Analysis of Heavy Metal Leaching Characteristics and Kinetic Mechanisms in Soils under Leaching Conditions

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Abstract: To investigate the release behavior of heavy metals from soils around acid mine-metallurgy polluted areas under rainfall leaching conditions, this study systematically examined the cumulative release characteristics and kinetic mechanisms of three typical heavy metals Zn, Pb, and As through leaching experiments. Different pH values (4, 5, 7, 8) and rainfall intensities (20, 30, 50 mm/h) were set to analyze the release patterns of heavy metals. Kinetic release models were constructed using the first-order kinetic equation, modified Elovich equation, double-constant rate equation, and parabolic diffusion equation. Results showed that the pH of the leachate gradually increased from an initially low value with prolonged leaching time and eventually stabilized around 7.5, while electrical conductivity exhibited a rapid decline followed by a steady trend. The release of Zn, Pb, and As all demonstrated significant pH dependence. Under acidic conditions (pH = 4), the release amounts of all three heavy metals increased substantially, with Zn being the most sensitive to pH variation. The release of As also showed a noticeable increase under alkaline conditions (pH = 8). With increasing rainfall intensity, both the cumulative release amount and the initial release rate of heavy metals increased, with Zn and As being particularly influenced by rainfall intensity. Kinetic fitting results indicated that, except for the first-order kinetic equation, the modified Elovich equation, double-constant rate equation, and parabolic diffusion equation could all adequately characterize the release process, with the parabolic diffusion equation providing the best fit ($R^2 > 0.99$). This study clarifies the release characteristics and kinetic patterns of typical heavy metals in contaminated soils from mining areas under rainfall leaching conditions, offering important theoretical insights and parameter support for risk assessment and control of heavy metal migration in acid mine-metallurgy polluted areas.

Keywords: Column Leaching; Heavy Metals; Rainfall; Release Behavior; Kinetics

1. Introduction

Soil serves as a critical environmental medium for maintaining ecosystem stability and ensuring food security, with its quality status directly impacting the sustainable development of human society. With the acceleration of industrialization, particularly the large-scale exploitation of mineral resources, soil heavy metal pollution has become increasingly prominent.

China's National Soil Pollution Status Survey Bulletin (2014) indicates that industrial and mining activities constitute a significant anthropogenic source of soil heavy metal contamination [1]. Specifically, tailings, waste residues, and acidic wastewater generated during ore mining, beneficiation, and smelting processes in mining and metallurgical industries accumulate heavy metals such as Pb, Zn, and As. These pollutants can leach into surrounding soil environments through processes like leaching and runoff, posing potential risks to ecological security and human health [2-3].

Current research by scholars worldwide has extensively investigated the migration and transformation patterns of heavy metals in contaminated soils from multiple perspectives. Soil column leaching tests have gained widespread adoption due to their ability to effectively simulate rainfall infiltration processes. Significant progress has been made in this methodology regarding leaching media, target elements, experimental conditions, and kinetic equations [4–7]. Researchers including Wang Zhaoyi et al. [8], Hu Peng et al. [9], and Feng

Liujun et al. [10] conducted systematic leaching experiments on heavy metals, fluorine, and rare earth elements, analyzing their vertical migration characteristics. These studies consistently demonstrate that pollutant transport capacity decreases with increasing soil depth. Separately, Xing Ying et al. [11], Wang Xinyi et al. [12], and Zarabi M. et al. [13] further investigated leaching behaviors of single pollutants such as dissolved organic carbon (DOC), dissolved organic matter, and nitrogen, along with their influencing factors. These studies provide crucial theoretical foundations for understanding fundamental pollutant migration processes. However, since mining-induced soil contamination typically involves coexisting multiple heavy metals, single-element studies often fail to capture potential synergistic, competitive, or antagonistic interactions between elements, resulting in significant uncertainties regarding environmental behavior under real-world pollution scenarios. Through in-depth research, WANG et al. [14], Wang Yuan et al. [15], Qiong Wang et al. [16], and Yong Wang et al. [17] have analyzed the migration and cumulative release characteristics of various heavy metals from different pollution media. Regarding influencing factors, existing studies indicate that acidic mine wastewater and weathering processes significantly enhance heavy metal release [18], while acid rain conditions markedly promote metal migration with stronger effects observed at lower pH levels [19]. Rapid heavy metal release predominantly occurs in surface soil layers [20-21]. However, most experimental designs focus on pH values or chemical environmental factors, lacking systematic consideration of physical infiltration conditions such as rainfall intensity and duration, which limits comprehensive modeling of pollutant dynamics under real rainfall scenarios. Additionally, while Gu Changhong et al. [22] and Ai Tao et al. [23] identified distinct stage-specific patterns in heavy metal leaching processes, their kinetic models often failed to integrate compound pollution mechanisms and dynamic rainfall conditions, leaving their applicability requiring further validation.

Therefore, this study focuses on the soil surrounding mining areas in Xisai Mountain region, Huangshi City, Hubei Province. Through leaching experiments simulating variable conditions including rainfall pH and intensity, we investigate the leaching characteristics of heavy metals under different leaching scenarios and their cumulative release patterns. By applying four kinetic models to fit heavy metal accumulation-leaching curves, we explore desorption mechanisms and summarize migration patterns of various heavy metals in soil. The derived kinetic migration equations provide scientific foundations for pollution control strategies.

2. Materials and Methods

2.1 Test Materials

The soil samples used in this study were collected near a typical acidic mining and metallurgical pollution area in Xisai Mountain, Huangshi City, Hubei Province, with geographical coordinates of east longitude 116°8′ and north latitude 30°11′. The soil sampling depth was 0–100 cm. After natural air-drying, impurities such as gravel and plant roots were removed, the samples were crushed and sieved through a 10-mesh (2 mm) sieve for use in soil column leaching tests. Measurements showed that the tested soil had a bulk density of 1.2 g/cm³, natural moisture content of 15%, and initial pH of 5.08, indicating it was a slightly acidic soil.

2.2 Test Equipment and Instruments

This experiment utilized a self-developed leaching apparatus comprising three key components: a simulated rainfall leaching system, a detachable soil column, and a leachate collection system. The rainfall simulation module consists of a target solution reservoir and a peristaltic pump. The detachable soil column features a base, a cylindrical core, a perforated plate, and a filtrate collection funnel. The collection system includes multiple graduated liquid containers with lids connected to flow channels. The leaching column measures 25 cm in height with an 8 cm inner diameter, featuring uniformly spaced solid sampling ports at 5 cm intervals along both sides. The lower end of the column serves as the liquid sampling port, as illustrated in Figure 1.

2.3 Trial Protocol

(1) Leachate pH values. Considering the severe acid rain problem in Huangshi City, simulated rainfall with pH levels of 4, 5, 7, and 8 was designed. The preparation of simulated rainfall primarily focused on pH and key chemical

components. The average pH of rainfall in Huangshi urban area is 4.50, with high acid rain frequency, and the city's acid rain is typically sulfuric acid-type (the equivalent concentration ratio of SO_4^{2-} to NO_3^- usually exceeds 2:1). The experiment used a mixture of H_2SO_4 (high-purity) and HNO_3 (high-purity) diluted with deionized water to prepare simulated rainfall at pH 4 and 5. Deionized water was employed as simulated rainfall at pH 7, while an appropriate amount of NaOH (high-purity) was added to deionized water to prepare simulated rainfall at pH 8.

(2) Rainfall Intensity. Based on Hubei Province's annual average precipitation data, the annual rainfall is calculated at approximately 1,200 mm. Using an 8 cm diameter test soil column as the standard, the annual rainfall volume is converted to simulate leaching volume in the soil column leaching experiment. After rounding calculations, the designed leaching water volume is determined to be 12 L. Literature indicates that heavy rainfall events in Hubei Province primarily occur at three intensity levels:>20 mm/h,>30 mm/h, and>50 mm/h, with>50 mm/h rainfall being particularly active during midsummer. Considering Hubei's rainfall intensity characteristics, this experiment adopts rounded values of 20 mm/h, 30 mm/h, and 50 mm/h as rainfall intensity thresholds. According to the operational parameters of the BL100C peristaltic pump, automatic conversion yields flow rates of 1.68 mL/min, 2.51 mL/min, and 4.19 mL/min respectively.

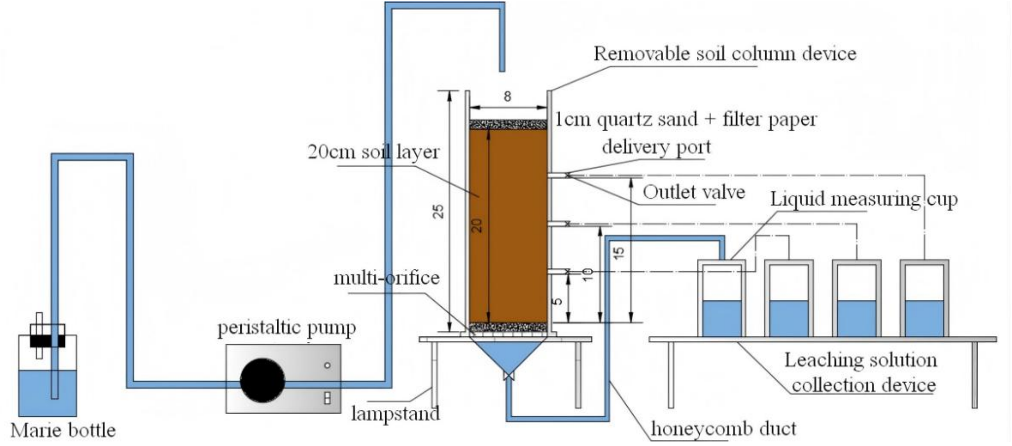

Figure 1. Schematic of the Experimental Setup

2.4 Test Methods

To minimize interference from preferential flow along pipe walls during leaching experiments, the inner walls of the leaching column were uniformly coated with petroleum jelly. The soil column was constructed using a bottom-up filling method: a 1 cm-thick quartz sand backfill layer was placed at both the column base and top, followed by medium-speed filter paper. Test soils were layered and compacted using the layered compaction method. During filling, strict control was maintained to ensure uniform thickness across all soil layers and prevent localized accumulation of coarse particles. After each compaction layer, surface roughening treatment was applied to enhance interlayer cohesion and ensure structural integrity and density uniformity throughout the column.

Prior to initiating the dynamic leaching experiment, soil samples were naturally air-dried and sieved through a 10-mesh sieve before being loaded into the leaching column at a height of approximately 20 cm, corresponding to a soil mass of about 1.2 kg, to simulate intermittent leaching under natural acid precipitation conditions. During the experiment, a multi-channel peristaltic pump was used to regulate leachate flow rate, with daily leaching lasting 12 hours and continuous operation maintained for 25 days. Both experimental procedures and sample pretreatment methods strictly adhered to the technical specifications outlined in the "Chemical Soil Column Leaching Test" (GB/T41667—2022). Leachate pH values were measured using an acidity meter (PHS-3E). After thermal digestion with four acids, soil samples were analyzed for zinc (Zn), lead (Pb), and arsenic (As) content using an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7800).

To ensure the accuracy and reliability of experimental data, systematic quality control measures were implemented: no less than 5% standard samples were added to each batch to evaluate analytical accuracy, with national first-grade reference materials used for precision control; two blank samples were prepared for each test batch, achieving a 100% result compliance rate; samples with abnormal test results underwent repeated measurements, and all retest results met quality requirements.

3. Results and Discussion

3.1 Variation Pattern of pH Value in Soil Leachate

Soil is a complex system with heterogeneous internal structure, typically exhibiting strong acid-base buffering capacity. The dynamic changes in leachate pH values can reflect, to some extent, the buffering characteristics of this system against external pH disturbances. The pH variation results under different leaching conditions are illustrated in the figure.

Figure 2 demonstrates that during the initial phase of the leaching experiment, the pH value of the leachate remains relatively low. However, as the leaching duration extends, the pH value gradually increases, with a significant rise observed by the fifth day. In the mid-stage of leaching, despite continued experimental conditions, the pH values of four leachates with different initial pH levels show only minor increases after passing through the soil column, exhibiting relatively gentle fluctuations. By the 20th day of leaching, the pH values stabilize around 7.5. This trend is primarily attributed to exchange reactions between exchangeable basic ions in the soil and externally introduced ions. During the initial stage, exchangeable basic ions undergo neutralization reactions with external hydrogen ions, consuming partial H^+ ions and causing rapid pH elevation. Subsequently, as exchangeable basic ions become depleted during the mid-stage, pH increase rates decelerate. However, the presence of buffering components in the soil helps regulate external pH changes, maintaining relatively stable leachate pH levels. Additionally, exogenous anions coordinate with hydroxyl groups on soil particle surfaces, causing partial hydroxyl groups to dissociate and bind with hydrogen ions, which also contributes to pH elevation. Notably, the final effluent pH values of leachates with four different initial pH levels showed no significant differences after leaching treatment, further confirming the strong acid-base buffering capacity of this soil type.

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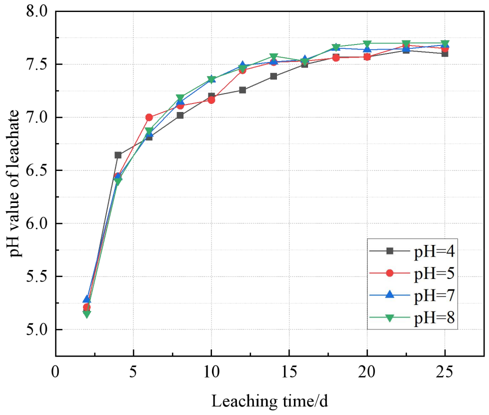


Figure 2. Patterns of pH Changes in Soil Leachate

3.2 Variation Pattern of Soil Leachate Conductivity

Electrical conductivity (EC) serves as a critical physicochemical parameter for characterizing total ion concentration variations in solutions, providing comprehensive insights into the migration and release patterns of soluble alkaline ions and heavy metal ions in soils. Under the experimental conditions, the initial EC values of leachate across all treatment groups ranged from 1554 to 1704 μS/cm, indicating that the tested mining area soils contain elevated baseline levels of soluble ions with significant migration potential under rainfall exposure.

Under varying rainfall conditions, the temporal variation trends of leachate conductivity demonstrated consistent patterns, all exhibiting a gradual decline as the leaching process progressed. Experimental data analysis revealed that the conductivity evolution throughout the leaching process could be divided into two distinct phases, with their characteristic changes illustrated in Figure 3.

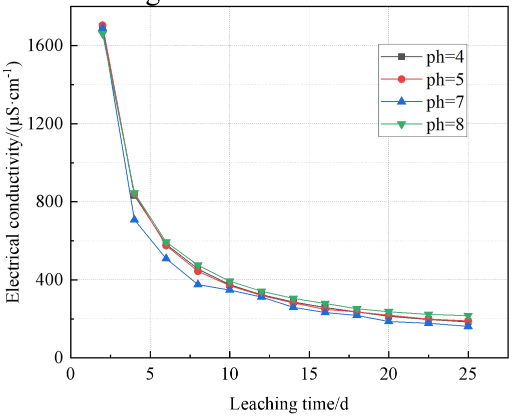
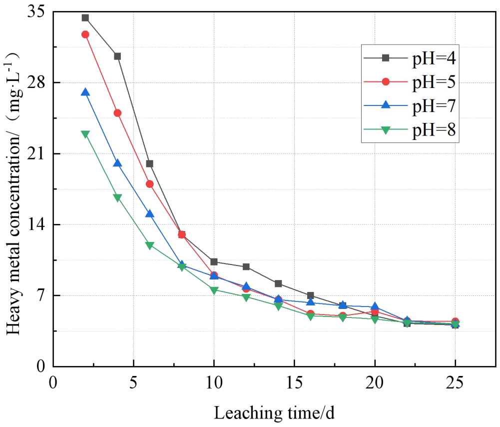


Figure 3. Patterns of Electrical Conductivity Changes in Soil Leachate

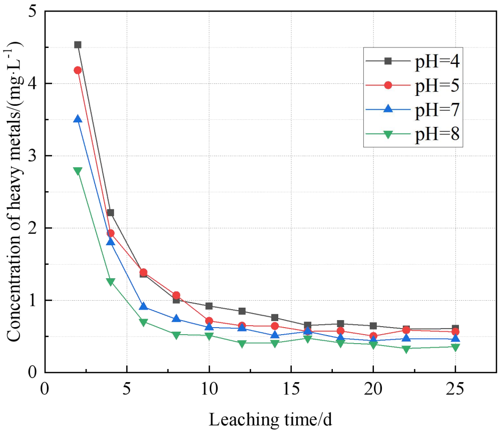
The first phase occurs during the initial 5 days after leaching begins, characterized by a rapid decline in leachate conductivity. This phenomenon primarily results from the rapid dissolution and desorption of salt base ions, soluble oxide mineral particles, and readily soluble salts adsorbed in soil surface layers and pores under water infiltration. These substances are subsequently transported out of the system through leachate flow, driven by intense ion exchange and dissolution reactions. Although leachate conductivity initially remains high, its subsequent decrease becomes markedly more pronounced. The second phase begins 5 days after leaching initiation, during which conductivity gradually stabilizes at lower levels with significantly reduced fluctuations. By this stage, most easily leachable soluble components have been released, reducing the pool of ions available for rapid exchange. Subsequent ion release is primarily governed by slow solid-liquid diffusion mechanisms within soil particles. Consequently, the conductivity decline rate slows substantially, eventually reaching a quasi-equilibrium state.

3.3 Heavy Metal Release Characteristics of Soil Leachate

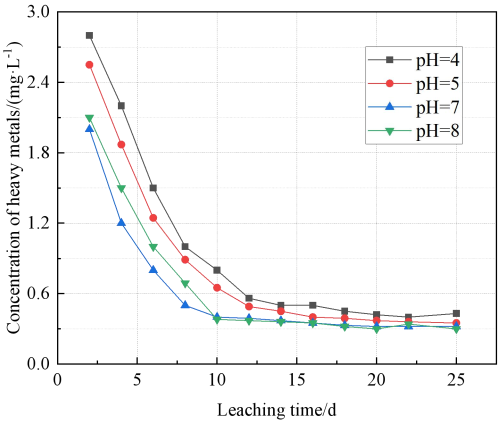
This study conducted simulated leaching experiments on mine soil using leachate with four different pH values and three varying rainfall intensities, and measured the release concentrations of Zn, Pb, and As in the leachate. The concentrations of each heavy metal element in the leachate after leaching from soil are shown in Figures 4 and 5.



(a) Zn



(b) Pb



(c) As

Figure 4. Patterns of Heavy Metal Variations in Soil Leachate at Different pH Values

3.3.1 Release patterns of heavy metal concentrations under different pH conditions

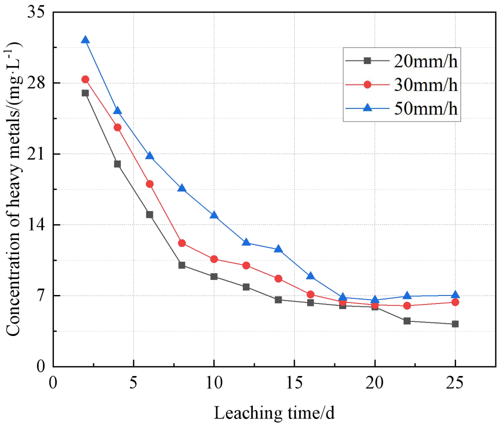
Under varying pH conditions, the leaching concentrations of Pb, Zn, and As generally decreased with extended leaching time, exhibiting a two-phase characteristic of "rapid initial release followed by stabilization." During the initial leaching stage, significantly higher initial release concentrations of heavy metals were observed at lower pH levels, indicating that acidic environments enhance ion exchange and mineral dissolution processes, thereby markedly promoting the migration of heavy metals from soil into the liquid phase.

As the leaching process progresses, the concentration decline rates of various heavy metals gradually slow down and stabilize, indicating that readily available components had been substantially leached during earlier stages. Subsequent release is primarily governed by particle internal diffusion and slow desorption processes. Different elements exhibit distinct pH responses: The release concentrations of Zn and Pb increase with decreasing pH, while As demonstrates relatively enhanced release intensity under alkaline conditions. This phenomenon may be attributed to charge inversion on iron-aluminum oxide surfaces, which weakens arsenate ion adsorption.

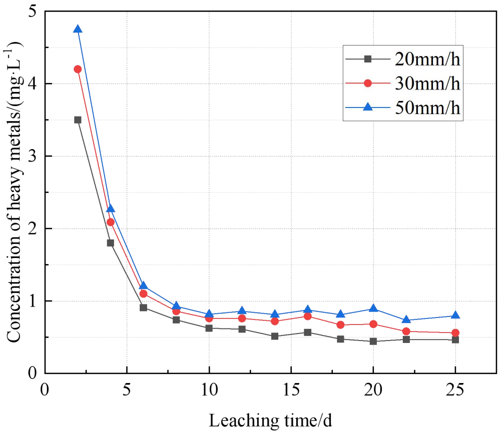
Overall, pH serves as a critical chemical factor in regulating the release intensity and migration rate of heavy metals. Acidic conditions significantly enhance the release of zinc (Zn) and lead (Pb), while arsenic (As) migration behavior is simultaneously governed by both acid-base environment and surface adsorption characteristics.

3.3.2 Release patterns of heavy metal concentrations under different rainfall intensity conditions

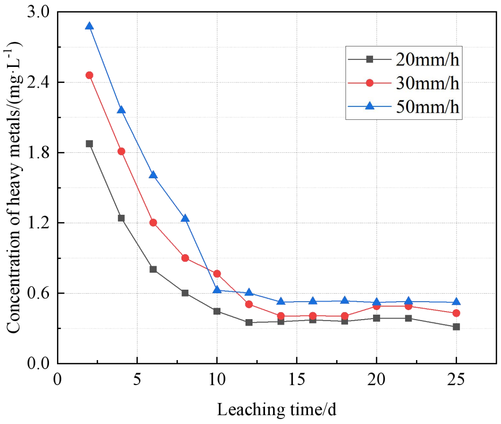
This study conducted soil column leaching experiments with varying rainfall intensities (20,30, and 50 mm/h) to analyze the leaching dynamics of Pb, Zn, and As. Results demonstrated that the leaching concentrations of all three heavy metals decreased with extended leaching time, exhibiting a two-phase characteristic of "rapid initial release followed by gradual stabilization." Rainfall intensity significantly influenced release behavior: under 50 mm/h conditions, although initial leaching concentrations were higher, the decay rate accelerated, indicating that heavy rainfall enhances short-term migration flux and increases instantaneous release risks.



(a) Zn



(b) Pb



(c) As

Figure 5. Patterns of Heavy Metal Variations in Soil Leachate at Different Rainfall Intensity Levels

From the perspective of elemental differences, arsenic leaching is governed by its anionic adsorption characteristics. Under high rainfall intensity, rapid initial release may be associated with the scouring and desorption of arsenic bound to iron-aluminum oxides. Subsequent rapid concentration decline indicates swift depletion of readily available arsenic, with later stages primarily controlled by diffusion processes. Zinc, as a highly mobile cation, exhibits the highest leaching concentration and greatest sensitivity to rainfall intensity, with heavy rainfall significantly promoting the desorption and migration of exchangeable and soluble Zn^{2+}. In contrast, lead demonstrates the lowest leaching concentration with minimal variation across rainfall intensities, reflecting its soil behavior being dominated by specific adsorption, complexation, and precipitation processes that limit migration capacity.

In conclusion, rainfall intensity is a critical factor in regulating heavy metal migration. Under heavy rainfall conditions, short-term water environment risks posed by As and Zn are particularly prominent, while Pb exhibits strong retention characteristics.

3.4 Accumulative Release Characteristics of Heavy Metals in Soil under Leaching Conditions

The formula for cumulative heavy metal release from leachate is:

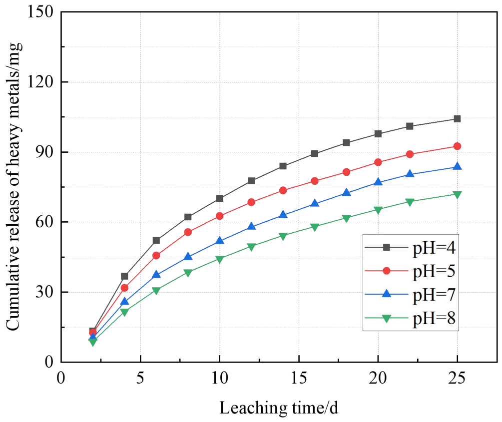
$$q=\sum_{i=1}^{n} C_i \tag{1}$$

In the formula, q represents the cumulative release of heavy metals from soil during simulated rainfall, measured in mg; Ci denotes the heavy metal concentration in the leachate collected on day i, expressed in mg/L; and vi indicates the volume of leachate collected on day i, measured in L.

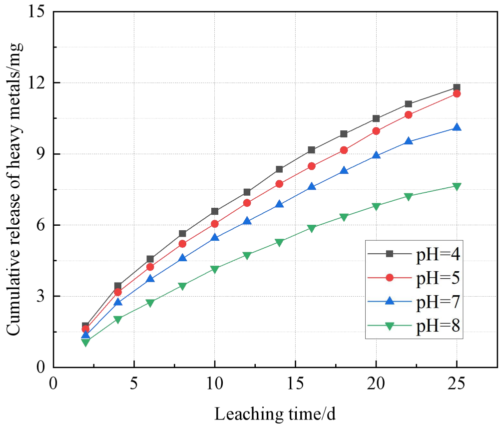
3.4.1 Cumulative release patterns of various heavy metals under different rainfall pH conditions

Soil acidification is a significant environmental factor that induces heavy metal activation and migration. Therefore, regulating soil acidity and rainfall pH conditions to mitigate heavy metal release represents a potential approach for reducing environmental risks.

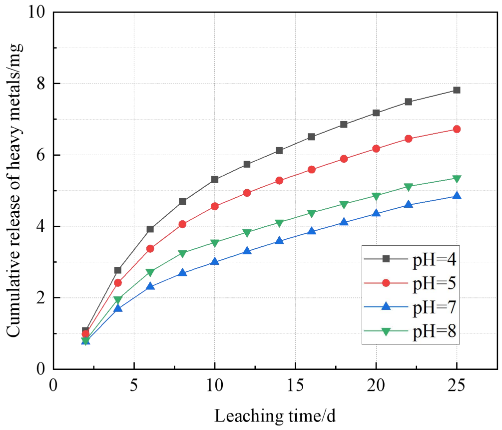
Figure 6 illustrates the cumulative release characteristics of Zn, Pb, and As with increasing leaching rates under varying rainfall pH conditions. Overall, the cumulative release amounts of these three heavy metals consistently rise during the leaching process, exhibiting a two-phase pattern of rapid initial growth followed by significantly slower increases in later stages. The impact of pH conditions on cumulative release is pronounced, demonstrating a clear correlation where lower pH values correlate with higher release amounts, with more pronounced variations observed under low pH conditions.



(a) Zn



(b) Pb



(c) As

Figure 6. Cumulative Amounts of Heavy Metals Released under Varying pH Values

Regarding element variations, both zinc (Zn) and lead (Pb) exhibited increased cumulative release rates with decreasing pH, demonstrating typical acid-promoted release characteristics. In contrast, arsenic (As) showed higher release rates at pH 8 compared to pH 7, indicating a certain alkaline enhancement trend. This reflects that its release behavior is influenced not only by acid dissolution effects but also by surface charge characteristics and anionic repulsion effects. During the initial leaching stage, lower pH conditions significantly increased the release rates and cumulative release amounts of the three heavy metals. As leaching progressed, the Pb release rate gradually stabilized, exhibiting a relatively slow yet sustained cumulative growth pattern.

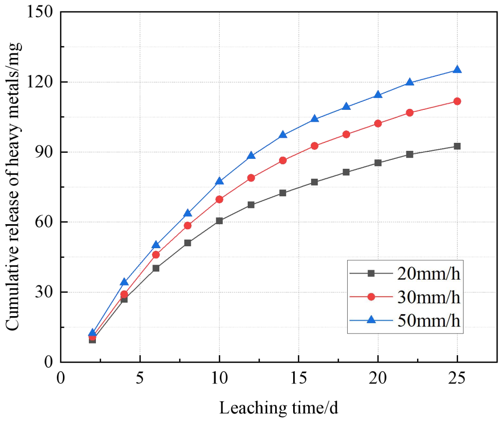
From a mechanistic perspective, the cumulative release process can be divided into two stages. The first stage, known as the pre-leaching phase, is characterized by high metal release rates and rapid accumulation, primarily driven by the rapid desorption and dissolution of adsorbed metals and active metal species on particle surfaces. The second stage, termed the slow-release phase, occurs as surface metals gradually deplete. During this phase, the release process shifts to be dominated by metal diffusion from internal micropores and the gradual transformation of weakly bound metal species, resulting in a significant reduction in cumulative growth rates.

3.4.2 Cumulative release patterns of various heavy metals under different rainfall intensity conditions

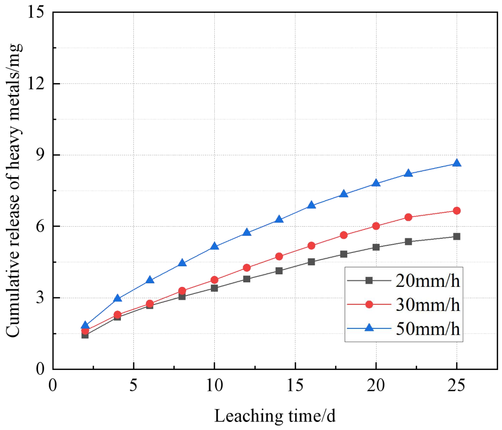
The study area exhibits significant seasonal climate variations with notable fluctuations in rainfall volume and intensity across different seasons. To simulate real-world hydrological conditions, this study employed varying rainfall intensities to analyze the cumulative release characteristics of zinc (Zn), lead (Pb), and arsenic (As) during leaching processes (Figure 7). Results demonstrate that under all rainfall intensity conditions, the cumulative release amounts of these three heavy metals consistently increased with prolonged leaching duration, exhibiting a distinct phase-specific pattern of "rapid initial growth followed by gradual stabilization in later stages."

Rainfall intensity significantly impacts cumulative release rates. As flow velocity increases, the cumulative release of heavy metals rises markedly, with significant differences observed across different flow velocity treatments. Under identical pH conditions, higher flow velocities enhance leachate infiltration and mass transfer processes within soil pores, increasing contact frequency at the solid-liquid interface and strengthening ion exchange interactions, thereby promoting the migration of heavy metals from solid to liquid phases.

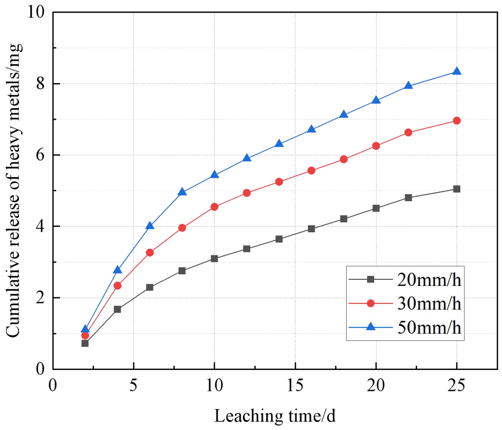
From a mechanistic perspective, the soil solid-liquid system remains in a dynamic equilibrium state. Higher rainfall flow rates increase infiltration flux, accelerate solution renewal rates, and reduce transient heavy metal concentrations in the liquid phase, which helps maintain concentration gradients and continuously drive heavy metal migration into the liquid phase. Consequently, under heavy rainfall conditions, the cumulative release of heavy metals exhibits significantly elevated levels.



(a) Zn



(b) Pb



(c) As

Figure 7. Cumulative Amounts of Heavy Metals Released under Different Rainfall Intensities

3.5 Accumulation and Release Model of Heavy Metals in Soil under Leaching Conditions

Further research on metal release kinetics processes in soil under leaching conditions aims to provide theoretical foundations for assessing potential heavy metal risks and release patterns in soil and water environments. Common mathematical models for metal release include first-order kinetic equations, modified Elovich equations, two-constant-rate equations, and parabolic diffusion equations. Simulation results of heavy metal release from soil using these four kinetic models are presented in Tables 1 and 2.

first-order kinetic equation:

$$Iny=a+bx \tag{2}$$

Modified Elovich equation:

$$y=a+bIny \tag{3}$$

Double constant-rate equation:

$$Iny=a+\mathrm{bInx} \tag{4}$$

Parabolic diffusion equation:

$$y=a+bx^{0.5} \tag{5}$$

The fitting results demonstrate that the parabolic diffusion equation provides optimal fit for the cumulative release processes of Zn, Pb, and As under various rainfall conditions, indicating that this model effectively characterizes the release kinetics of these three heavy metals during leaching. The parabolic diffusion equation is commonly used to describe solute diffusion behavior within porous media particles, suggesting that heavy metal migration and release are primarily governed by internal particle diffusion rather than surface reactions or instantaneous dissolution processes.

Table 1. Summary of Kinetic Model Parameters for Heavy Metal Leaching under Different Initial pH Conditions

element	optimal kinetic equation	pH price	a	b	R2
Zn	Parabolic diffusion equation	4	-3.2678	1.0492	0.98449
		5	-2.2569	0.9152	0.98527
		7	-6.89582	0.85988	0.9978
		8	-6.39477	0.74165	0.99806
Pb	Parabolic diffusion equation	4	-1.27679	0.12006	0.99702
		5	0.99702	0.99702	0.99233
		7	-1.38047	0.10459	0.99463
		8	-1.06151	0.07998	0.99428
As	Parabolic diffusion equation	4	-0.11527	0.07613	0.98512
		5	-0.05018	0.06498	0.98611
		7	-0.12837	0.04629	0.99729
		8	0.00906	0.05069	0.98696

Table 2. Summary of Kinetic Model Parameters for Heavy Metal Leaching under Different Rainfall Intensities

element	optimal kinetic equation	rainfall intensity	a	b	R2
Zn	Parabolic diffusion equation	20mm/h	-8.97804	0.9801	0.9899
		30mm/h	-14.34736	1.21011	0.99338
		50mm/h	-16.28447	1.35582	0.994
Pb	Parabolic diffusion equation	20mm/h	0.19841	0.04972	0.99619
		30mm/h	-0.17571	0.0623	0.98605
		50mm/h	-0.24329	0.08184	0.99719
As	Parabolic diffusion equation	20mm/h	-0.25565	0.04911	0.99713
		30mm/h	-0.26037	0.06793	0.9921
		50mm/h	-0.28166	0.08136	0.9891

4. Conclusion

(1) The soil in the Huangshi mining area exhibited strong acid-base buffering capacity during leaching. The pH of the leachate gradually increased with prolonged leaching time and eventually stabilized at approximately 7.5. The conductivity of the leachate generally showed a characteristic of first rapid decline followed by stabilization, indicating that soluble basic ions and heavy metals primarily underwent rapid migration and release during the initial stage of leaching.

(2) Rainfall pH significantly influences heavy metal release. Under acidic conditions (pH=4), the release amounts of Zn, Pb, and As increased markedly, with Zn demonstrating the highest sensitivity to pH variations. In alkaline conditions (pH=8), As release showed a notable rise. The initial heavy metal release exhibited an overall upward trend with increasing rainfall intensity, particularly pronounced for Zn and As under high-intensity rainfall conditions (50mm/h). In contrast, Pb exhibited relatively less sensitivity to rainfall intensity, indicating strong soil retention characteristics.

(3) Under simulated acid rain leaching conditions, the cumulative release amounts of various heavy metals in soil exhibited a characteristic pattern of rapid initial increase followed by gradual stabilization over time. Kinetic model fitting results demonstrated that first-order kinetic equations had limited capacity to describe cumulative release processes. In contrast, modified Elovich equations, double-constant-rate equations (Freundlich correction), and parabolic diffusion equations all effectively characterized heavy metal leaching release processes, with the parabolic diffusion

equation showing optimal fitting performance (R^2>0.99). Comprehensive analysis indicates that heavy metal release behavior in simulated leaching systems is governed by multiple physicochemical processes, exhibiting complex kinetic characteristics.

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