Assessment of Cd Pollution in Paddy Soil–Rice System in Silver Mining-Affected Areas: Pollution Status, Transformation and Health Risk Assessment

Lv Lv 1,†, Zhiqiang Jiao 1,2,†, Shiji Ge 1,2, Wenhao Zhan 3, Xinling Ruan 1,2,4,* and Yangyang Wang 1,2,4,*

1 National Demonstration Center for Environmental and Planning, College of Geography and Environmental Science, Henan University, Kaifeng 475004, China
2 Henan Engineering Research Center for Control & Remediation of Soil Heavy Metal Pollution, Henan University, Kaifeng 475004, China
3 National Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Center, Beijing 100094, China
4 Key Laboratory of Geospatial Technology for the Middle and Lower Yellow River Regions, Henan University, Ministry of Education, Kaifeng 475004, China

* Correspondence: 0412420xx@163.com (X.R.); wangyy@henu.edu.cn (Y.W.)
† These authors contributed equally to this work.

Abstract: Mining activities are one of the main contamination sources of Cd in soil. However, the information about the influence of silver mining on Cd pollution in soil in mining-affected areas is limited. In the present study, sixteen paired soil and rice grain samples were collected from the farmland along the Luxi River nearby a silver mine in Yingtan City, Jiangxi Province, China. The total, bioavailable, and fraction of Cd in soil and Cd content in rice grain were determined by inductively coupled plasma mass spectrometry. The transformation of Cd in the soil–rice system and potential health risk via consumption of these rice grains were also estimated. The results showed that Cd concentration in these paddy soils ranged from 0.21 to 0.48 mg/kg, with the mean Cd concentration (0.36 mg/kg) exceeded the national limitation of China (0.3 mg/kg, GB 15618-2018). Fortunately, all these contaminated paddy soils were just slightly polluted, with the highest single-factor pollution index value of 1.59. The DTPA- and CaCl2-extractable Cd in these paddy soils ranged from 0.16 to 0.22 mg/kg and 0.06 to 0.11 mg/kg, respectively, and the acid-soluble Cd occupied 40.40% to 52.04% of the total Cd, which was the highest among different fractions. The concentration of Cd in rice grain ranged from 0.03 to 0.39 mg/kg, and the mean Cd concentration in rice grain (0.16 mg/kg) was within the national limitation of China (0.2 mg/kg, GB 2762-2017). The bioaccumulation factor of Cd in rice grain ranged from 0.09 to 1.18, and its correlation with various indicators was nonsignificant (p < 0.05).

Health risk assessment indicated that the noncarcinogenic risk for local rice consumers was within the acceptable range, but the carcinogenic risk (CR) was ranging from 1.24 × 10⁻² to 1.09 × 10⁻³ and higher than the acceptable range (1.0 × 10⁻⁴), indicating that the local rice consumers suffered serious risk for carcinogenic diseases. The results of the present study can provide reference for safety production of rice in silver mining-affected areas.

Keywords: Cadmium; health risk assessment; toxic metal; silver mining; transformation

1. Introduction

Anthropic activities, including mining, smelting, wastewater irrigation, and excessive application of pesticides and fertilizer, have resulted in serious toxic metal contamination in soil [1,2], especially for Cadmium (Cd) [3,4]. Based on the national soil contamination survey in China, about 7% of the soil was contaminated with Cd [5]. Cd has been classified as Group I carcinogen by the International Agency for Research on Cancer, and is toxic, nondegradable, persistent, and mobile in the soil environment [6,7]. In addition, Cd also can be accumulated through the food chain, posing long-term health risk to ecosystem and...
human health [8,9]. Therefore, investigating the pollution status and transfer behavior of Cd in the soil–crop system is of significance to local food safety and health of residents.

At present, great attention has been paid to Cd contamination in soil, and a lot of studies regarding the transformation of Cd in the soil–crop system have been conducted [10–12]. Previous studies indicated that Pb/Zn smelting caused serious Cd contamination in surrounding soil; this Cd can be accumulated easily in wheat grain and posed a serious health risk to local wheat consumers [13,14]. Wastewater irrigation (occurs mainly in arid and semi-arid areas) also resulted in the accumulation of Cd in agricultural soil, and Cd concentration in vegetables, wheat grains and fruits all increased significantly and exceeded the limit standard of the local government or FAO/WHO [15–17].

In addition, as one of the major pollution sources, the mining of non-ferrous mines also released large amounts of Cd into the surrounding soil environment, such as the mining of lead, zinc, arsenic, manganese, antimony, gold, barium, and uranium [18–20]. As the major concentration region of non-ferrous production and also the main rice production region, the exploitation of non-ferrous mines in southern China has resulted in a Cd concentration in some rice grain that exceeded the national standard limitation of China (GB 2762-2017) and posed serious potential health risk of local residents [18,21,22]. However, the influence of silver mining on Cd contamination in the soil–rice system has not been reported.

Rice is the staple food for more than 50% of the people in the world and has strong accumulation capacity for Cd [23,24]. Therefore, it is of great significance to investigate the transformation of Cd in the soil–rice system and its influencing factors. In fact, various environmental factors can influence the transformation of Cd from soil to crops, such as the total, bioavailable and fraction of Cd in soil, the pH value, cation exchange capacity (CEC), organic matter content (OM), and types of soil [25,26]. However, which one of these is the key factor influencing Cd transformation from soil to crops remains to be further studied. Generally speaking, it is difficult (or expensive) to reduce the total Cd concentration in soil [27,28], but the activity of Cd and Cd adsorption by plants can be inhibited by regulation of soil properties [29]. Therefore, exploring the key factor influencing the transformation of Cd in the soil–crop system can provide significant support for soil remediation and safety production of rice.

We hypothesize that silver mining can affect the Cd concentration in soil in the surrounding environment seriously and can cause serious health risks to local residents. To test this hypothesis, 16 paddy soil and corresponding rice grain samples were collected from the farmland along the Luxi River nearby a silver mine. The total, bioavailable, and fraction of Cd in soil, selected soil properties, and Cd concentration in rice were determined accordingly. Then, the bioaccumulation factor of Cd and the potential health risk of Cd to rice consumers were calculated. The results of the present study can provide more information for the impact of silver mining on the surrounding environment.

2. Materials and Methods

2.1. Study Area, Samples Collection, and Preparation

The study area was located in Longhushan Town, Yingtan City, Jiangxi Province, China (116°59′12.17″–117°0′52.05″ E, 28°07′59.79″–28°07′50.74″ N), which was influenced by subtropical monsoon climate (Figure 1). The average annual precipitation and temperature are 1750 mm and 17.9 °C, respectively. The tested soil was classified as Typic Hapli-Udic Ferrosols based on the Chinese Soil Taxonomy CRG-CST (2001). The main crop in this area is rice, and all these farmlands are flooded intermittently according to the water demand of rice. The main river in this town is the Luxi River, the upstream of the river flows through the Yinluling silver mine (put into operation in 1992), and caused certain pollution to the downstream farmland soil.
Int. J. Environ. Res. Public Health 2022, 19, 12362

The available potassium and CEC were extracted or exchanged by ammonium acetate for Cd in agricultural soil in China (0.3 mg/kg, GB 15618-2018). The concentration of Cd in rice grain was measured according to the description of our previous study [31]. The reference materials for soil (GBW07413) and rice (GBW10011) were used for quality control, the recoveries of Cd were within the acceptable range, and the detection limit for Cd was 0.0008 μg/L.

2.2. Chemical Analysis

The pH and OM content of these paddy soils was measured according to the national standard of China (NY/T 1121.2-2006 for pH value, NY/T 1121.6-2006 for OM content). The available phosphorus was extracted by NaHCO₃ (0.5 mol/L) and measured by molybdenum antimony anti-colorimetry. The total Cd concentration in these paddy soils was measured by inductively coupled plasma mass spectrometry (ICP-MS, Thermo Fisher X2, Waltham, MA, USA) after digestion with mixed strong acids (HNO₃, HF and HClO₄). The bioavailable Cd was extracted by DTPA-CaCl₂-TEA and CaCl₂ solution (0.01 M), and then determined by ICP-MS [30]. The fractions of Cd were analyzed by modified BCR sequential extraction according to our previous study [31]. The concentration of Cd in rice grain was measured according to the description of our previous report [32]. The reference materials for soil (GBW07413) and rice (GBW10011) were used for quality assurance and quality control, the recoveries of Cd were within the acceptable range, and the detection limit for Cd was 0.0008 μg/L.

2.3. Pollution Index and Bioaccumulation Factor

To evaluate the Cd pollution status in these paddy soils, the single-factor pollution index (\( P_i \)) of each soil sample was calculated based on the following equation:

\[
P_i = \frac{C_i}{C_o}
\]

where \( C_i \) is the Cd concentration in paddy soils (mg/kg), \( C_o \) is the risk screening value for Cd in agricultural soil in China (0.3 mg/kg, GB 15618-2018). The \( P_i \) was classified as

![Figure 1. Location of the Yingtan City, the study area and sampling sites.](image-url)
unpolluted \((P_i \leq 1)\), slightly polluted \((1 < P_i \leq 2)\), moderately polluted \((2 < P_i \leq 3)\), and highly polluted \((P_i > 3)\) [15].

The bioaccumulation factor (BF) was used to evaluate the transfer of Cd from soil to rice grain. The equation is as follows:

\[
BF = \frac{C_{\text{rice}}}{C_{\text{soil}}} 
\] (2)

where \(C_{\text{rice}}\) is the Cd concentration in rice grain (mg/kg), \(C_{\text{soil}}\) is the total concentration of Cd in the corresponding soil sample (mg/kg).

2.4. Potential Health Risk Assessment

To evaluate the noncarcinogenic risk of Cd to local residents via consumption of rice, the target hazard quotient (HQ) and hazard index (HI) were calculated according to the description of a previous report [28]. The equations are as follows:

\[
ADI = \frac{C_i \times IR \times EF \times ED}{AT \times BW} 
\] (3)

\[
HQ = \frac{ADI}{RFD} 
\] (4)

where \(ADI\) is the average daily intake of Cd via rice ingestion (mg/kg/day); \(C_i\) represents the Cd concentration in rice grain (mg/kg); \(IR\) represents the daily intake of rice grain, 0.328 and 0.198 kg/day were selected for adults and children, respectively; \(EF\) is the exposure frequency, 365 d/a for both adult and children; \(ED\) represents the exposure time, 72 years and 12 years were selected for adults and children, respectively; \(AT\) can be calculated by \(ED \times 365\) days; \(BW\) represents the body weight of local rice consumers, 61.75 and 32.75 kg were selected as the average \(BW\) for adults and children, respectively; \(RFD\) is the reference dose of Cd by the U.S. Environmental Protection Agency Integrated Risk Information System (0.001 mg/kg/day) [33]. A HQ higher than 1 was considered as unacceptable non-carcinogenic risk.

The carcinogenic risk (CR) of Cd to local rice consumers is determined by the following equation:

\[
TCR = ADI \times SF 
\] (5)

where \(SF\) is the cancer slope factor of Cd, 6.1 mg/kg/day was selected in the present study [34]. The CR value could be classified to be negligible risk \((CR \leq 10^{-6})\), acceptable/tolerable risk \((10^{-6} < CR \leq 10^{-4})\), and unacceptable risk \((CR > 10^{-4})\). The unacceptable risk means that the rice consumers suffered the risk of cancer diseases.

2.5. Statistical Analysis

The experiment data were processed and statistically analyzed by Microsoft Excel 2010 and SPSS 25.0 (IBM, Armonk, NY, USA). The correlation analysis and drawing of the figures were conducted with origin 8.5 (OriginLab, Northampton, MD, USA).

3. Results and Discussion

3.1. Selected Soil Properties and Concentration of Cd in Paddy Soil

The statistical description of selected soil properties and Cd concentration in these paddy soils are shown in Table 1. The general properties of these paddy soils ranged from 4.54 to 5.07 for pH, 33.79 to 67.31 g/kg for OM content, 179.43 to 1220.05 mg/kg for available K, 6.93 to 46.94 mg/kg for available P, and 2.66 to 3.67 cmol/kg for CEC, with the means of 4.81, 48.79 g/kg, 642.04 mg/kg, 19.86 mg/kg, and 3.21 cmol/kg, respectively. The soil in the research region is acid, and the mean OM content is relatively high, which belonged to ‘extremely high’ based on the second national soil census of China [35]. In addition, the CVs of pH, OM content, and CEC were lower than 17.32% and classified as low variability, but the CVs of available K (44.22%) and P (56.15%) were classified as
moderate and high variability, respectively [36]. These results indicate that the available K and available P may more easily be influenced by different agronomic measures.

Table 1. Total Cd concentration and selected properties of paddy soil (n = 16).

| Property          | Range            | Mean  | SD   | CV (%) |
|-------------------|------------------|-------|------|--------|
| pH                | 4.54–5.07        | 4.81  | 0.15 | 3.16%  |
| OM (g/kg)         | 33.79–67.31      | 48.79 | 8.45 | 17.32% |
| Available K (mg/kg) | 179.43–1220.05 | 642.04| 283.88 | 44.22% |
| Available P (mg/kg) | 6.93–46.94    | 19.86 | 11.15| 56.15% |
| CEC (cmol/kg)     | 2.66–3.67        | 3.21  | 0.34 | 10.47% |
| Total Cd (mg/kg)  | 0.21–0.48        | 0.36  | 0.07 | 19.09% |

SD: standard deviation, CV: coefficient of variation.

The total Cd concentration in these paddy soils ranged from 0.21 to 0.48 mg/kg, with the mean concentration of 0.36 mg/kg (Table 1), which is much higher than the background value (0.01 mg/kg). In addition, the Cd concentration in 13 out of 16 soil samples was higher than the risk screening values in agricultural soil in China (0.3 mg/kg, pH < 5.5, GB 15618-2018), indicating that Cd is a widespread pollutant in the study region. The CV of Cd concentration in these soils is 19.09% and classified into ‘low variability’ [36], which can be attributed to the limited research area (along the Luxi River in Longhushan Town).

The results of single-factor pollution assessment are shown in Figure 2. Just 3 out of 16 paddy soil samples were not polluted with Cd. Fortunately, all other soil samples were just slightly polluted with Cd (P < 1.59), and no soil samples were moderately or highly polluted. However, previous studies revealed that the accumulation capacity of Cd in rice grain is much higher than in other crops, and the concentration of Cd in rice grain may be higher than the national limitation even though the Cd concentration in soil is lower than the national limitation [37–39]. In addition, the soil pH is acid (4.54–5.07), which can enhance the migration of Cd in these paddy soils and may pose a risk to local residents even if most of these soils were just slightly polluted.

Figure 2. Pollution status of Cd in these paddy soil samples (n = 16).

3.2. Bioavailable and Fraction of Cd in Paddy Soil

The bioavailable Cd in these paddy soils is shown in Figure 3. The DTPA-extractable and CaCl₂-extractable Cd in these soils ranged from 0.16 to 0.22 mg/kg and 0.06 to 0.11 mg/kg, with the mean concentration of 0.19 and 0.09 mg/kg, respectively. The bioavailable Cd in soil was not limited in the national standard of China, and it is im-
possible to evaluate their pollution degree. However, the bioavailable Cd in these soils was much lower than in many previous studies [40,41]. In addition, the correlation between the selected soil properties and bioavailable Cd in these soils was nonsignificant ($p > 0.05$) except for the pH and CaCl$_2$-extractable Cd ($p < 0.05$) (Table 2), which is consistent with a previous report [38]. The activated ratio (bioavailable concentration/total concentration) of Cd based on the DTPA and CaCl$_2$ extraction ranged from 40.75% to 86.18% and 13.44% to 46.08%, respectively (Figure S1), indicating that Cd in these soils is highly active and may more likely to be accumulated in rice grain.

Figure 3. The bioavailable Cd in these paddy soils (mg/kg). (a): DTPA-extractable Cd; (b): CaCl$_2$-extractable Cd.

Table 2. Relationship between the bioavailable Cd and selected soil properties.

|               | Total Cd | pH  | OM  | Available K | Available P | CEC |
|---------------|----------|-----|-----|-------------|-------------|-----|
| DTPA-extractable Cd | 0.451    | 0.131 | -0.481 | -0.042 | 0.244 | -0.139 |
| CaCl$_2$-extractable Cd | -0.133   | -0.603 *  | -0.066    | 0.301    | -0.018  | 0.037 |

*Significance level of 0.05.

The fractions of Cd in these soils are shown in Figure 4. Obviously, the concentration of acid-soluble Cd in these soils is the highest and occupied 40.40% to 52.04% of total Cd in different soil samples, which further verified that Cd has high activity in these paddy soils. In addition, the residual, reducible and oxidizable Cd occupied 28.23% to 45.69%, 8.72% to 17.99% and 5.06% to 12.86% of total Cd, respectively. Correlation analysis indicated that the reducible and acid-soluble Cd was significantly positively correlated with OM ($p < 0.05$) and available K ($p < 0.05$), respectively, and available P was significantly positively correlated with acid-soluble ($p < 0.05$) and oxidizable Cd in the soil (Table 3). However, the correlation between the CEC and pH was not significant ($p > 0.05$). In fact, the fraction of Cd in different soils is similar, such as the calcareous soil in Henan Province, China [31] and the natural soil in Saudi Arabia [42], and the acid soil in the present study. These results imply that the pH of soil may just have limited influence on the Cd fraction in soils.

3.3. Cd Concentration in Rice Grain

The concentration of Cd in these rice grains ranged from 0.03 to 0.39 mg/kg, with the mean Cd concentration of 0.16 mg/kg (Figure 5), which was within the national limitation of China (0.2 mg/kg, GB 2762-2017). In fact, more than 81.25% of these paddy soils were slightly contaminated with Cd (Figure 2), but just 31.25% of the rice grain with Cd concentration exceeded the national standard of China. This result may indicate that the concentration of Cd in rice grain just partly depended on the Cd concentration in soil, and other environmental factors can also influence the Cd concentration in rice grain, which
is consistent with many previous reports [38,43]. Correlation analysis revealed that Cd concentration in rice grain was positively correlated with total, reducible and residual Cd, and negatively correlated with DTPA-extractable, CaCl₂-extractable, acid-soluble and oxidizable Cd, soil pH, OM content, available K, available P, and CEC. However, all these correlations are nonsignificant (p < 0.05, Table S2), which further verified that multiple factors regulated the content of Cd in rice grain.

### Table 3. Relationship between the Cd fractions and selected soil properties.

|                  | pH   | OM   | Available K | Available P | CEC  |
|------------------|------|------|-------------|-------------|------|
| Acid-soluble     | −0.036 | 0.465 | 0.640 **    | 0.566 *     | 0.328 |
| Reducible        | 0.194 | 0.514 * | 0.471     | 0.407       | 0.421 |
| Oxidizable       | 0.218 | 0.204 | 0.343       | 0.820 **    | −0.006 |
| Residual         | −0.283 | 0.550 * | 0.486     | 0.434       | 0.359 |

*Significance level of 0.05; ** Significance level of 0.05.

![Figure 4](image1.png)

**Figure 4.** Fraction of Cd in these paddy soils.

![Figure 5](image2.png)

**Figure 5.** Cd concentration in rice grain samples (mg/kg). The dashed line indicates the national standard limits of China (GB 2762-2017).
The BF of Cd in these rice grains varied greatly and ranged from 0.09 to 1.18, with the mean BF of 0.48 and CV of 64.17% (moderate variability) (Figure 6). Correlation analysis showed that the BF is negatively correlated with soil pH, OM content, available K, available P, and CEC, but none of the correlations is significant ($p < 0.05$) (Table S1). This result further verified that multiple factors can influence the accumulation of Cd in rice. A previous report indicated that soil pH (negatively correlated) and bioavailable Cd (positively correlated) are the main factors influencing the Cd accumulation in rice [37], which are inconsistent with our present study. In fact, it is very important to determine the key factors influencing the Cd accumulation in rice grains, which can provide important reference for the selection of soil remediation technology. Unfortunately, the correlation of Cd in rice grains and BF value with various indicators is nonsignificant, which may increase the difficulty for remediation of Cd-contaminated soil.

![Figure 6. The BF value of Cd in these rice grains.](image)

### 3.4. Potential Health Risk Assessment

The potential health risk via the consumption of this rice grain is shown in Table 4. The HQ for adults and children ranged from 0.18 to 2.05 and 0.20 to 2.33, with the means of 0.87 and 0.99, respectively. The HQ of a part of these rice samples (7 and 8 out of 16 for adults and children) are higher than 1, indicating that approximately 50% of the local residents suffered noncarcinogenic risk. Fortunately, the mean HQs for adults and children are all lower than the acceptable range. In fact, the influence of Pb/Zn, Cu, Au, As, and Sb mining and smelting on surrounding farmland and crops have been reported in several previous studies [44–46]. However, the impact of silver mining and smelting on toxic metals in agricultural soil has not been reported. The results of the present study indicate that more attention should be paid to the influence of silver mining on the surrounding environment and health of local residents.

| Table 4. Potential health risk of rice grain for local residents. |
|---------------------------------------------------------------|
| HQ   | Max       | Min       | Mean   | SD    |
| Adult | 2.05     | 0.18      | 0.87   | 0.55  |
| Children | 2.33 | 0.20      | 0.99   | 0.63  |
| CR     | $1.24 \times 10^{-2}$ | $1.09 \times 10^{-3}$ | $5.31 \times 10^{-3}$ | $3.36 \times 10^{-3}$ |

The maximum and minimum CR values were $1.24 \times 10^{-2}$ and $1.09 \times 10^{-3}$, respectively, with the mean value of $3.36 \times 10^{-3}$. The CR values of all rice grain samples are higher than the acceptable value recommended by EPA ($1.0 \times 10^{-4}$) [47]. This result indicates that local rice consumers suffered serious risk for carcinogenic diseases. In addition,
this study just considered the potential health risk of Cd in rice, while As, Pb, and other toxic metals (associated with Cd in ore) are not considered. The integrated potential health risk of local residents must be higher than that reported in the present study, and effective measures should be implemented by the local government to reduce the potential health risk of local residents, such as the adjustment of planting structure, remediation of soil, and relocation of residents.

4. Conclusions

In conclusion, silver mining results in slight Cd contamination in surrounding paddy soils. The bioavailable Cd has nonsignificant correlation with the total Cd in these soils. The activated ratio and fraction of acid-soluble Cd was relatively high, which resulted in Cd concentration in part of the rice grains higher than the national limitation of China. In addition, the BF of Cd in rice grains varied greatly and has nonsignificant correlation with various environmental indicators. The noncarcinogenic risk for most of the local rice consumers was within the acceptable range, but the carcinogenic risk was much higher than the acceptable level. Therefore, targeted remediation technology on Cd contamination in soil should also be developed in follow-up studies, which can reduce the potential health risk of silver mining on local residents.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph191912362/s1, Figure S1: Activated ratio of Cd in these paddy soils, a: based on the extraction of DTPA; b: based on the extraction of CaCl₂; Table S1: Relationship between the BF and selected soil properties; Table S2: Correlation between the Cd content in rice grain and various indicators.

Author Contributions: Conceptualization and writing—original draft preparation, L.L. and Z.J.; data curation, S.G.; investigation, L.L. and Z.J.; supervision, W.Z.; writing—review and editing, Y.W.; methodology, X.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Science and Technology Development Project of Henan Province China (212102310503; 212102310067); China Postdoctoral Science Foundation Funded Project (2020M682284); Open Funding Project of National Key Laboratory of Human Factors Engineering (SYFD062007, 614222211001); and the Natural Science Foundation of Henan Province China (202300410088).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Zhang, L.; Liu, Y.; Wang, Y.L.; Li, X.; Wang, Y. Investigation of phosphate removal mechanisms by a lanthanum hydroxide adsorbent using p-XRD, FTIR and XPS. *Appl. Surf. Sci.* 2022, 557, 112370. [CrossRef]
2. Han, L.; Chen, Y.; Chen, M.; Wu, Y.; Su, R.; Du, L.; Liu, Z. Mushroom residue modification enhances phytoremediation potential of *Paulownia fortunei* to lead-zinc slag. *Chemosphere* 2020, 253, 126774. [CrossRef] [PubMed]
3. Oubane, M.; Khadra, A.; Ezzariai, A.; Kouisi, L.; Hafidi, M. Heavy metal accumulation and genotoxic effect of long-term wastewater irrigated peri-urban agricultural soils in semiarid climate. *Sci. Total Environ.* 2021, 794, 148611. [CrossRef] [PubMed]
4. Markovic, J.; Jovic, M.; Smiciklas, I.; Slijivic-Ivanovic, M.; Onjia, A.; Trivunac, K.; Popovic, A. Cadmium retention and distribution in contaminated soil: Effects and interactions of soil properties, contamination level, aging time and in situ immobilization agents. *Ecotoxicol. Environ. Saf.* 2019, 174, 305–314. [CrossRef]
5. Chen, Z.; Pei, J.; Wei, Z.; Ruan, X.; Hua, Y.; Xu, W.; Zhang, C.; Liu, T.; Guo, Y. A novel maize biochar-based compound fertilizer for immobilizing cadmium and improving soil quality and maize growth. *Environ. Pollut.* 2021, 277, 116455. [CrossRef]
6. Zhou, Q.X.; Liu, Y.X.; Li, T.; Zhao, H.Z.; Alessi, D.S.; Liu, W.T.; Konhauser, K.O. Cadmium adsorption to clay-microbe aggregates: Implications for marine heavy metals cycling. *Geochim. Cosmochim. Acta* 2020, 290, 124–136. [CrossRef]
7. Ma, X.; Ren, Q.; Zhan, W.; Zheng, K.; Chen, R.; Wang, Y. Simultaneous stabilization of Pb, Cd, Cu, Zn and Ni in contaminated sediment using modified biochar. *J. Soil. Sediment.* 2022, 22, 392–402. [CrossRef]
8. Zheng, H.; Ren, Q.; Zheng, K.X.; Qin, Z.K.; Wang, Y.Y.; Wang, Y.G. Spatial distribution and risk assessment of metal(loid)s in marine sediments in the Arctic Ocean and Bering Sea. *Mar. Pollut. Bull.* 2022, 179, 113729. [CrossRef]

9. Vais, S.; Bansal, R.; Rana, N.; Kumawat, S.; Bhath, V.; Jadhav, P.; Kale, V.; Sathe, A.; Sonah, H.; Jugdeo Singh, R.; et al. Unexplored nutritive potential of tomato to combat global malnutrition. *Crit. Rev. Food. Sci.* 2022, 62, 1003–1034. [CrossRef]

10. Wang, F.; Tan, H.; Huang, L.; Cai, C.; Ding, Y.; Bao, H.; Chen, Z.; Zhu, C. Application of exogenous salicylic acid reduces Cd toxicity and Cd accumulation in rice. *Ecotoxicol. Environ. Saf.* 2020, 207, 111198. [CrossRef]

11. Liu, J.; Qian, M.; Cai, G.; Yang, J.; Zhu, Q. Uptake and translocation of Cd in different rice cultivars and the relation with Cd accumulation in rice grain. *J. Hazard. Mater.* 2007, 143, 443–447. [CrossRef] [PubMed]

12. Ge, L.; Cang, L.; Liu, H.; Zhou, D. Effects of warming on uptake and translocation of cadmium (Cd) and copper (Cu) in a contaminated soil-riese system under Free Air Temperature Increase (FATI). *Chemosphere* 2016, 155, 1–8. [CrossRef] [PubMed]

13. Yang, L.; Ren, Q.; Ge, S.; Jiao, Z.; Zhan, W.; Hou, R.; Ruan, X.; Pan, Y.; Wang, Y. Metal(loid)s spatial distribution, accumulation and potential health risk assessment in soil-wheat systems near a Pb/Zn smelter in Henan Province, central China. *Int. J. Environ. Res. Pub. Health.* 2022, 19, 2527. [CrossRef]

14. Wang, Y.Y.; Li, F.F.; Song, J.; Xiao, R.Y.; Luo, L.; Yang, Z.H.; Chai, L.Y. Stabilization of Cd-, Pb-, Cu- and Zn-contaminated calcareous agricultural soil using red mud: A field experiment. *Environ. Geochem. Health.* 2018, 40, 2143–2153. [CrossRef] [PubMed]

15. Yang, L.; Ren, Q.; Zheng, K.; Jiao, Z.; Ruan, X.; Wang, Y. Migration of heavy metals in the soil-grape system and potential health risk assessment. *Sci. Total Environ.* 2020, 806, 150646. [CrossRef] [PubMed]

16. Nawaz, H.; Anwar-ul-Haq, M.; Akhtar, J.; Arfan, M. Cadmium, chromium, nickel and nitrate accumulation in wheat (*Triticum aestivum*) L. using wastewater irrigation and health risks assessment. *Ecotoxicol. Environ. Saf.* 2021, 208, 111685. [CrossRef] [PubMed]

17. Guadie, A.; Yesigat, A.; Gatew, S.; Worku, A.; Liu, W.Z.; Ajibade, F.O.; Wang, A.J. Evaluating the health risks of heavy metals from vegetables grown on soil irrigated with untreated and treated wastewater in Arba Minch, Ethiopia. *Sci. Total Environ.* 2021, 761, 143302. [CrossRef]

18. Lei, M.; Tie, B.Q.; Song, Z.G.; Liao, B.H.; Lepo, J.E.; Huang, Y.Z. Heavy metal pollution and potential health risk assessment of white rice around mine areas in Hunan Province, China. *Food. Secur.* 2015, 7, 45–54. [CrossRef]

19. Kinimo, K.C.; Yao, K.M.; Marcotte, S.; Kouassi, N.L.B.; Trokourey, A. Trace metal(loid)s contamination in paddy rice (*Oryza sativa* L.) from wetlands near two gold mines in Cote d’Ivoire and health risk assessment. *Environ. Sci. Pollut. Res.* 2021, 28, 22779–22788. [CrossRef]

20. Wang, Y.Y.; Li, F.F.; Song, J.; Xiao, R.Y.; Luo, L.; Yang, Z.H.; Chai, L.Y. Stabilization of Cd-, Pb-, Cu- and Zn-contaminated calcareous agricultural soil using red mud: A field experiment. *Environ. Geochem. Health.* 2018, 40, 2143-2153. [CrossRef] [PubMed]

21. Lei, M.; Tie, B.Q.; Song, Z.G.; Liao, B.H.; Lepo, J.E.; Huang, Y.Z. Heavy metal pollution and potential health risk assessment of white rice around mine areas in Hunan Province, China. *Food. Secur.* 2015, 7, 45–54. [CrossRef]

22. Guadie, A.; Yesigat, A.; Gatew, S.; Worku, A.; Liu, W.Z.; Ajibade, F.O.; Wang, A.J. Evaluating the health risks of heavy metals from vegetables grown on soil irrigated with untreated and treated wastewater in Arba Minch, Ethiopia. *Sci. Total Environ.* 2021, 761, 143302. [CrossRef]

23. Lei, M.; Tie, B.Q.; Song, Z.G.; Liao, B.H.; Lepo, J.E.; Huang, Y.Z. Heavy metal pollution and potential health risk assessment of white rice around mine areas in Hunan Province, China. *Food. Secur.* 2015, 7, 45–54. [CrossRef]

24. Kinimo, K.C.; Yao, K.M.; Marcotte, S.; Kouassi, N.L.B.; Trokourey, A. Trace metal(loid)s contamination in paddy rice (*Oryza sativa* L.) from wetlands near two gold mines in Cote d’Ivoire and health risk assessment. *Environ. Sci. Pollut. Res.* 2021, 28, 22779–22788. [CrossRef]

25. Wang, L.; Liu, P.H.; Jiang, X.F.; Chen, P.J. Health risk assessment and spatial distribution characteristics of heavy metal pollution in rice samples from a surrounding hydrometallurgy plant area in No. 721 uranium mining, East China. *J. Geochem. Explor.* 2019, 207, 106360. [CrossRef]

26. Lu, Q.H.; Xu, Z.D.; Xu, X.H.; Liu, L.; Liang, L.C.; Chen, Z.; Dong, X.; Li, C.; Wang, Y.J.; Qiu, G.L. Cadmium contamination in a soil-riese system and the associated health risk: An addressing concern caused by barium mining. *Ecotoxicol. Environ. Saf.* 2019, 183, 109590. [CrossRef] [PubMed]

27. Hao, H.J.; Li, P.P.; Lv, Y.T.; Chen, W.M.; Ge, D.B. Probabilistic health risk assessment for residents exposed to potentially toxic elements near typical mining areas in China. *Environ. Sci. Pollut. Res.* 2022, 29, 58791–58809. [CrossRef] [PubMed]

28. Zheng, B.L.; Tian, Z.X.; Rao, Y.C.; Dong, G.J.; Yang, Y.L.; Huang, L.C.; Leng, Y.J.; Xu, J.; Sun, C.; Zhang, G.H.; et al. Rational design of high-yield and superior-quality rice. *Nat. Plants* 2017, 3, 17031. [CrossRef] [PubMed]

29. Iskra, S.; Rahman, M.; Islam, M.; Naidu, R. Arsenic accumulation in rice: Consequences of rice genotypes and management practices to reduce human health risk. *Environ. Int.* 2016, 96, 139–155. [CrossRef] [PubMed]

30. Liu, X.; Yu, T.; Yang, Z.F.; Hou, Q.Y.; Yang, Q.; Li, C.; Ji, W.B.; Li, B.; Duan, Y.R.; Zhang, Q.Z.; et al. Transfer mechanism and bioaccumulation risk of potentially toxic elements in soil-riese systems comparing different soil parent materials. *Ecotoxicol. Environ. Saf.* 2021, 216, 112214. [CrossRef]

31. Yu, H.Y.; Liu, C.P.; Zhu, J.S.; Li, F.B.; Deng, D.M.; Wang, Q.; Liu, C.S. Cadmium availability in rice paddy fields from a mining area: The effects of soil properties highlighting iron fractions and pH value. *Environ. Pollut.* 2016, 209, 38–45. [CrossRef]

32. Cameselle, C.; Gouveia, S. Phytoremediation of mixed contaminated soil enhanced with electric current. *J. Hazard. Mater.* 2019, 361, 95–102. [CrossRef]

33. Zhang, H.; Shao, J.G.; Zhang, S.H.; Zhang, X.; Chen, H.P. Effect of phosphorus-modified biochars on immobilization of Cu (II), Cd (II), and As (V) in paddy soil. *J. Hazard. Mater.* 2020, 390, 121349. [CrossRef]

34. Zhou, Y.L.; Sun, B. Nitrogen use efficiency of rice under Cadmium contamination: Influence of rice cultivar versus soil type. *Pedosphere* 2017, 27, 1092–1104. [CrossRef]

35. Zang, F.; Wang, S.L.; Nan, Z.R.; Ma, J.M.; Li, Y.P.; Zhang, Q.; Chen, Y.Z. Immobilization of Cu, Zn, Cd and Pb in mine drainage stream sediment using Chinese loess. *Chemosphere* 2017, 181, 83–91. [CrossRef]

36. Wang, Y.Y.; Zheng, K.X.; Zhan, W.H.; Huang, L.Y.; Liu, Y.D.; Li, T.; Yang, Z.H.; Liao, Q.; Chen, R.H.; Zhang, C.S.; et al. Highly effective stabilization of Cd and Cu in two different soils and improvement of soil properties by multiple-modified biochar. *Ecotoxicol. Environ. Saf.* 2021, 207, 111294. [CrossRef] [PubMed]
32. Wang, Y.Y.; Liu, Y.D.; Zhan, W.H.; Zheng, K.X.; Lian, M.M.; Zhang, C.S.; Ruan, X.L.; Li, T. Long-term stabilization of Cd in agricultural soil using mercapto-functionalized nano-silica (MPTS/nano-silica): A three-year field study. *Ecotoxicol. Environ. Saf.* 2020, 197, 110600. [CrossRef]

33. Mao, C.P.; Song, Y.X.; Chen, L.X.; Ji, J.F.; Li, J.Z.; Yuan, X.Y.; Yang, Z.F.; Ayoko, G.A.; Frost, R.L.; Theiss, F. Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. *Catena* 2019, 175, 339–348. [CrossRef]

34. Antoniadis, V.; Shaheen, S.M.; Levizou, E.; Shahid, M.; Niazi, N.K.; Vithanage, M.; Ok, Y.S.; Bolan, N.; Rinklebe, J. A critical prospective analysis of the potential toxicity of trace element regulation limits in soils worldwide: Are they protective concerning health risk assessment?—A review. *Environ. Int.* 2019, 127, 819–847. [CrossRef]

35. Zhang, G.; Bai, J.; Xi, M.; Zhao, Q.; Lu, Q.; Jia, J. Soil quality assessment of coastal wetlands in the Yellow River Delta of China based on the minimum data set. *Ecol. Indic.* 2016, 66, 458–466. [CrossRef]

36. Xiao, Q.; Zong, Y.T.; Lu, S.G. Assessment of heavy metal pollution and human health risk in urban soils of steel industrial city (Anshan), Liaoning, Northeast China. *Ecotoxicol. Environ. Saf.* 2015, 120, 377–385.

37. Yang, J.L.; Cang, L.; Wang, X.; Xu, H.T.; Zhou, D.M. Field survey study on the difference in Cd accumulation capacity of rice and wheat in rice-wheat rotation area. *J. Soil. Sediment.* 2020, 20, 2082–2092. [CrossRef]

38. Du, Y.; Hu, X.F.; Wu, X.H.; Shu, Y.; Jiang, Y.; Yan, X.J. Affects of mining activities on Cd pollution to the paddy soils and rice grain in Hunan province, Central South China. *Environ. Monit. Assess.* 2013, 185, 9843–9856. [CrossRef]

39. Ngo, T.; Chiang, K. The migration, transformation and control of trace metals during the gasification of rice straw. *Chemosphere* 2020, 260, 127540.

40. Xiao, L.; Guan, D.S.; Peart, M.R.; Chen, Y.J.; Li, Q.Q.; Dai, J. The influence of bioavailable heavy metals and microbial parameters of soil on the metal accumulation in rice grain. *Chemosphere* 2017, 185, 868–878. [CrossRef]

41. Rehman, M.Z.U.; Batool, Z.; Ayub, M.A.; Hussaini, K.M.; Murtaza, G.; Usman, M.; Naem, A.; Khalid, H.; Rizwan, M.; Ali, S. Effect of acidified biochar on bioaccumulation of cadmium (Cd) and rice growth in contaminated soil. *Environ. Technol. Inno.* 2020, 19, 101015. [CrossRef]

42. Ahmad, M.; Usman, A.R.A.; Al-Faraj, A.S.; Ahmad, M.; Sallam, A.; Al-Wabel, M.I. Phosphorus-loaded biochar changes soil heavy metals availability and uptake potential of maize (Zea mays L.) plants. *Chemosphere* 2018, 194, 327–339. [CrossRef]

43. Rafiq, M.T.; Aziz, R.; Yang, X.E.; Xiao, W.D.; Rafiq, M.K.; Ali, B.; Li, T.Q. Cadmium phytoavailability to rice (Oryza sativa L.) grown in representative Chinese soils. A model to improve soil environmental quality guidelines for food safety. *Ecotoxicol. Environ. Saf.* 2014, 103, 101–107. [CrossRef] [PubMed]

44. Shen, F.; Liao, R.; Ali, A.; Mahar, A.; Guo, D.; Li, R.; Sun, X.; Awasthi, M.K.; Wang, Q.; Zhang, Z. Spatial distribution and risk assessment of heavy metals in soil near a Pb/Zn smelter in Feng County, China. *Ecotoxicol. Environ. Saf.* 2017, 139, 254–262. [CrossRef] [PubMed]

45. Guo, W.; Zhang, Z.; Wang, H.; Qin, H.; Fu, Z. Exposure characteristics of antimony and coexisting arsenic from multi-path exposure in typical antimony mine area. *J. Environ. Manag.* 2021, 289, 112493. [CrossRef]

46. Fashola, M.O.; Ngole-Jeme, V.M.; Babalola, O.O. Physicochemical properties, heavy metals, and metal-tolerant bacteria profiles of abandoned gold mine tailings in Krugersdorp, South Africa. *Can. J. Soil. Sci.* 2020, 100, 217–233. [CrossRef]

47. Aendo, P.; Thongyuan, S.; Songserm, T.; Tulayakul, P. Carcinogenic and non-carcinogenic risk assessment of heavy metals contamination in duck eggs and meat as a warning scenario in Thailand. *Sci. Total Environ.* 2019, 689, 215–222. [CrossRef]