Characteristics of Heavy Metal Migration In Farmland

Xuefang Tang

Chengdu University of Technology

Yong Wu (✉ ywu@cdut.edu.cn)

State key laboratory for Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology

Libi Han

Chengdu University of Technology

Zhen Lan

Chengdu University of Technology

Xingping Rong

Chengdu University of Technology

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Abstract

Compared with water and air pollution, soil pollution is highly concealed, has poor self-purification ability, and has high risks associated with accumulation. Characteristics of heavy metal migration directly affect the quality of the environment, and comparative studies utilizing column leaching and natural leaching experiments have rarely been performed. In this study, we used farmland soil samples from Xiba Town in the Wutongqiao district to determine the differences in leaching characteristics between column leaching and natural leaching tests. The results indicate the following. (1) The release of heavy metals in soil is divided into two stages: the first stage is a rapid release period, while the leaching solution has an extremely low heavy metal concentrations during the second stage. The cumulative amount released during the second stage exhibits regular fluctuations, while the heavy metal release rate is consistent with the heavy metal adsorption properties of the soil. (2) The release and accumulation of heavy metals in the soil are influenced by many factors that may interact with each other, which leads to low correlations between the cumulative heavy metals released in the column leaching and natural leaching tests. Simulating natural heavy metal migration trends using the column leaching test is effective to some extent, but there are significant differences between the accumulation sites and accumulated amounts. This study provides a theoretical basis for improving the remediation of soil contaminated by heavy metals.

Introduction

In recent years, soil pollution by heavy metals in China has become a critical issue. Heavy metal pollution poses threats to the local environment, food safety, and human health. Compared with water and air pollution, soil pollution by heavy metals is invisible, has poor self-purification ability, and has high associated risks due to accumulation. Heavy metal pollution also increases the risk of cancer in children and residents living near heavily polluted areas (Fan et al. 2013; Li et al. 2014). Pollution risk assessments, migration simulations, source analyses, and remediation of heavy metal pollutants in farmland soils have been conducted to address widespread concerns (Gu et al. 2014; Xu et al. 2017; Zhao et al. 2018; Qiao et al. 2019). Approximately 2×10^7 hm² of cultivated land is affected by heavy metal pollution in China, while as much as 1.2×10^7 t of grain is contaminated annually, with an economic loss of 2×10^{10} yuan (Wu et al. 2010). In the past 20 years, research on heavy metal pollution in the soil has indicated that heavy metal pollution levels differ depending on the area, such as farmland, cities, suburbs, and rural regions. In China, 83.9% of the provinces and 22.5% of the prefecture-level cities are affected by heavy metal pollution (Song et al. 2013). The pollution of regional farmland soil by heavy metals is an important issue, which is especially prominent in regions such as southwest China (Yunnan, Guizhou), central China (Hunan, Jiangxi), the Yangtze River Delta, and the Pearl River Delta (Zhao and Luo 2015). In North China, the main source of heavy metal pollution sources in farmland soil is atmospheric subsidence, while the sources in South China are mainly agriculture and livestock production (Peng et al. 2019). Imperfect remediation technology and a shortage of long-term risk control mechanisms for restoration measures are major challenges for effectively preventing and controlling heavy metal

pollution in farmland soil (Chen et al. 2018). In May 2016, the State Council issued *the Soil Pollution Prevention Action Plan* (referred to as the "Ten Articles"), which reflect the importance of preventing and controlling heavy metal pollution in soil. It also strengthened the current regional treatment and remediation practices (Luo and Teng 2018).

Heavy metal migration is part of the solute transport system in soil. Two common methods used to analyze heavy metal migration in soil are column leaching and natural leaching tests (Yang 2017; Zhang et al. 2018). In recent years, column leaching (filtration) has become a commonly applied method for analyzing heavy metal migration and accumulation. Current research includes analyses of the migration rate and morphological compositions of heavy metals, as well as exploring the migration characteristics of different heavy metals under different conditions (Shangguan et al. 2015; Li and Wu 2017). Under natural conditions, the vertical distribution and migration of soil elements in a profile are affected by the chemical and physical properties of the soil (Ye et al. 2012; Ye et al. 2016). In general, the heavy metal contents in soil colloids are much higher than what is observed in coarse soils. The distribution of heavy metals in soils is affected by the composition of organic matter, iron/aluminum oxides, and clay minerals in the soil (Liu et al. 2018). Organic matter in the soil, particularly humic and fulvic acid, has a high adsorption capacity for many pollutants, including heavy metals. This can reduce the heavy metal absorption by plants, fix heavy metals in the soil, and reduce the migration of heavy metals into the groundwater (Jolanta 2018). The pH affects the presence of various elements in the soil and determines their migration, thereby affecting the migration, enrichment, and transformation of heavy metals (Chen et al. 2016; Yang et al. 2017). Currently, there is little research on heavy metal leaching characteristics under natural conditions, and available research methods are limited. Compared to column leaching, which is performed in the laboratory, natural leaching tests have conditions that are similar to the natural environment and can be performed at larger scales (Shangguan et al. 2015). Therefore, this study used column leaching and natural leaching to compare the heavy metal leaching and release characteristics at different soil depths under simulated rainfall conditions. We also clarified the accumulation and migration mechanisms of heavy metals at different depth, and provide a theoretical basis for improving and remediating the soil after heavy metal pollution.

Geological And Hydrogeological Setting

The study area is located in the southwestern Wutongqiao District, Leshan City, Sichuan Province (azimuth 253°) and is adjacent to the Xiba-Shilin Highway (Wutongqiao District) and the Leshan-Yibin Expressway, which pass through the western part of the study area. The study area is within the subtropical humid climate zone, with an average annual precipitation of 1264.2 mm and an annual average evaporation of 1076.1 mm. The study area is in a river valley and flat dam zone: the overall terrain is high in the north and low in the south. The highest point is the Hongyue coal mine, located in the northern part of the study area, with an altitude of ~ 368 m. The lowest point is the Muxi River, located in the southern part of the study area, with an elevation of ~ 343.2 m. The left bank of the Muxi River contains Grade I terraces, Grade II terraces, and hills. The Grade I terrace adjacent to the Muxi River are limited due to the vicinity of the riverbed. As a result of long-term erosion, extensive damage has occurred

and the remaining land is difficult to preserve. Hence, it is distributed in strips. The northern part of the study area is hilly, with a surface morphology that has low absolute heights and relatively small fluctuations. The exposed strata in the study area mainly comprise Quaternary alluvial deposits, Middle and Lower Jurassic strata and artesian wells, and the sedimentary Triassic Xujiahe Formation (Figs. 1, 2, and 3).

The main aquifer in the study area is the Xujiahe Formation (T_3x_j) feldspar quartz sandstone. The sandstone has good water content, resulting from the fracturing of clastic rocks. The single hole water inflow is $50\text{--}100\text{ t d}^{-1}$. The pH of the shallow groundwater in the study area ranges from 6.41 to 7.53, with a mean of 7.17. It is generally weakly alkaline and neutral. The total dissolved solids (TDS) ranges from 302 to 881 mg L^{-1} , and the EC ranges from 439 to 1357 $\mu\text{S cm}^{-1}$. The average Ca^{2+} , Mg^{2+} , Na^+ , and K^+ contents in the groundwater account for 65.8%, 17.5%, 13.5%, and 3.2% of the total cation content, respectively. The average HCO_3^- , SO_4^{2-} , Cl^- , and NO_3^- contents account for 50.7%, 23.7%, 5.3%, and 20.3% of the total anion content, respectively. The shallow groundwater cations in the study area are dominated by Ca^{2+} , with the mean values ranked as follows: $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$. The anions are dominated by HCO_3^- , with the mean values ranked as follows: $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$. The shallow groundwater samples were divided into two types: Ca- HCO_3 and Ca- SO_4 , which accounted for 66.7% and 33.3% of the total samples, respectively. Large amounts of alkaline earth metal ions and weak acid ions were also observed in the shallow groundwater.

Materials And Methods

Sampling

Representative samples were collected from the perennially unsaturated zone and the seasonally saturated zone in May 2018 using GPS positioning, and labeled TK01 (seasonally saturated zone) and TK02 (perennially unsaturated zone). The soil samples were divided into yellow cinnamon soil and paddy soil according to their textures. The soil samples were collected at depths of 0–80 cm, and a mixed sample of 1 kg were collected at 0–20 cm, 20–40 cm, 40–50 cm, 60–80 cm respectively. The soil samples were air-dried and stored in wooden boxes in a storage room with a constant humidity (65–70%) and temperature (20°C). In order to study the migration characteristics of heavy metals in the seasonally saturated zone and the perennially unsaturated zone under natural leaching conditions, the soil was systematically sampled near the TK01 and TK02 sampling sites in December 2019. These samples were labeled TK01-1 and TK02-1 (Fig. 3). Mixed soil samples (1 kg) were collected at 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm. All of the soil samples were gently milled using an agate mortar after being air-dried and sieved to 200 mesh fractions.

Heavy metal analyses

Samples were carefully crushed using an agate mortar and passed through a 200 mesh sieve. Approximately 0.100 g of the dried and ground fine powder underwent total digestion using 1.0 ml HNO_3

(Chengdu Kelong Chemical Reagent Co., Ltd. Analytically pure) and 1.0 ml HF(Chengdu Kelong Chemical Reagent Co., Ltd. Analytically pure) in high pressure digestion tank for 48 h at 180°C. Then, 1 ml of HNO₃ was added to the residue on the hot plate at 120°C to remove any remaining HF. The residue was solubilized using 3 ml HNO₃ and kept in an oven for 8 h at 150°C. The heavy metal (including Cd, Cu, and Zn) contents were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, PerkinElmer Elan DRC-e, American) after the extraction solution was diluted to 50 ml with deionized water. National standard reference materials GSD-9 and GSD-12 were used as control samples for data quality assurance. The recoveries of the standard reference materials ranged from 92–106%. Three replicates of each sample solution were analyzed. All the reagents used were of super quality and of analytical grade. All solutions were prepared using ultrapure water. All acid proof plastic and Teflon apparatus were soaked in HNO₃ (10%) for at least 24 h and rinsed repeatedly with ultrapure water. Analytical blanks and standard reference material were run in the same way as the samples, and heavy metal concentrations were determined using standard solutions prepared in the same acid matrix.

Physicochemical properties

Samples were collected using a cutting ring ($V=100\text{ cm}^3$) for laboratory analyses of soil bulk density (SBD) and moisture content. In the laboratory, the soil samples were dried in an oven, and an electronic balance was used to weigh the dry mass of each soil sample and cutting ring, after which the cutting ring was weighed separately. The SBD was calculated using Eq. (1):

$$\rho_B = \frac{M_1 - M_2}{V} \quad (1)$$

where ρ_B represents the SBD (g cm^{-3}), M_1 represents the mass of the dry soil and the cutting ring (g), M_2 represents the mass of the cutting ring (g), and V represents the volume of the cutting ring (cm^3).

Soil gravimetric moisture contents were measured by oven-drying the soil samples at 105°C for 24 h. The pH (1:2.5 soil:water, m:v) of the soil samples was analyzed using an electrode pH meter(PHS-3C, Leici, Shanghai). Soil organic matter was measured using dichromate oxidation (Du and Gao, 2006). The particle density was measured using the pycnometer method (Wei et al., 2015), The clay mineral types and their relative contents (%) were determined using X-ray diffraction after pre-treatment (Li, 1997). The cation exchange capacity (CEC) was analyzed using the ammonium exchange method (Bao, 2018).

The soil physicochemical properties were also analyzed (Table 1). The yellow cinnamon soil and paddy soil were composed primarily of silt, which accounted for 59.7% of their compositions. The sand content of the paddy soil was higher than that of the yellow cinnamon soil. The pH ranged from 5.73 to 6.84, placing the samples in the weakly acidic soil category. The amount of organic matter in the paddy soil was approximately twice that of the yellow cinnamon soil.

Table 1 Physical and chemical characteristics of the surface soil in the study area

Soil type	pH	Organic matter (%)	Cation exchange capacity (cmol kg ⁻¹)	Bulk density (g cm ⁻¹)	Soil particle composition (%)		
					Clay <0.005mm	Silt 0.005-0.075mm	Sand 0.075-2mm
Yellow cinnamon soil (TK01, seasonally saturated zone)	5.73	2.77	17.52	1.27	26.4	59.7	14.9
Sandy soil in paddy field (TK02, perennial unsaturated zone)	6.84	4.53	22.35	1.36	24.2	42.8	33.0

The mineral compositions and contents were identified using the X-ray diffraction patterns (Jade 6.5). The phase compositions of the yellow cinnamon soil and the paddy soil were similar (Table 2), but had some differences in the phase contents that were mainly determined by the sample properties.

Table 2
Phase compositions of the major mineral component of the surface soil in the study area

Yellow cinnamon soil (TK01)		Sandy soil in paddy field (TK02)	
Mineral phase	Content (%)	Mineral phase	Content (%)
SiO ₂	45.2	SiO ₂	58.3
(K,Na)(Al,Mg,Fe) ₂ (Si _{3.1} Al _{0.9})O ₁₀ (OH) ₂	15.3	(K,Na)(Al,Mg,Fe) ₂ (Si _{3.1} Al _{0.9})O ₁₀ (OH) ₂	14.2
Ca _{0.3} (Cr,Mg) ₂ (Si,Al) ₄ O ₁₀ (OH) ₂ 4H ₂ O	18.7	Na ₆ Al ₆ Si ₁₀ O ₃₂	4.7
Na ₆ Al ₆ Si ₁₀ O ₃₂	5.8	Ca _{0.1} Fe ₂ (Si,Al) ₄ O ₁₀ (OH) ₂ 4H ₂ O	12.3
KMg ₃ AlSi ₃ O ₁₀ OHF	4.9	KMg ₃ AlSi ₃ O ₁₀ OHF	11.5

Leaching experiments

Leaching apparatus

In order to perform the column leaching test, a 25 m long glass tube with an inner diameter of 5 cm (upper opening) and a uniform mesh outlet hole at the bottom was connected to a 200 mL sampling bottle. A 1000 mL medical saline bottle was used as a high-level liquid storage device. The infusion tube was modified and applied as the flow rate control device. The flow was controlled using the switch on the upper half of the medical catheter to ensure even simulated rainfall (Fig. 4).

Soil Column

The profile samples were collected from the perennially unsaturated zone and seasonally saturated zone in May 2019. Stratified filling occurred according to the bulk density of the dry soil in the field. According to the soil collected from the different depths (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm), the soil column was packed using four 5 cm thick layers. The amount of soil required for each filling was calculated according to the following formula: [soil total mass = soil column volume × soil bulk density × (1 + initial mass water content)]. A plastic compactor was used to compact the soil, scratched the surface of the compacted soil, and filling continued until the specified height was reached, and until the bulk density of the experimental soil column was similar to that of the natural soil. This ensured a uniform distribution of soil particles. Quartz sand (1 cm thick) treated by acid washing and rinsed with deionized water was used as the filter layer in the upper and lower layers of the soil column. A filter screen was placed on the filter layer to prevent blockage by large particles or excess silt or sand. The parameters of the soil column before leaching are listed in Table 3.

Table 3
Parameters of the soil column

Type	Soil column size. Diameter× High (cm)	The depth of sampling point (cm)	Heavy metal content (mg kg ⁻¹)			Bulk density (g cm ⁻¹)	Quality of packed soils (g)
			Cu	Zn	Cd		
TK01	5×20	0–20	29.98	135.47	0.26	1.27	124.2
	5×20	20–40	31.51	114.51	0.19	1.22	119.8
	5×20	40–60	30.05	116.94	0.16	1.34	131.6
	5×20	60–80	31.35	119.70	0.14	1.34	131.1
TK02	5×20	0–20	28.74	114.92	0.16	0.12	121.4
	5×20	20–40	27.31	113.51	0.14	0.11	145.8
	5×20	40–60	27.06	102.76	0.15	0.12	136.7
	5×20	60–80	28.05	140.46	0.27	0.21	140.1

Leachate setting

pH is an important factor that governs the adsorption and migration of heavy metals in the soil. The migration, accumulation, and leaching loss of heavy metals at different soil depths were simulated under rainfall conditions. The leaching filtrate was similar to local rain, with a pH of 6.5 and a rainwater composition of: Ca²⁺ = 5.42 mg L⁻¹, Mg²⁺ = 1.08 mg L⁻¹, K⁺+Na⁺ = 5.54 mg L⁻¹, SO₄²⁻ = 10.50 mg L⁻¹, and Cl⁻ = 3.19 mg L⁻¹. The rainfall infiltration coefficient is 0.20 in the study area, and the average

rainfall was 992 mm from May to December of 2019. The leaching amount was 400 mL (leaching amount = rainfall × cross-section area of soil column × infiltration coefficient), which is equivalent to the average rainfall over 6 months.

Leaching test

At the beginning of the test, a small amount of deionized water was added to the soil column to wet the soil. The leachate was injected into the top of soil column after reaching the saturated field water holding capacity. The capacity of the rainfall device was 1200 mL. The diversion hose was connected to the lower part, and the flow control switch was attached to the middle of the hose to adjust the leaching speed. Leachate was collected every 24h to analyze the heavy metal concentrations. The column leaching test was stopped when the leached amount reached 400 mL.

Cumulative amount released

$$Q = \frac{\sum_i^n C_i \times V}{m} \quad (2)$$

Here, Q is the cumulative heavy metals released in the soil under simulated rainfall conditions ($\mu\text{g kg}^{-1}$), C_i is the heavy metal concentration ($\mu\text{g L}^{-1}$), V is the volume of the leachate (0.04 L), and m is the mass of the test soil (kg).

The heavy metal release rate in the soil column is expressed as follows:

$$K = \frac{Q}{S} \times 100\% \quad (3)$$

where K is the heavy metal release rate in the soil column, Q is the cumulative amount of heavy metals released in the soil under simulated rainfall conditions (mg kg^{-1}), and S is the initial heavy metal content in the soil column (mg kg^{-1}).

Soil Heavy Metal Contents after Leaching

The soil was air dried after leaching. Samples were collected from the 0–5 cm, 5–10 cm, 10–15 cm, and 15–20 cm layers. All of the soil samples were gently milled using an agate mortar and sieved to 200 mesh fractions, after which the total Cu, Cd, and Zn contents of the soil were determined.

Date analysis

One-way ANOVA (Duncan test) was performed to identify the differences of metal concentrations. A significance level of 0.05 was used for all statistical analysis. This common statistical analysis was performed in SPSS 22.0 for Windows.. All values are the mean of three parallel samples.

Results And Discussion

Leaching Characteristics under Simulated Rainfall Conditions

Release during Leaching

The release of heavy metals under simulated rainfall conditions is shown in Fig. 5. The amounts of Cu and Cd released in the soil column were higher. The change in release was also more dramatic during the first three days, which is consistent with the steps of the rapid release process. The release of Cu and Cd slowly decreased after three days. The release of Zn in the seasonally saturated zone was high during the first two days as part of the rapid release process, while the entire process had regular changes indicated by “transverse waves.” The amount of Zn released decreased linearly in the perennial unsaturated zone during the first four days. Towards the end of the experiment, the release of Zn changed regularly in “transverse waves.” The Cu, Cd, and Zn released during the first stage may have become ionic, which is more easily exchanged. In this form, the heavy metals were easily released once the solution was leached out. The release rate is affected by the soil column height, soil bulk density, and testing method (Xie et al. 1991). The pH of the rainwater was weakly acidic, allowing H^+ to enter the soil solution. This increased the adsorption competitiveness of H^+ on the heavy metals; thus, the heavy metals adsorbed in the soil were more easily released. Following this initial release, the second release stage (slow release) occurred.

The leaching amount used in the experiment was equivalent to the rainfall infiltration in the study area over a six month period. Combined with the national groundwater standard (GB/T 14848 – 2017), after leaching with 400 mL, the concentrations of Cd, Zn, and Cu in the leachate were lower than those of the national groundwater quality II standard. This indicates that the soil had a specific purification capacity and the groundwater will not be polluted during short-term rainfall.

2.1.2 Cumulative Amounts Released and Release Rates

The cumulative release rates of the three heavy metals after leaching are shown in Table 4. The release rates varied depending on the heavy metal. The annual heavy metal release rates in the perennial unsaturated zone and the seasonally saturated zone was in the order of $Cd > Cu > Zn$. The heavy metal release rates were consistent with the heavy metal adsorption capacity of the soil. A stronger adsorption capacity typically resulted in a lower release rate.

Table 4
Release percentages and rates

Type	Cu		Zn		Cd	
	Q ($\mu g\ kg^{-1}$)	K (%)	Q ($\mu g\ kg^{-1}$)	K (%)	Q ($\mu g\ kg^{-1}$)	K (%)
TK01	3.66	0.012	23.09	0.019	0.29	0.123
TK02	2.86	0.011	19.09	0.022	0.21	0.070

2.1.3 Heavy Metal Contents of the Soil Layers after Leaching

The heavy metal contents of each layer before and after leaching of the soil column are shown in Fig. 6. The cumulative heavy metal accumulation is not obvious under the allowable error for Cu and Zn in TK01 and TK02. Cd was released at the surface of the 0–5 cm layer in the TK01 soil column and accumulated in the 10–15 cm layer with the continuous entry of the leaching filtrate. In the TK02 soil column, Cd was released in the 5–10 cm layer and accumulated in the 10–15 cm layer, but the Cd content decreased in the 15–20 cm layer.

Release under Natural Leaching Conditions

Distribution Characteristics

The vertical heavy metal distributions in TK01-1 and TK02-1 are shown in Fig. 7. The heavy metal contents changed with increasing depth in both profiles. The Cd content of the perennially unsaturated zone was significantly higher than those in the seasonally saturated zone (0–20 cm). Below 20 cm, the opposite was true. The Cu content of the seasonally saturated zone (0–20 cm) was slightly higher than that of the perennially unsaturated zone, while it was slightly lower below 20 cm. The Zn content of the seasonally saturated zone was higher than that of the perennially unsaturated (0–60 cm), while it was lower in the 60–80 cm layer. In general, the Cd contents had the same trend in both profiles, while the changes in the Cu and Zn contents were also similar. The Cd content was $0.13\text{--}0.32\text{ mg kg}^{-1}$, the Cu content was $25.03\text{--}33.80\text{ mg kg}^{-1}$, and the Zn content was $81.23\text{--}139.49\text{ mg kg}^{-1}$. The differences in heavy metal contents may be related to geochemical processes related to the compounds in the atmosphere, water, and sediment (Wan et al. 2013).

Vertical migration before and after leaching

The heavy metal distributions in the soil after six months of natural leaching and column leaching (see *Leaching experiments*) are shown in Fig. 8. The Cd content was released in the 0–20 cm after the leaching test in TK01, and heavy metals accumulated at 40 cm. The heavy metals leached naturally accumulated in the 20–40 cm and 60–80 cm layers, and were released in the 0–20 cm layer. Cd migration occurred at the soil surface in both the column and natural leaching, but there were significant differences in the accumulation locations. Heavy metals accumulated only at 20–40 cm in the TK02 column leaching test. The heavy metals migrated to the surface layer in natural leaching and accumulated at 40–60 cm and 60–80 cm. The Cu content in TK01 exhibited significant migration and accumulation (within error) in column leaching, while heavy metal migration occurred in the 0–20 cm and 20–40 cm layers under natural leaching. Cu entered the groundwater under natural leaching; therefore, there was no accumulation in the bottom layer. In the TK02 column leaching test, Cu migrated in the 0–20 cm layer and accumulated in the 20–40 cm layer. However, Cu accumulated in different layers below 20 cm in the natural leaching test. The Zn content in TK01 exhibited no obvious migration or accumulation of Zn in the column leaching test, while Zn migrated in the 0–20 cm layer in the natural

leaching test and accumulated in the 40–60 cm and 60–80 cm layers, with a higher accumulation in the 60–80 cm layer. In TK02, the Zn migration and accumulation depths were similar in both the column leaching and natural leaching tests, and the Zn accumulation in the 20–40 cm layer was higher under natural leaching than in the column leaching test.

In general, simulating the naturally leached migration of heavy metals using the column leaching test was effective to some extent, but there were significant differences in the accumulation locations and amounts accumulated. The release and accumulation of heavy metals in soil is a highly complicated process and is affected by many factors. Further, there may be interactions between factors; therefore, the correlation between the column leaching and natural leaching may be weak (Zheng et al. 2011).

Table 5
Heavy metal contents under different leaching conditions

	Depth (cm)	TK01, Soil (Raw soil, April)	Leaching experiment (TK01)	TK01-1, Soil (Natural leaching, December)	TK02, Soil (Raw soil, April)	Leaching experiment (TK02)	TK02-2, Soil (Natural leaching, December)
Cu	0–20	33.785	31.657	26.144	29.413	28.227	25.031
	20–40	32.883	33.594	25.031	20.366	24.522	27.806
	40–60	30.819	26.534	30.801	27.449	26.959	37.969
	60–80	28.475	25.867	28.283	24.260	25.867	33.798
Zn	0–20	113.295	100.335	81.231	116.783	112.809	93.121
	20–40	94.241	102.542	93.121	91.371	97.410	110.165
	40–60	90.686	85.575	99.616	123.235	137.553	139.494
	60–80	100.426	91.889	127.575	87.924	91.889	86.582
Cd	0–20	0.3330	0.2136	0.1616	0.2853	0.2410	0.2531
	20–40	0.2552	0.2486	0.3151	0.1270	0.1286	0.1286
	40–60	0.2190	0.3538	0.1765	0.1325	0.1538	0.2088
	60–80	0.2456	0.2716	0.2654	0.0988	0.1160	0.1317

Conclusions

The release of Cu, Cd, and Zn under simulated rainfall conditions can be divided into two stages. The first stage is a rapid release period, wherein the heavy metal concentrations in the leachate were higher and the release rate decreased over time, also called the rapid release process. During the second stage, the heavy metal concentrations in the leachate were extremely low and the cumulative release amount fluctuated regularly. The stronger the soil's ability to adsorb heavy metals, the lower the heavy metal release rates. The heavy metal release rates were affected by the properties of the soil and leachate, as well as the testing method.

The leaching tests under simulated rainfall conditions indicate that the heavy metal concentrations in the leachates of the two soil profiles during the initial leaching stage were higher, which poses a threat to the environment and groundwater. The risk gradually decreased with leaching, indicating that the soil has a certain purification capacity and will not cause groundwater pollution during short-term rainfall.

The column leaching test can simulate the heavy metal migration that occurs in natural leaching to a certain extent. However, there were significant differences between the accumulation locations and accumulated amounts. The release and accumulation of heavy metals in soil is a complex process that is affected by many factors, which can also interact with each other. We found that the cumulative release correlation between the column leaching and natural leaching in this study was extremely low. Heavy metal adsorption increased with increases in pH, which may be related to large numbers of active adsorption sites on the soil surfaces.

Declarations

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Figures

Figure 1

Cross section of the study area

Figure 2
 Map of the distribution of pollution sources in the study area

Figure 3

The topography and geomorphology map

Figure 4

Experimental setup for the leaching tests

Figure 5

Heavy metals released in the soil under simulated rainfall conditions

Figure 6

Heavy metal contents in the soil columns before and after leaching

Figure 7

Vertical distributions of Cd, Cu, and Zn contents in the soil

Figure 8

Heavy metal contents under different leaching conditions