Finally, the assessment results were used to provide remediation guidance. The results showed that (1) the average contents of As, Cd, Cr, Cu, Hg, and Ni in the mining area exceeded the background values of the soil elements. (2) The mining area was polluted by heavy metals to different degrees and had strong potential ecological hazards. (3) The total carcinogenic risk of heavy metals exceeded the health risk standard. The main components of pollution in the mining area were As, Cd, Cr, and Hg. Results from this study are expected to play a positive role in pollution treatment and the balance between humans and ecology.

Keywords: mining area; soil-heavy metal; pollution assessment; ecological risk; human health risk

1. Introduction

The exploitation of mineral resources not only promotes rapid economic growth but also threatens the surrounding ecological environment [1]. Soil-heavy metals have become a topic of focus all over the world because of their strong toxicity, high concealment, easy residue, and difficult treatment. The identification and environmental risk assessment of soil-heavy metal pollution characteristics in mining areas are the basis for regional soil-heavy metal pollution control [2]. In recent years, efforts have been made for the problem of soil-heavy metal pollution caused by mining. Chitsaz et al. [3] assessed soil pollution after copper mining in the Darreh Zereshk region of central Iran using I_{geo} and principal factor analysis and spatial distribution of elements. Liu et al. [4] used NCPI and I_{geo} to evaluate the levels of concentration of heavy metals in soil for potential ecological risk assessment in the Zhundong mining district. Wang et al. [5] combined SPI, NCPI, and a human health risk model to analyze soil Cr content in rural, urban, and suburban farmland soil. The spatial variability of soil pollution and geostatistical and statistical approaches to pollution are necessary and should be carried out at regular intervals [6,7]. Therefore, the continuous recording and monitoring of the pollution are established. In addition, data are emerging, which must be taken into account by policymakers [8]. On the other hand, determining and identifying the possible sources of pollution must be reliable; thus, the assessment of the...
problem becomes holistic and environmental management is more sustainable [9]. During a soil pollution investigation, the geoaccumulation index ($I_{\text{geo}}$) [10], single-factor index (SPI) [11,12], Nemerow comprehensive index (NCPI) [13], potential ecological risk index (PERI) [14,15], and human health risk assessment [16–18] methods have been commonly used for the evaluation of pollution.

Previous studies have shown that land-use types have a certain impact on the migration and diffusion of soil-heavy metals [19]. For example, Chrastny et al. [20] showed that forest soils are much more affected with smelting processes, while agriculture soils are much more affected by downward metal migration. In addition, different land-use types have different reference values in pollution assessment [21]. Evaluating the degree of heavy metal pollution and potential ecological risk hazards based on different land use types is conducive to formulating targeted solutions, improving the quality of the soil environment, improving the living environment, and providing necessary support for the ecological environment management of mining areas. On this basis, to understand the pollution status and harm to the ecological environment and human health of soil-heavy metal pollution of different land use types in a mining area and its surroundings, soil samples were collected to determine the content of soil-heavy metals, and the pollution degree of soil-heavy metals in different land-use types in the mining area was analyzed by $I_{\text{geo}}$, SPI, NCPI, and PERI to analyze the main pollution elements. Moreover, the human risk assessment model based on the heavy metal exposure pathway was used to evaluate the health risk to the surrounding population. Finally, the corresponding control measures were proposed according to the ecological environment and land-use types of the mining area and its surrounding areas. This study can provide a scientific basis and useful reference for remediating soil-heavy metal pollution in mining areas and residents’ health.

2. Materials and Methods

2.1. Study Area

The city of Shangluo is located in the southeastern part of Shaanxi Province, China (Figure 1). It is between 108º34'20′–111º1'25′ E and 33º2'30′–34º24'40″ N and has a warm temperate climate. The annual average temperature is 7.8–13.9 ºC; the annual average precipitation is 696.8–830.1 mm; the annual average sunshine duration is 1848.1–2055.8 h. The soil’s type is yellow cinnamon soil. A gold production company in the research area began operation in 1993; it ceased production after a dam failure in 2006. The comprehensive treatment project that adopted “microorganism + phytoremediation” technology for heavy metal pollution in farmland soil (area C) was launched by Shangluo Municipal Ecology Environment Bureau from 2016 to 2018. Even after several years, bare slag poses a serious threat to human health, and the research area is listed as one of the national key areas for heavy metal prevention and control. According to the Chinese Soil Environmental Quality Risk Control Standard for Soil Contamination of Development Land [22] and the Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land [23], the study area can be divided into three subregions with different types (Figure 1). Area A is a pulp deposition area belonging to category 2 development lands where abandoned sludge accumulates with high heavy metal content. Area B is a hillside belonging to category 1 development lands, which is the buffer zone between the sludge deposition area and sloping farmland. Area C is farmland, belonging to agricultural land.
When the error between samples and their parallel samples was not more than 5%, it was judged to be qualified. Standard soil samples were used for quality control. In the sample determination, one sample was randomly selected from each 10 samples as a parallel sample for detection. Soil samples were then used to extract topsoil with a thickness of 0–20 cm. Diagonal sampling was used in five locations inside the quadrant. After uniformly mixing the collected materials from these five sites, the samples were quartered to reduce them to 1 kg and sealed in numbered polyethylene plastic bags. In total, 114 topsoil samples were collected, and their geographical coordinates were determined via real-time kinematic positioning with a precision of 1 cm.

Soil samples were dried indoors to a constant weight, and soil was then ground using a porcelain mortar, passed through a size-100 mesh, and stored. Soil samples were microwave-digested by using HNO$_3$ ($\rho = 1.42$ g·mL$^{-1}) + H_2O_2$ ($\omega = 30\%$), and As, Cd, Cr, Cu, Ni, and Pb contents were measured using ICP-MS (Agilent 7700e ICP-MS) [24]. The detection limits were 0.5 mg·kg$^{-1}$, 0.6 mg·kg$^{-1}$, 1.0 mg·kg$^{-1}$, 1.2 mg·kg$^{-1}$, 1.9 mg·kg$^{-1}$, 2.1 mg·kg$^{-1}$, and 3.2 mg·kg$^{-1}$. Hg content was measured by HNO$_3$ ($\rho = 1.42$ g·mL$^{-1}) + HCl$ ($\rho = 1.19$ g·mL$^{-1})$ heating digestion and atomic fluorescence spectrometry (Haiguang AFS-9760 atomic fluorescence spectrophotometer) [25]. The detection limit was 0.002 mg·kg$^{-1}$. Soil Cr (VI) content was determined by alkaline digestion (30 g Na$_2$CO$_3$ and 20 g NaOH dissolved in water, diluted to 1 L) and flame atomic absorption spectrometry (Sherwood Scientific M420 flame spectrometry) [26]. The detection limit was 0.5 mg·kg$^{-1}$. The soil’s pH value was determined by potentiometry [27]. All reagents used in this study were high-purity reagents, and Chinese national standard soil samples were used for quality control. In the sample determination, one sample was randomly selected from each 10 samples as a parallel sample for detection. When the error between samples and their parallel samples was not more than 5%, it was judged to be qualified.

![Figure 1. Location of the study area and sampling points (background image from Google Maps).](image-url)
2.3. Evaluation of Heavy Metal Pollution

2.3.1. Geoaccumulation Index

$I_{geo}$ is a pollution degree evaluation index proposed by Müller and is widely used to evaluate the metal pollution degree in water, ocean, and soil environments [28]. The calculation formula can be expressed as follows:

$$I_{geo} = \log_2 \left( \frac{C_i}{1.5B_i} \right)$$

where $C_i$ (mg·kg$^{-1}$) is the measured value of the target metal content in the soil, and $B_i$ (mg·kg$^{-1}$) is the background value of the element. $I_{geo}$ is divided into seven levels, as shown in Table 1.

| Classification | $I_{geo}$ | Pollution Degree                  |
|----------------|----------|-----------------------------------|
| 0              | $I_{geo} < 0$ | Unpolluted                        |
| 1              | $0 \leq I_{geo} < 1$ | Lightly polluted                  |
| 2              | $1 \leq I_{geo} < 2$ | Moderately polluted               |
| 3              | $2 \leq I_{geo} < 3$ | Moderately to heavily polluted    |
| 4              | $3 \leq I_{geo} < 4$ | Heavily polluted                  |
| 5              | $4 \leq I_{geo} < 5$ | Heavily to extremely polluted     |
| 6              | $I_{geo} \geq 5$ | Extremely polluted                |

2.3.2. Single-Factor Pollution Index

The SPI describes the relationship between the measured value and the environmental limited standard value, which is used to evaluate a single pollution project. This method is simple and applicable to various types of pollution assessment [29]. The calculation formula is as follows:

$$P_i = \frac{C_i}{S_i}$$

where $P_i$ is the single-factor pollution index, $C_i$ (mg·kg$^{-1}$) is the measured value, and $S_i$ (mg·kg$^{-1}$) is the reference standard value.

NCPI is a comprehensive index used to evaluate the level and degree of pollution in soil, water, and other environments under the action of various pollution factors [30]. The calculation formula is provided as follows:

$$P_{com} = \sqrt{\frac{\text{ave}(P_i)^2 + \text{max}(P_i)^2}{2}}$$

where $P_{com}$ is the Nemerow pollution index, $\text{ave}(P_i)$ is the average value of a single pollution index of various pollution factors, and $\text{max}(P_i)$ is the maximum value of a single pollution index. NCPI can be divided into five levels, as shown in Table 2.

| Classification | $P_i$ | Pollution Degree | $P_{com}$ | Pollution Assessment |
|----------------|------|------------------|-----------|---------------------|
| I              | $P_i \leq 1$ | Clean          | $P_{com} \leq 0.7$ | Clean (security)  |
| II             | $1 < P_i < 2$ | Slight pollution  | $0.7 < P_{com} \leq 1$ | Still clean (cord) |
| III            | $2 \leq P_i < 3$ | Moderate pollution | $1 < P_{com} \leq 2$ | Light pollution   |
| IV             | $P_i \geq 3$ | Severe pollution | $2 < P_{com} \leq 3$ | Moderate pollution |
| V              | -     | -                | $P_{com} > 3$ | Severe pollution    |
2.3.3. Potential Ecological Risk Index

PERI is proposed by Hakanson to evaluate the ecological, environmental, and toxicological effects of heavy metals [31]. This method is widely used in related research [32] to reflect the impact of pollutants on the environment under specific environments and quantitatively classify the potential hazards of heavy metals.

The calculation formula of the potential ecological risk index of a single heavy metal element is as follows.

$$E_i = T_i \times (C_i / S_i)$$  \hspace{1cm} (4)

The calculation formula of the comprehensive potential ecological risk index of multiple heavy metals is as follows:

$$RI = \sum E_i$$  \hspace{1cm} (5)

where $T_i$ is the toxic response factor, $C_i$ (mg·kg$^{-1}$) is the measured content of heavy metal $i$, and $S_i$ (mg·kg$^{-1}$) is the reference ratio of heavy metal $i$. Table 3 shows the potential ecological risk index classification standard based on $E_i$ and $RI$.

| Ecological Risk | Low | Moderate | Considerate | High | Very high |
|-----------------|-----|----------|-------------|------|------------|
| $E_i$           | <40 | 40–80    | 80–160      | 160–320 | >320        |
| $RI$            | <150| 150–300  | 300–600     | -    | >600       |

2.4. Human Health Risk Assessment

The health risk assessment model of chemical substances recommended by the United States Environmental Protection Agency (U. S. EPA) [33] is used to assess the health risk of soil-heavy metal pollution in the study area. It mainly considers two heavy metal exposure pathways: the oral intake pathway and skin contact pathway.

1. The daily exposure of heavy metals through oral intake and skin contact is calculated as follows:

$$ADD_i = \frac{C_i \times IR_{ing} \times EF \times ED}{BW \times AT} \times 10^{-6}$$  \hspace{1cm} (6)

$$ADD_i = \frac{C_i \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6}$$  \hspace{1cm} (7)

where $C_i$ (mg·kg$^{-1}$) is the measured content of heavy metals in the soil, and the other parameters are shown in Table 4.

2. The noncarcinogenic risk of a single pollutant is calculated as follows:

$$HQ_{ij} = \frac{ADD_{ij}}{R_{ij}D_{ij}}$$  \hspace{1cm} (8)

where $R_{ij}D_{ij}$ (mg·(kg·d)$^{-1}$) is the reference dose of heavy metal $i$ under exposure pathway $j$, and the specific parameter values are shown in Table 5. An HQ value greater than 1 indicates that the pollutant has a certain noncarcinogenic risk; when it is less than 1, the noncarcinogenic risk is small or can be ignored.

3. The carcinogenic risk of a single pollutant is calculated as follows:

$$ILCR_{ij} = ADD_{ij} \times SF_{ij}$$  \hspace{1cm} (9)

where $SF_{ij}$ (kg·d·mg$^{-1}$) is the carcinogenic tilt factor of heavy metal element $i$ under exposure pathway $j$, and the specific parameter values are shown in Table 5.
4. Total noncarcinogenic risk:

\[ HQ_T = \sum_{i=1}^{m} \sum_{j=1}^{n} HQ_{ij} \tag{10} \]

5. Total carcinogenic risk:

\[ ILCR_T = \sum_{i=1}^{m} \sum_{j=1}^{n} ILCR_{ij} \tag{11} \]

Table 4. Specific values of health risk assessment model parameters.

| Symbol | Parameter Meaning | Value   | Unit     | References |
|--------|-------------------|---------|----------|------------|
| IR_{soi} | Daily soil intake  | 20      | mg·d^{-1} | [34]       |
| SA     | Exposed skin surface area | 4350   | cm^{-2}  | [35]       |
| AF     | Skin adherence factor | 0.22   | mg·cm^{-2}·d^{-1} | [34] |
| ABS    | Dermal absorption factor | 0.001  | -        | [35]       |
| EF     | Exposure frequency | 350     | d·a^{-1} | [34]       |
| ED     | Exposure duration  | 30      | a        | [34]       |
| BW     | Average body weight | 59.0   | kg       | [34]       |
| AT (carcinogenic) | Average time | 70 × 365 | d    | [34]       |
| AT (noncarcinogenic) | Average time | 30 × 365 | d    | [34]       |

Table 5. Carcinogenic and noncarcinogenic factors of heavy metals under different exposure methods.

| Item            | Element | \( R_f \)_{Dij} through Oral Intake | \( R_f \)_{Dij} through Skin Contact | \( SF_f \) through Oral Intake | \( SF_f \) through Skin Contact |
|-----------------|---------|-------------------------------------|-------------------------------------|-----------------------------|--------------------------------|
| Carcinogenic heavy metals | As      | \( 3 \times 10^{-4} \)             | \( 3 \times 10^{-4} \)             | 1.5                         | 7.5                            |
|                  | Cd      | \( 1 \times 10^{-3} \)             | \( 1 \times 10^{-5} \)             | 6.1                         | 6.1                            |
|                  | Cr      | \( 3 \times 10^{-3} \)             | \( 6 \times 10^{-5} \)             | 0.5                         | 20                             |
|                  | Ni      | \( 2 \times 10^{-2} \)             | \( 5.4 \times 10^{-3} \)           | -                           | 0.84                           |
|                  | Cu      | \( 4.2 \times 10^{-2} \)           | \( 1.2 \times 10^{-2} \)           | -                           | -                              |
|                  | Hg      | \( 3 \times 10^{-4} \)             | \( 2.4 \times 10^{-5} \)           | -                           | -                              |
|                  | Pb      | \( 3.5 \times 10^{-3} \)           | \( 5.25 \times 10^{-4} \)          | -                           | -                              |
|                  | Zn      | \( 3 \times 10^{-1} \)             | \( 6 \times 10^{-2} \)             | -                           | -                              |
| Noncarcinogenic heavy metals | As      | \( 11.1 \text{ mg·kg}^{-1} \) | \( 0.094 \text{ mg·kg}^{-1} \) | \( 62.2 \text{ mg·kg}^{-1} \) | \( 21.4 \text{ mg·kg}^{-1} \) | \( 0.03 \text{ mg·kg}^{-1} \) | \( 28.8 \text{ mg·kg}^{-1} \) | \( 21.4 \text{ mg·kg}^{-1} \) | \( 69.4 \text{ mg·kg}^{-1} \) |

If \( ILCR \) is less than \( 1.00 \times 10^{-4} \), the heavy metal element does not have carcinogenic risk. Otherwise, the heavy metal element has carcinogenic risk [36].

2.5. Parameter Selection

The degree of soil-heavy metal pollution is mainly determined by comparison with a reference value. Therefore, selecting an appropriate parameter is an important part of reliable pollution evaluation. In this study, the filter values of development land and agricultural land were used as the reference value of the SPI, and the background value of Shaanxi Province was used as the reference value of the \( I_{geo} \) and potential ecological risk index. The main purpose here is to determine the excess of soil-heavy metals based on different land-use types and analyze the potential risk of heavy metals to the local ecological environment.

2.5.1. Background Value of the Geoaccumulation Index

In the geoaccumulation index, \( B_k \) is the geochemical background value of the heavy metal element in the local area. According to the background values of soil elements in Shaanxi Province [37], \( B_{As} = 11.1 \text{ mg·kg}^{-1} \), \( B_{Cd} = 0.094 \text{ mg·kg}^{-1} \), \( B_{Cr} = 62.2 \text{ mg·kg}^{-1} \), \( B_{Cu} = 21.4 \text{ mg·kg}^{-1} \), \( B_{Hg} = 0.03 \text{ mg·kg}^{-1} \), \( B_{Ni} = 28.8 \text{ mg·kg}^{-1} \), \( B_{Pb} = 21.4 \text{ mg·kg}^{-1} \), and \( B_{Zn} = 69.4 \text{ mg·kg}^{-1} \) were selected as the background values of heavy metals.
2.5.2. Toxicity Coefficient of the Potential Ecological Risk Index

In the process of health risk assessment, appropriate population parameters can improve the accuracy of the assessment results. In this study, the exposure dose of soil-heavy metals and population health risks in mining areas and surrounding areas were evaluated based on the partial parameter information of the rural population in Shaanxi Province according to the Handbook of Population Exposure Parameters in China [34] and the relevant parameters based on the technical guidelines for risk assessment of contaminated sites [35] (Table 5).

2.5.3. Reference Value of the Single-Factor Pollution Index and Potential Ecological Risk Index

In the formula calculating SPI, $S_i$ refers to the reference standard value. For different regions, the $S_i$ value can be selected as the filter value of the corresponding land-use type according to the soil environmental quality standard (Table 6), where the Cr in development lands is Cr(VI).

Table 6. Filter and control values of the heavy metal pollution risk for farmlands (pH > 7.5) and development lands (mg·kg$^{-1}$).

| Pollutant | Farmlands | Development Lands | Filter Values (mg·kg$^{-1}$) | Control Values (mg·kg$^{-1}$) | Filter Values (mg·kg$^{-1}$) | Control Values (mg·kg$^{-1}$) |
|-----------|-----------|-------------------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|
|           |           |                   | Category 1 Lands             | Category 2 Lands              | Category 1 Lands             | Category 2 Lands              |
| As        | 25        | 100               | 20                          | 60                            | 120                          | 140                            |
| Cd        | 0.6       | 4                 | 20                          | 65                            | 47                           | 172                            |
| Cr        | 250       | 1300              | 3.0                         | 5.7                           | 30                           | 78                            |
| Cu        | 100       | -                 | 2000                        | 18,000                        | 8000                         | 36,000                        |
| Hg        | 3.4       | 6                 | 8                           | 38                            | 33                           | 82                            |
| Ni        | 190       | -                 | 150                         | 900                           | 600                          | 2000                          |
| Pb        | 170       | 1000              | 400                         | 800                           | 800                          | 2500                          |
| Zn        | 300       | -                 | -                           | -                             | -                            | -                             |

3. Results

3.1. Descriptive Statistics of Soil-Heavy Metals

The statistical results of the soil-heavy metal content in different subregions of the mining area are displayed in Table 7. All soil pH values in the study area were greater than 7.5, showing that the soil was weakly alkaline. The average contents of As and Hg in the three subregions and Cd in area C exceeded the filter value of the corresponding land-use types. Except for Pb and Zn, the average content of heavy metal pollutants in the three subregions exceeded the corresponding soil background value. These results indicate that the mining area and its surrounding soil were polluted by heavy metals to varying degrees. The average content of heavy metals was in the order of area A > area B > area C. The average As content in area A was 15.4- and 45.6-fold higher than that in area B and area C, respectively. The average Hg content in area A was 4.8- and 6.7-fold higher than that in area B and area C, respectively. The average coefficient of variation in each subregion followed the order of B > A > C. The coefficient of variation of As was the largest in area A and follow by area B and that of Hg was the largest in area C. The Kolmogorov–Smirnov test showed that concentrations of all elements are normally distributed with a statistical significance at the $\alpha = 0.05$ level.
Table 7. Soil-heavy metal concentrations in the mining area.

| Area | Parameter | As (mg·kg⁻¹) | Cd (mg·kg⁻¹) | Cr (mg·kg⁻¹) | Cr(VI) (mg·kg⁻¹) | Cu (mg·kg⁻¹) | Hg (mg·kg⁻¹) | Ni (mg·kg⁻¹) | Pb (mg·kg⁻¹) | Zn (mg·kg⁻¹) | pH |
|------|-----------|--------------|--------------|--------------|------------------|--------------|--------------|--------------|--------------|--------------|----|
| A    | Max       | 1904.79      | 2.09         | 128.67       | 3.96             | 69.75        | 93.82        | 68.37        | 19.77        | 74.79        | 8.9|
| A    | Min       | 678.11       | 1.17         | 94.23        | 0.73             | 27.54        | 6.13         | 43.32        | 3.71         | 32.62        | 8.0|
| A    | Mean      | 1257.39      | 1.43         | 115.21       | 2.33             | 39.96        | 45.14        | 52.15        | 20.92        | 44.37        | 8.5|
| A    | Standard deviation | 234.56 | 0.13 | 7.44 | 0.21 | 9.67 | 22.87 | 4 | 53 | 9.09 | 0.43 |
| A    | Coefficient of variation | 1.19 | 0.09 | 0.01 | 0.02 | 0.24 | 0.51 | 0.11 | 0.14 | 0.21 | 0.16 |
| B    | Max       | 1229.13      | 2.13         | 136.52       | 2.33             | 46.35        | 38.88        | 76.37        | 35.83        | 95.80        | 8.6|
| B    | Min       | 12.79        | 1.15         | 86.82        | 0.57             | 24.07        | 2.77         | 44.49        | 6.38         | 51.78        | 7.7|
| B    | Mean      | 81.42        | 1.39         | 107.64       | 0.86             | 33.47        | 9.23         | 54.08        | 20.95        | 74.91        | 8.2|
| B    | Standard deviation | 273.59 | 0.15 | 11.09 | 0.18 | 5.02 | 8.69 | 5.94 | 5.41 | 8.87 | 0.49 |
| B    | Coefficient of variation | 2.25 | 0.11 | 0.10 | 0.01 | 0.15 | 0.94 | 0.11 | 0.26 | 0.12 | 0.23 |
| C    | Max       | 64.76        | 1.45         | 123.72       | -                | 40.14        | 15.56        | 64.50        | 24.70        | 85.49        | 8.7|
| C    | Min       | 15.66        | 1.19         | 86.83        | -                | 25.13        | 3.25         | 46.19        | 15.59        | 62.19        | 7.5|
| C    | Mean      | 27.52        | 1.34         | 104.51       | -                | 33.21        | 6.66         | 54.32        | 18.87        | 76.46        | 8.4|
| C    | Standard deviation | 19.55 | 0.08 | 9.48 | - | 4.06 | 2.99 | 4.12 | 1.72 | 5.93 | 0.47 |
| C    | Coefficient of variation | 0.31 | 0.06 | 0.09 | - | 0.12 | 0.45 | 0.08 | 0.09 | 0.08 | 0.08 |
| C    | Kolmogorov–Smirnov test | 0.12 | 0.35 | 0.32 | 0.12 | 0.40 | 0.22 | 0.26 | 0.31 | 0.19 | 0.21 |

3.2. Evaluation of Heavy Metal Pollution in Soil

3.2.1. Pollution Degree Analysis

1. Evaluation by the geoaccumulation pollution index

The background values of soil elements in Shaanxi Province were used as the reference values, and the Igeo method was applied to analyze the pollution degree in and near the mining area. The results are shown in Table 8. The three subregions were polluted to varying degrees by As, Cd, and Hg, with areas A and B being heavily to extremely heavily polluted, while Pb and Zn were not pollutants.

Table 8. Calculation results of Igeo.

| Item          | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---------------|----|----|----|----|----|----|----|----|
| Pollution degree |    |    |    |    |    |    |    |    |
| A             | 6.24 | 3.34 | 0.30 | 0.32 | 9.97 | 0.27 | -0.42 | -1.23 |
| B             | 2.29 | 3.30 | 0.21 | 0.06 | 7.68 | 0.32 | -0.62 | -0.47 |
| C             | 0.72 | 3.25 | 0.16 | 0.05 | 7.21 | 0.33 | -0.77 | -0.45 |

2. Evaluation by the single-factor pollution index

The calculation results of the SPI and NCPI of heavy metals in the mining area (Table 9) show that the soil As pollution in areas A and B reached a severe level and the Cd element pollution in area C reached a moderate level. The results of the Nemerow index suggest that area A was severely polluted, and areas B and C were slightly polluted.

Table 9. Calculation results of the SPI and NCPI.

| As | Cd | Cr/Cr (VI) | Cu | Hg | Ni | Pb | Zn |
|----|----|------------|----|----|----|----|----|
| Pollution degree |    |    |    |    |    |    |    |
| A             | 20.96 | 0.02 | 0.41 | 0.00 | 1.19 | 0.06 | 0.03 | - |
| B             | 0.02 | 0.41 | 0.00 | 1.19 | 0.06 | 0.03 | - | Clean |
| C             | 0.72 | 3.25 | 0.16 | 0.05 | 7.21 | 0.33 | -0.77 | -0.45 |

| SPI | NCPI |
|-----|------|
| As | Cd | Cr/Cr (VI) | Cu | Hg | Ni | Pb | Zn |     |
| A | 20.96 | 0.02 | 0.41 | 0.00 | 1.19 | 0.06 | 0.03 | - | 15.74 | Severe |
| B | Clean | Clean | Clean | Clean | Slight | Clean | Clean | Clean | Severe |
| C | 0.02 | 0.41 | 0.00 | 1.19 | 0.06 | 0.03 | - | Clean | Severe |
3.2.2. Potential Ecological Risk Assessment

The calculation results of the single potential ecological risk index and comprehensive potential ecological risk index (Table 10) indicate that Hg and Cd posed strong potential ecological hazard risks in the three subregions, As posed strong and moderate potential ecological hazard risks in areas A and B, respectively, and the other elements posed slight ecological hazard risks. On the whole, the potential comprehensive risk index of soil-heavy metals in the three subregions was 9350.97–61,796.91, with an average of 10,036.58, which posed a high ecological potential hazard risk.

Table 10. Calculation results of the potential ecological risk index.

| As   | Cd  | Cr  | Cr/Cr (VI) | Cu  | Hg  | Ni  | Pb  | Zn  | NCPI |
|------|-----|-----|------------|-----|-----|-----|-----|-----|------|
| A    | 1132.78 | 456.38 | 3.70 | 9.34 | 60,186.67 | 1.81 | 5.59 | 0.64 | 61,796.91 |
| B    | 73.35  | 443.62 | 3.46 | 7.82 | 12,306.67 | 1.88 | 4.89 | 1.08 | 12,842.77 |
| C    | 24.79  | 427.66 | 3.36 | 7.76 | 8880.00  | 1.89 | 4.41 | 1.10 | 9350.97  |

Table 10. Calculation results of the potential ecological risk index.

| Risk degree | As  | Cd  | Cr  | Cr/Cr (VI) | Cu  | Hg  | Ni  | Pb  | Zn  | RI    |
|-------------|-----|-----|-----|------------|-----|-----|-----|-----|-----|-------|
| Very high   | A   | 1132.78 | 456.38 | 3.70 | 9.34 | 60,186.67 | 1.81 | 5.59 | 0.64 | 61,796.91 |
| Low         | B   | 73.35  | 443.62 | 3.46 | 7.82 | 12,306.67 | 1.88 | 4.89 | 1.08 | 12,842.77 |
| Low         | C   | 24.79  | 427.66 | 3.36 | 7.76 | 8880.00  | 1.89 | 4.41 | 1.10 | 9350.97  |

3.3. Human Health Risk Assessment of Heavy Metals in Soil

3.3.1. Exposure of Soil-Heavy Metals through Mouth and Skin Contact

The total noncarcinogenic exposure dose of heavy metals in soils of different land-use types (Figure 2) suggests that the noncarcinogenic exposure dose of heavy metals was between $10^{-8}$ and $10^{-4}$ mg·(kg·d$^{-1}$) through the mouth and between $10^{-8}$ and $10^{-5}$ mg·(kg·d$^{-1}$) through skin contact. The total carcinogenic exposure dose of heavy metals in the three subregions (Figure 3) show that the carcinogenic exposure dose of heavy metals was between $10^{-7}$ and $10^{-4}$ mg·(kg·d$^{-1}$) through the mouth and between $10^{-8}$ and $10^{-6}$ mg·(kg·d$^{-1}$) through skin contact.

Figure 2. Noncarcinogenic exposure to heavy metals in soil. A, B and C represent area A, area B and area C, respectively.
3.3.2. Human Health Risk Assessment Results of Soil Heavy Metals

Figures 4 and 5 show the noncarcinogenic risk and carcinogenic risk contribution rates caused by oral intake with soil-heavy metals. Among the three subregions, the noncarcinogenic risk of As through oral intake was greater than 1 in area A and less than 1 elsewhere. The total noncarcinogenic risks of areas A, B, and C were 1.43, $1.57 \times 10^{-1}$, and $5.18 \times 10^{-2}$, respectively, indicating that soil-heavy metals in the mining area posed a certain noncarcinogenic health risk to the surrounding population. The contribution rates of the noncarcinogenic risk of As through oral intake were 95.55%, 80.89% and 57.60%, accounting for most of the total noncarcinogenic risk. The carcinogenic risk of oral intake of the carcinogenic heavy metal elements ranged from $10^{-6}$ to $10^{-4}$, among which the contribution rate of As in area A was the highest, 96.63%.

![Figure 3. Carcinogenic exposure to heavy metals in soil. A, B and C represent area A, area B and area C, respectively.](image)

![Figure 4. Noncarcinogenic risk contribution rate for oral intake of heavy metals in soil. A, B and C represent area A, area B and area C, respectively.](image)

![Figure 5. Carcinogenic risk contribution rate for oral intake of heavy metals in soil. A, B and C represent area A, area B and area C, respectively.](image)
Compared with oral intake, the health risk of people exposed to heavy metals through skin contact was relatively small. The health risks of skin contact with As, Hg, and Cr in area A and Cr in areas B and C were higher than $1 \times 10^{-2}$. The noncarcinogenic risk contribution rates of skin contact with Cr in area B and area C were as high as 74.01% and 75.09%, respectively (Figure 6). The carcinogenic risk of soil-heavy metals was between $10^{-8}$ and $10^{-5}$, and the carcinogenic risk rate of skin contact with As in area A was as high as 80.21% (Figure 7). In summary, the soil As pollution caused the greatest risk to human health in area A, area B, and area C, and Cr was the largest threat to human health through skin contact in area B and area C.

![Figure 6. Noncarcinogenic risk contribution rate for skin contact with heavy metals in soil. A, B and C represent area A, area B and area C, respectively.](image)

![Figure 7. Carcinogenic risk contribution rate for skin contact with heavy metals in soil. A, B and C represent area A, area B and area C, respectively.](image)

Figures 8 and 9 show the carcinogenic and noncarcinogenic risk contribution rates of soil-heavy metals through mouth and skin contact. The noncarcinogenic risks of heavy metals in the three subregions were $1.55, 2.00 \times 10^{-1}$ and $8.75 \times 10^{-2}$, respectively. The top three heavy metal elements were As, Hg and Cr. The sum of the multipath carcinogenic risks of the heavy metals in the three subregions was higher than the maximum acceptable carcinogenic risk value, which is $3.51 \times 10^{-4}$, $5.48 \times 10^{-5}$ and $2.98 \times 10^{-5}$. Notably, the carcinogenic risks of As in areas A, B, and C were $3.26 \times 10^{-4}, 3.14 \times 10^{-5}$, and $7.13 \times 10^{-6}$, respectively. The highest contribution rate was in area A, up to 84.44%. The carcinogenic risk of Cr was $2.34 \times 10^{-5}, 2.18 \times 10^{-5}$ and $2.12 \times 10^{-5}$, respectively, in areas A, B, and C. The highest contribution rate of total carcinogenic risk in area C was 85.82%.
The NCPI and PERI are two common methods for evaluating heavy metal pollution [38]. In this study, the calculation results of the NCPI (Table 9) show that area A was severely polluted, and areas B and C were lightly polluted. The calculation results of the PERI (Table 10) indicate that the three subregions had a very high ecological risk. These indices showed some differences because their emphasis points are different. NCPI can amplify the impact of the highest content of pollutants among the sample points, while the PERI is used to differentiate the potential harm of different heavy metals to the ecosystem by weighting the toxicity response coefficient. Arsenic was the main pollutant in area A. The extremely high soil As content enlarged the characteristics of NCPI; thus, NCPI in area A was relatively high. When calculating PERI, the contents of Hg and Cd with high toxicity (high Ti value) in the three subregions were far beyond the local background value of the corresponding elements, and the As content in area A was high. Therefore, in general, strong potential ecological risks were found in the three subregions. Pollution assessment can reflect the potential harm of heavy metals to the ecological environment and provide the basis for improving the ecological environment. Human health risks can directly reflect the adverse health effects of heavy metals on exposed populations [39,40]. The results of the pollution assessment suggest that the main pollutants were As, Hg, and Cd. The results of the human health risk assessment indicate that As, Cr, Hg, and Cd had a high contribution rate to the carcinogenic and noncancerous risks of the population in the study area (Figures 6 and 7). This finding is due to the strong carcinogenicity of Cr under skin exposure; thus, the carcinogenic tilt factor SF$_{ij}$ of Cr is higher [41]. Different evaluation methods have different emphases, so multiple evaluation indices should be comprehensively considered when evaluating the degree of heavy metal pollution to obtain more objective results.

**Figure 8.** Noncancerous risk contribution rate for soil-heavy metals. A, B and C represent area A, area B and area C, respectively.

**Figure 9.** Carcinogenic risk contribution rate for soil-heavy metals. A, B and C represent area A, area B and area C, respectively.

### 4. Discussion

The NCPI and PERI are two common methods for evaluating heavy metal pollution [38]. In this study, the calculation results of the NCPI (Table 9) show that area A was severely polluted, and areas B and C were lightly polluted. The calculation results of the PERI (Table 10) indicate that the three subregions had a very high ecological risk. These indices showed some differences because their emphasis points are different. NCPI can amplify the impact of the highest content of pollutants among the sample points, while the PERI is used to differentiate the potential harm of different heavy metals to the ecosystem by weighting the toxicity response coefficient. Arsenic was the main pollutant in area A. The extremely high soil As content enlarged the characteristics of NCPI; thus, NCPI in area A was relatively high. When calculating PERI, the contents of Hg and Cd with high toxicity (high Ti value) in the three subregions were far beyond the local background value of the corresponding elements, and the As content in area A was high. Therefore, in general, strong potential ecological risks were found in the three subregions. Pollution assessment can reflect the potential harm of heavy metals to the ecological environment and provide the basis for improving the ecological environment. Human health risks can directly reflect the adverse health effects of heavy metals on exposed populations [39,40]. The results of the pollution assessment suggest that the main pollutants were As, Hg, and Cd. The results of the human health risk assessment indicate that As, Cr, Hg, and Cd had a high contribution rate to the carcinogenic and noncancerous risks of the population in the study area (Figures 6 and 7). This finding is due to the strong carcinogenicity of Cr under skin exposure; thus, the carcinogenic tilt factor SF$_{ij}$ of Cr is higher [41]. Different evaluation methods have different emphases, so multiple evaluation indices should be comprehensively considered when evaluating the degree of heavy metal pollution to obtain more objective results.
The risk control ability of heavy metal pollution in the soil of mining areas is relatively weak. Many pollutants accumulate and diffuse in the soil, resulting in an increase in heavy metal content in the soil around the mining area and a decrease in soil quality, which seriously threatens the regional ecological environment and human health. Previous studies have shown that the heavy metal content in a mining area and surrounding soil exceeds the local background value and has a certain accumulation [42,43]. The potential sources of the soil-heavy metals can be determined by $I_{geo}$ [21]. In this study, the contents of As, Cd, and Hg in the soil of the three sub-regions were seriously polluted, which were far higher than the local background values. This indicates that most of soil As, Cd, and Hg originated primarily from processing the ores and the disposal of tailings and high metal wastewaters around the mines [44]. Soil Cr, Cu, Ni, Pb, and Zn were unpolluted to lightly unpolluted, and with low coefficient deviation, indicating that the source was parent rocks and affected by human activities to some extent, for example, combustion of fuels used during processing is a potential source of Ni, Cr, and Cu in soils [45]. Area A was mainly composed of exposed mineral pulp, and the pollution degree was the highest. The pollution sources of areas B and C were pulp leakage caused by dam breaks. On the one hand, in the long-term erosion process of rain and sand, the soil interacted with the flow of water, resulting in heavy metal pollution in the surrounding soil. On the other hand, exposed pulps and soils with high concentrations of heavy metals can also be suspended in the atmosphere as dust and land in the periphery with the wind, endangering the health of agricultural land and the surrounding residents at low altitudes downwind (area C). In addition, the use of Hg-containing agricultural agents, such as ethyl mercuric chloride and phenylmercuric acetate, can also lead to an increase in Hg content in agricultural land [46].

Based on these findings, it is necessary to regularly detect and evaluate the heavy metal content and health risks in a mining area and its surrounding soil and take certain control measures [8]. In our study, area A, as the source of pollution, has the highest pollution degree and is in the upwind direction at high altitude, which poses a serious threat to areas B and C at low altitude. Therefore, the focus of area A is to prevent the diffusion of heavy metal pollution. Despite 15 years of natural weathering, area A still has a seriously excessive soil-heavy metal content, and strengthening the control measures is urgently needed. Because of the long-term accumulation of mineral pulp and a thick sludge layer, improved soil imported from other locations cannot be easily implemented and easily causes secondary pollution. Thus, chemical and biological remediation methods can be combined for treatment. First, in situ remediation should be carried out by chemical methods and then the contaminated site can be treated by phytoremediation and microbial remediation. The remediation plants should possess characteristics that include adaptation to the local environmental conditions and tolerance to a high concentration of metal pollutants [47]. Area B is the transition zone between polluted fields and farmland, where the pollution degree is low and the diffusion of contaminated soil to area C is possible. Therefore, the focus of treatment can be placed on blocking the spread of pollution from area A to area C. Plants can limit the dispersal of heavy metals by surface runoff and wind and, reduce entry into aquifers will be controlled [48]. Considering that area B is a hillside and the soil layer is thin, a practical method can be planting shrubs and grasses in this area to prevent the diffusion of contaminated soil to area C through scouring rainwater. Area C comprises farmland with a low pollution degree but still has potential ecological risks and human health risks. Suggestions for using improve soil imported from other places and combining soil amendments (e.g., organic, inorganic, and minerals) to quickly control heavy metal pollution in farmland soil surfaces are recommended. Tang et al. [49] found that the combined application of amendments improved the features of contaminated soil and reduced the availability of heavy metals more effectively. Then, selecting suitable crop species can not only ensure the safety of the regional ecological environment but also bring economic benefits.
5. Conclusions

The heavy metal pollution of soil in metal mining areas has been a focus of attention all over the world, and it is a focus of research for scholars. In this research, we analyzed the characteristics of soil-heavy metal pollution in the mining area by comparing various indicators and assessing human health risk; the main conclusions are as follows: (1) The average soil As, Cd, Cr, Cu, and Hg contents in the study area exceeded the corresponding soil background values in the city of Shangluo, Shaanxi Province, China. The soil-heavy metal content in area A was significantly higher than that in areas B and C and presented obvious spatial heterogeneity. (2) The calculation results of $I_{geo}$, SPI, and NCPI demonstrate that the main pollutants in the three subregions of the mining area were As, Cd, and Hg. Area A was heavily polluted, and areas B and C were slightly polluted. (3) The calculation results of PERI suggest that Cd and Hg posed strong ecological risks in the three subregions. Among them, As in area A and B had a very high ecological risk. The comprehensive potential ecological risk index of the three subregions was very high. (4) The calculation results of the human health risk assessment indicate that the total noncancer risk and the total cancer risk of heavy metals in the three subregions was in the order of area A > B > C. In summary, the pollution of As, Cd, Cr, and Hg in the mining area exceeds the acceptable risk, which is harmful to the surrounding ecological environment and people and needs to be used as the main pollution for the subsequent remediation of contaminated sites. These results can provide basic data for protecting and improving the soil environment in the research area, and the results provide useful references for soil environmental quality monitoring in mining areas.

Author Contributions: Conceptualization, L.H.; data curation, L.H.; formal analysis, R.C., Y.Z., and Z.L.; funding acquisition, L.H.; investigation, L.H., R.C., Z.L., Y.F., and L.X.; methodology, R.C.; project administration, L.H.; resources, R.L.; software, R.C. and L.X.; supervision, Z.L. and Y.Z.; validation, Y.Z. and R.L.; visualization, R.C. and L.X.; writing—original draft, L.H. and R.C.; writing—review and editing, R.L., L.X., and Y.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the funding from the Key Laboratory of Degraded and Unused Land Consolidation Engineering, Ministry of Natural Resources of the People’s Republic of China (Program No. SXDJ2017-9), and the Shaanxi Key Laboratory of Land Reclamation Engineering: (Program No. 2018-ZZ03).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to the anonymous reviewers whose comments have helped to clarify and improve the text.

Conflicts of Interest: The authors declare no conflict of interest.

List of Abbreviations

- **ABS**: Dermal absorption factor
- **ADD$_i$**: The daily exposure of heavy metals through i pathway
- **AF**: Skin adherence factor
- **AT**: Average time
- **ave**($P_i$): The average value of a single pollution index of various pollution factors
- **B$_i$**: The background value of the element i
- **BW**: Average body weight
- **C$_i$**: The measured value of the heavy metal element i in the soil
- **ED**: Exposure duration
References

1. Bourliva, A.; Papadopoulou, L.; Aidona, E.; Giouri, K.; Simeonidis, K.; Vourlias, G. Characterization and geochemistry of technogenic magnetic particles (TMPs) in contaminated industrial soils: Assessing health risk via ingestion. *Geoderma* **2017**, *295*, 86–97. [CrossRef]

2. Kim, B.; Angeli, J.; Ferreira, P.; Mahiques, M.D.; Figueira, R. Critical evaluation of different methods to calculate the Geoaccumulation Index for environmental studies: A new approach for Baixada Santista–Southeastern Brazil. *Mar. Pollut. Bull.* **2018**, *127*, 548–552. [CrossRef] [PubMed]

3. Maedeh, C.; Amir, H.H.; Babak, M.Z.; Dalvand, M.; Seyyed, A.A.M. Heavy metals and related properties in farming soils adjacent to a future copper mine, interpretation using GIS, and statistical methods. *Arab. J. Geosci.* **2021**, *40*, 102646. [CrossRef] [PubMed]

4. Liu, W.; Yang, J.J.; Wang, J.; Wang, G.; Cao, Y.E. Contamination assessment and sources analysis of soil heavy metals in opencast mine of east Junggar Basin in Xinjiang. *Environ. Sci.* **2020**, *10*, 190, 104554. [CrossRef]

5. Jabbar, K.; Rani, S.; Pallavi, U.; Rajesh, K.Y. Geo-statistical assessment of soil quality and identification of Heavy metal contamination using Integrated GIS and Multivariate statistical analysis in Industrial region of Western India. *Environ. Technol. Innov.* **2022**, *40*, 2723–2732.

6. Fernando, S.F.; Antonio, M.G.; Carmelo, A.Z.; Antonio, G.S.; Pilar, A.R. Spatial Distribution of Heavy Metals and the Environmental Quality of Soil in the Northern Plateau of Spain by Geostatistical Methods. *Int. J. Environ. Res. Public Health* **2017**, *14*, 568. [CrossRef]

7. Golia, E.E.; Dimirkou, A.; Floras, S.A. Spatial monitoring of arsenic and heavy metals in the Almyros area, Central Greece. A statistical approach for assessing the sources of contamination. *Environ. Monit. Assess.* **2015**, *187*, 399. [CrossRef]

8. Jabbar, K.; Rani, S.; Pallavi, U.; Rajesh, K.Y. Geo-statistical assessment of soil quality and identification of Heavy metal contamination using Integrated GIS and Multivariate statistical analysis in Industrial region of Western India. *Environ. Technol. Innov.* **2022**, *40*, 102646. [CrossRef] [PubMed]

9. Liu, H.; Anwar, S.; Fang, L.Q.; Chen, L.H.; Xu, W.J.; Xiao, L.L.; Zhong, B.; Liu, D. Source Apportionment of Agricultural Soil Heavy Metals Based on PMF Model and Multivariate Statistical Analysis. *Environ. Forensics* **2022**, *23*, 1–9. [CrossRef]

10. Liu, K.H.; Zhang, H.C.; Liu, Y.F.; Li, Y.; Yu, F.M. Investigation of plant species and their heavy metal accumulation in manganese mine tailings in Pingle Mn mine, China. *Environ. Sci. Pollut. Res* **2020**, *27*, 19933–19945. [CrossRef]

11. Han, L.; Chen, R.; Liu, Z.; Chang, S.S.; Zhao, Y.H.; Li, L.S.; Li, R.S.; Xia, L.F. Sources of and control measures for PTE pollution in soil at the urban fringe in Weinan, China. *Land* **2021**, *10*, 762. [CrossRef]

12. Liu, X.Y.; Bai, Z.K.; Shi, H.D.; Zhou, W.; Liu, X.C. Heavy metal pollution of soils from coal mines in China. *Nat. Hazards* **2019**, *99*, 1163–1177. [CrossRef]

13. Arab, L.H.; Boutaleb, A.; Berdous, D. Environmental assessment of heavy metal pollution in the polymetallic district of Kef Oum Teboul (El Kala, Northeast Algeria). *Environ. Earth Sci.* **2021**, *80*, 227. [CrossRef]

14. Yang, P.G.; Drohan, P.J.; Yang, M.; Li, H.J. Spatial variability of heavy metal ecological risk in urban soils from Linfen, China. *Catena* **2020**, *190*, 104554. [CrossRef]

15. U.S. Environmental Protection Agency (EPA). *Risk Assessment Guidance for Superfund, Human Health Evaluation Manual Part A*; Office of Emergency and Remedial Response: Washington, DC, USA, 1989. Available online: [https://www.epa.gov/risk/risk-assessment-guidance-superfund-volume-i-human-health-evaluation-manual-supplemental](https://www.epa.gov/risk/risk-assessment-guidance-superfund-volume-i-human-health-evaluation-manual-supplemental) (accessed on 13 October 1989).
16. Mohammadi, A.A.; Zarei, A.; Esmailizadeh, M.; Taghavi, M.; Yousefi, M.; Yousefi, Z.; Sedighi, F.; Javan, S. Assessment of heavy metal pollution and human health risks assessment in soils around an industrial zone in Neyshabur, Iran. *Biol. Trace Elem. Res.* 2020, 195, 343–352. [CrossRef]

17. Yang, Q.Q.; Li, Z.Y.; Lu, X.N.; Duan, Q.N.; Huang, L.; Bi, J. A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment. *Sci. Total Environ.* 2018, 642, 690–700. [CrossRef]

18. Xiao, R.; Wang, S.; Li, R.H.; Wang, J.J.; Zhang, Z.Q. Soil heavy metal contamination and health risks associated with artisanal gold mining in Tongguan, Shaanxi, China. *Ecotoxicol. Environ. Saf.* 2017, 141, 17–24. [CrossRef]

19. Gao, X.; Tian, J.P.; Huo, Z.; Wu, Y.B.; Li, C.X. Evaluation of redevelopment priority of abandoned industrial and mining land based on heavy metal pollution. *PloS ONE* 2021, 16, e0255509. [CrossRef]

20. Chrastny, V.; Vanek, A.; Teper, L.; Jerzy, C.; Jan, P.; Libor, P.; Fetr, D.; Vit, P.; Michael, K.; Martin, N. Geochemical position of Pb, Zn and Cd in soils near the Olkusze mine/smelter, South Poland: Effects of land use, type of contamination and distance from pollution source. *Environ. Monit. Assess* 2012, 184, 2517–2536. [CrossRef]

21. Katarzyna, S.; Leslaw, T.; Tomasz, C.; Tomasz, H.; Michał, O.; Jan, Z. Quality of peri-urban soil developed from ore-bearing carbonates: Heavy metal levels and source apportionment assessed using pollution indices. *Minerals* 2020, 10, 1140. [CrossRef]

22. GB 36600-2018; Soil Environmental Quality—Risk Control Standard for Soil Contamination of a Development Land. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2018. Available online: [http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201807/t20180703_446027.shtml](http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201807/t20180703_446027.shtml) (accessed on 22 June 2018).

23. GB 15618-2018; Soil Environmental Quality—Risk Control Standard for Soil Contamination of Agricultural Land. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2018. Available online: [http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201807/t20180703_446029.shtml](http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201807/t20180703_446029.shtml) (accessed on 6 June 2018).

24. HJ 766-2015; Solid Waste—Determination of Metals—Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2015. Available online: [https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/2015111/20151130_317999.shtml](https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/2015111/20151130_317999.shtml) (accessed on 20 November 2015).

25. HJ 680-2013; Soil and Sediment—Determination of Mercury, Arsenic, Selenium, Bismuth, Antimony—Microwave Dissolution/Atomic Fluorescence Spectrometry. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2013. Available online: [https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201312/t20131203_264304.shtml](https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201312/t20131203_264304.shtml) (accessed on 21 November 2013).

26. HJ 1082-2019; Soil and Sediment—Determination of Cr(VI)—Alkaline Digestion/Flame Atomic Absorption Spectrometry. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2019. Available online: [https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/202001/t202001012_756539.shtml](https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/202001/t202001012_756539.shtml) (accessed on 31 December 2019).

27. HJ 962-2018; Soil—Determination of pH—Potentiometry. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2018. Available online: [https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201808/t20180815_451430.shtml](https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201808/t20180815_451430.shtml) (accessed on 29 July 2018).

28. Oylumuyiwa, O.O.; Simiso, D.; Omotayo, R.A.; Nindi, M.M. Assessing the enrichment of heavy metals in surface soil and plant (Digitaria eriantha) around coal-fired power plants in South Africa. *Environ. Sci. Pollut. Res.* 2014, 21, 4686–4696. [CrossRef]

29. Jiang, P.H.; Huang, F.L.; Wan, Y.; Peng, K.J.; Chen, C. Heavy metal contamination and risk assessment of water, sediment, and farmland soil around a Pb/Zn mine area in Henan province, China. *Fresenius Environ. Bull.* 2020, 29, 2250–2259.

30. Nemerow, N. *Scientific Stream Pollution Analysis*; McGraw Hill: New York, NY, USA, 1974.

31. Hakanson, L. An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Res.* 1980, 14, 975–1001. [CrossRef]

32. Chen, Z.; Xu, J.; Duan, R.; Lu, S.; Hou, Z.; Yang, F.; Peng, M.; Zong, Q.; Shi, Z.; Yu, L. Ecological health risk assessment and source identification of heavy metals in surface soil based on a high geochemical background: A Case Study in Southwest China. *Toxics* 2022, 10, 282. [CrossRef]

33. U.S. Environmental Protection Agency (EPA). *Exposure Factors Handbook: 2011 Edition*; National Center for Environmental Assessment: Washington, DC, USA, 2011. Available online: [http://www.epa.gov/ncera/efh](http://www.epa.gov/ncera/efh) (accessed on 3 October 2011).

34. Ministry of Ecology and Environment of the People’s Republic of China. *Exposure Factors Handbook of Chinese Population*; China Environmental Press: Beijing, China, 2013; pp. 156–164.

35. HJ 25.3—2019; Technical Guidelines for Risk Assessment of Soil Contamination of Land for Construction. Ministry of Ecology and Environment of the People’s Republic of China: Beijing, China, 2019. Available online: [https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/trjh/201912/t20191224_749893.shtml](https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/trjh/201912/t20191224_749893.shtml) (accessed on 2 December 2019).

36. Li, Z.Y.; Ma, Z.W.; Van Der Kuijp, T.J.; Yuan, Z.W.; Huang, L. A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Sci. Total Environ.* 2014, 468, 843–853. [CrossRef]

37. State Environmental Protection Administration of China. *China Background Value of Soil Element*; China Environmental Press: Beijing, China, 1990.

38. Wang, R.; Chen, N.; Zhang, E.X. Ecological and health assessment based in the total amount and speciation of heavy metals in soils around mining areas. *Environ. Sci. 2021*, 40, 1–15. (In Chinese) [CrossRef]

39. Pan, L.B.; Ma, J.; Hu, Y.; Su, B.Y.; Fang, G.L.; Wang, Y.; Wang, Z.S.; Wang, L.; Xiang, B. Assessments of levels, potential ecological risk, and human health risk of heavy metals in the soils from a typical county in Shanxi Province, China. *Environ. Sci. Pollut. Res.* 2016, 23, 19330–19340. [CrossRef]
40. Nasirzadeh, N.; Mohammadian, Y.; Dehgan, G. Health risk assessment of occupational exposure to hexavalent chromium in Iranian workplaces: A meta-analysis study. *Biol. Trace Elem. Res.* **2021**, *200*, 1551–1560. [CrossRef]
41. Zhu, D.W.; Wei, Y.; Zhao, Y.H.; Wang, Q.L.; Han, J.C. Heavy metal pollution and ecological risk assessment of the agriculture soil in xunyang mining Area, Shaanxi Province, northwestern China. *Bull. Environ. Contam. Toxicol.* **2018**, *101*, 178–184. [CrossRef]
42. Elouear, Z.; Bouhamed, F.; Boujelben, N.; Bouzid, J. Assessment of toxic metals dispersed from improperly disposed tailing, Jebel Ressas mine, NE Tunisia. *Environ. Earth Sci.* **2016**, *75*, 254. [CrossRef]
43. Huang, S.H.; Yuan, C.Y.; Li, Q.; Yang, Y.; Tang, C.J.; Ouyang, K.; Wang, B. Distribution and risk assessment of heavy metals in soils from a typical Pb-Zn mining area. *Pol. J. Environ. Stud.* **2017**, *26*, 1105–1112. [CrossRef]
44. Sutkowska, K.; Czech, T.; Teper, L.; Krzykawski, T. Heavy metals soil contamination induced by historical zinc smelting in Jaworzno. *Ecol. Chem. Eng. A* **2013**, *20*, 1441–1450. [CrossRef]
45. Joshua, P.; John, A.; Anke, B.; Justus, P.D.; Stefan, Z. Soil heavy metal(loid) pollution and phytoremediation potential of native plants on a former gold mine in Ghana. *Water Air Soil Pollut.* **2019**, *230*, 267. [CrossRef]
46. Qin, G.W.; Niu, Z.D.; Yu, J.D.; Li, Z.H.; Ma, J.Y.; Xiang, P. Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. *Chemosphere* **2021**, *267*, 129205. [CrossRef]
47. Mahar, A.; Wang, P.; Ali, A.; Awasthi, M.K.; Lahoro, A.H.; Wang, Q.; Li, R.H.; Zhang, Z.Q. Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicol. Environ. Saf.* **2016**, *126*, 111–121. [CrossRef]
48. Sheoran, V.; Sheoran, A.S.; Poonia, P. Phytomining: A review. *Min. Eng.* **2009**, *22*, 1007–1019. [CrossRef]
49. Tang, J.Y.; Zhang, L.H.; Zhang, J.C.; Ren, L.H.; Zhou, Y.Y.; Zheng, Y.Y.; Luo, L.; Yang, Y.; Huang, H.L.; Chen, A.W. Physicochemical features, metal availability and enzyme activity in heavy metal-polluted soil remediated by biochar and compost. *Sci. Total Environ.* **2020**, *701*, 134751. [CrossRef]