

Article

Enhancing Electrokinetic Removal of Cu and Pb from Loess by Alleviating the Focusing Effect: Influence of Electric Field Strength, EKG Electrodes, and Catholyte pH

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Abstract

Severe Cu and Pb enrichment in loess areas of northwestern China, mainly associated with mining and smelting activities, has increased the demand for efficient soil decontamination. Electrokinetic (EK) remediation is a promising in situ technology because it can drive ionic contaminants through low-permeability porous media with limited excavation and relatively low secondary disturbance. In this study, the effects of electric field strength, electrode type, and catholyte pH on Cu and Pb removal from contaminated loess were systematically evaluated using a large-scale EK reactor. The full name of EKG is electrokinetic geosynthetics. During treatment, pH, electrical conductivity, electric current, cumulative electroosmotic flow (EOF), and the spatial distributions of Cu and Pb were monitored. Increasing the electric field from 1.0 to 2.0 V cm⁻¹ increased current and EOF and accelerated anodic acid-front propagation, but it also strengthened cathodic alkalization and precipitation. Compared with graphite electrodes, electrokinetic geosynthetics (EKG) electrodes maintained higher current and EOF, generated stronger acidification, and increased Cu and Pb removal by approximately 25% and 5%, respectively. Among the tested catholyte conditions, pH 7.0 provided the best balance between electromigration and electroosmosis, achieving overall soil-phase removal efficiencies of approximately 19.0% for Cu and 8.0% for Pb. These results show that coordinated regulation of the electric field, electrode architecture, and electrolyte chemistry can mitigate the focusing effect in loess, although further enhancement is still required for field-scale decontamination.

Keywords: loess soil; electrokinetic remediation; heavy metal; electrodes; controlling electrolyte pH

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1. Introduction

Accelerated industrial development, urban expansion, mining, and smelting activities in northwestern China have resulted in the continuous input of Cu and Pb into loess areas. Once released into the vadose zone, these metals can be retained by loess particles, migrate with infiltrating water, and accumulate around foundations, slopes, and underground structures. Therefore, heavy-metal contamination in loess is not only an environ-

mental pollution issue, but also a coupled soil–groundwater–geotechnical problem involving groundwater security, soil structural stability, and potential human exposure risks [1,2]. Mining and smelting activities are recognized as the major anthropogenic sources of these pollutants, and nearly 20% of China's cultivated land has been reported to exceed heavy metal limits, with the western loess region being particularly vulnerable [1]. Owing to its highly porous structure, weak interparticle bonding, and limited water-holding capacity under unsaturated conditions, loess readily permits the infiltration and retention of heavy metals. At the same time, its pronounced hydromechanical sensitivity makes the soil structure highly susceptible to degradation upon wetting, thereby increasing remediation difficulty and compromising engineering stability [3–6]. The long-term persistence, toxicity, and subsurface mobility of heavy metals further complicate site management [7]. Therefore, developing practical and scalable treatment strategies capable of reducing Cu and Pb contamination while preserving the engineering integrity of loess is of considerable importance.

A variety of technologies have been applied to heavy-metal-contaminated soils, including phytoremediation, thermal desorption, soil replacement, stabilization/solidification, chemical leaching, microbial remediation, and electrokinetic (EK) treatment [8–20]. Among these methods, EK remediation has attracted growing attention, particularly for low-permeability soils, because it relies on externally applied low-voltage direct current to induce contaminant transport through the soil matrix [15]. During EK treatment, water electrolysis at the electrodes produces acidic and alkaline fronts, generating a pronounced pH gradient, with H^+ accumulating near the anode and OH^- near the cathode. Under such conditions, electroosmosis drives pore-water movement, whereas electromigration governs the transport of ionic species; together, these processes constitute the main removal pathways in EK systems [15,21]. Anodic acidification generally promotes the dissolution and desorption of metal species from soil surfaces, while cathodic alkalization tends to induce hydroxide precipitation, thereby immobilizing heavy metals and suppressing both electroosmotic flow and ionic migration. These constraints are especially pronounced in loess, which is typically weakly alkaline, unsaturated, highly porous, and metastable in structure. Under EK treatment, the transport and release of heavy metal ions in loess are therefore further restricted, and wetting-induced structural collapse may narrow pore channels and reduce ionic conductivity [1,7]. As a result, the remediation efficiency of contaminated loess remains limited, and a better understanding of metal migration behavior in this special soil medium is needed to improve Cu and Pb removal and reduce groundwater risk. In addition to total metal concentration, the chemical speciation of Cu and Pb is also critical for understanding their electrokinetic removal behavior in loess. Owing to the alkaline environment and carbonate-rich mineral background of loess, Cu and Pb may exist not only as soluble and exchangeable species, but also as carbonate-bound, oxide-bound, organic-bound, and residual fractions. Among these forms, carbonate-associated metals are particularly sensitive to pH variation. The H^+ front generated at the anode can promote carbonate dissolution and release carbonate-bound Cu and Pb into the pore solution, whereas OH^- accumulation near the cathode can induce secondary precipitation as hydroxides or carbonates. Therefore, the apparent removal efficiency in EK remediation should be interpreted together with possible speciation transformation and metal redistribution within the soil–electrolyte system. However, the coupled effects of pH-front evolution, metal speciation transformation, and loess structural alteration remain insufficiently clarified.

To improve EK performance, many previous studies have focused on the enrichment of heavy metals near the cathode, where the rise in pH favors precipitation of metal species that have migrated from the anode mainly via electromigration and, secondarily, via

electroosmotic transport. One common strategy has been to optimize power supply conditions, for example by adjusting voltage gradients, current modes, or pulsed operation, as these parameters strongly influence contaminant removal efficiency and energy consumption [22–29]. However, remediation efficiency is still frequently restricted by electrode polarization caused by direct connection of conventional electrodes to the power source. Consequently, increasing attention has been directed toward the development of alternative electrode materials and configurations. Among these alternatives, electrokinetic geosynthetics (EKG) electrodes have attracted attention because they combine electrical conductivity with geosynthetic-type drainage and reinforcement functions. Compared with conventional graphite or metal electrodes, EKG electrodes usually provide a larger electroactive surface area, more distributed current pathways, and better contact with the soil matrix. These characteristics can reduce electrode polarization, improve charge transfer, sustain electroosmotic flow, and regulate pH-front propagation during EK treatment. Recent studies have further emphasized the importance of electrode architecture, voltage-gradient optimization, and hybrid EK systems for improving heavy-metal transport and reducing energy consumption [30–35]. Electrode type has been shown to exert a decisive influence on EK performance [36,37]. For instance, composite and auxiliary electrodes, such as PET-CNT yarns and conductive polymer systems, can enhance current density, strengthen electroosmotic transport, and modify pH evolution, thereby improving metal removal in fine-grained soils [38–40]. Electrolyte regulation provides another important means of process enhancement. Appropriate selection of anolytes and catholytes, including organic acids such as citric acid, may promote metal desorption and complex stabilization compared with deionized water, although inadequate pH control can still result in secondary precipitation and constrain overall removal efficiency [41–43].

Although meaningful progress has been achieved in enhanced EK treatment, recent studies have focused mainly on voltage-gradient optimization, EK-permeable reactive barrier systems, hybrid EK processes, and advanced electrode materials in sands, clays, tailings, and other fine-grained soils [31–36]. By contrast, carbonate-rich loess has received far less attention, despite its weakly alkaline condition, metastable structure, strong buffering capacity, and sensitivity to wetting-induced structural disturbance. These characteristics may strongly influence acid-front propagation, metal speciation transformation, electroosmotic flow, and cathodic focusing. In particular, the coupled effects of electric field intensity, EKG electrode architecture, and catholyte pH regulation on Cu and Pb transport in loess remain insufficiently clarified. Therefore, this study systematically investigates these factors to identify the key mechanisms controlling metal mobilization, focusing mitigation, and soil-phase removal in Cu- and Pb-contaminated loess.

2. Materials and Methods

2.1. Sampling and Specimen Preparation

In northwestern China, wind-transported aeolian dust has accumulated extensively across the Loess Plateau and undergone progressive pedogenic evolution through leaching, illuviation, and renewed aeolian deposition. Geomorphologically, the region is characterized mainly by loess ridges, loess hills, and bedrock-incised gullies. Borehole investigations have shown a typical stratigraphic sequence consisting of Palaeosol overlying Malan (Q₃) loess, which in turn rests on sandstone bedrock, with corresponding thicknesses of approximately 22–31 m and 2–5 m, respectively [1,44]. In the present study, loess samples were collected from Lantian, Shaanxi Province, located about 22 km southeast of Xi'an, at a sampling depth of 3.0–4.5 m. The basic physical properties of the soil were determined in accordance with the Standard for Soil Test Method of P. R. China [45], and the results are listed in Table 1. The loess had a specific gravity of 2.69 and a natural water

content of 16.5%. Particle-size analysis using a laser particle analyzer (WJL-602, Rise Instruments Co., Ltd., Nanjing, China) showed that the soil consisted of 87.40% silt, 9.30% clay, and 3.30% sand, while the plasticity index was 12.1%. Major soluble ions were analyzed using an Ion Analyzer IA-300 (Toa DKK, Tokyo, Japan). No detectable Cu or Pb was found in the original loess, indicating that the collected soil was suitable for use as a clean background matrix in subsequent spiking experiments designed to simulate Cu and Pb migration during EK remediation.

The zeta potential (ζ) represents the electrostatic potential at the shear plane relative to the bulk solution. Because loess particles generally carry negatively charged mineral surfaces, a cation-rich Stern layer forms adjacent to the particle surface, followed by an outer Gouy–Chapman diffuse layer (Figure 1a). An increase in the absolute value of ζ generally indicates a thicker diffuse double layer and a higher concentration of counterions. When a direct current electric field is applied, hydrated counterions within the diffuse layer migrate toward the cathode. Owing to viscous drag between the moving ionic layer and pore fluid, electroosmotic flow is generated in the direction of the negative electrode (Figure 1b). However, EOF in an EK system is not governed solely by ζ potential. It is also affected by the effective electric field, current intensity, pore-water ionic strength, hydraulic connectivity, and precipitation-induced pore blockage. Therefore, changes in pH may influence EOF through both surface-charge modification and indirect effects on ion transport and pore structure. This phenomenon further confirms that loess particles possess an overall negative surface charge. The BET specific surface area (BET-SSA) refers to the total surface area per unit mass of loess particles and can be used as an indicator of the soil's potential capacity to adsorb different cationic species.

To prepare contaminated specimens, air-dried loess was artificially spiked with $\text{Cu}(\text{NO}_3)_2$ and $\text{Pb}(\text{NO}_3)_2$ solutions to obtain target concentrations of 500 mg kg^{-1} for each metal. This approach ensured a well-controlled contamination condition for mechanistic investigation under laboratory settings. After spiking, the soil was sealed and allowed to equilibrate in a humid chamber for 72 h to promote uniform distribution of the contaminants and to adjust the water content to 15%. The conditioned loess was then filled into the electrokinetic reactor and compacted to a degree of compaction of 0.80 at the target water content of 15%. For each specimen, the prepared soil was divided into five equal portions and placed into the reactor in five successive layers. Each layer was tamped using a wooden block to achieve a uniform density throughout the specimen. All reagents used for soil digestion, including CH_3COOH , MgCl_2 , NaNO_3 , HCl , and NaOH , were of reagent grade. $\text{Cu}(\text{NO}_3)_2$ and $\text{Pb}(\text{NO}_3)_2$ were of analytical grade. All chemicals were supplied by Shanghai Macklin and Sinopharm, China.

Table 1. Physicochemical properties of the loess used in this study. The basic soil properties were reported in our previous related work and are reused here as background characterization for the present EK tests (adapted from [46]). © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Property	Loess
Sand (%)	3.3
Silt (%)	87.4
Clay (%)	9.3
Void ratio, e	0.898
Bulk unit weight, γ (kN/m^3)	16.2
Specific gravity, G_s	2.69
Water content, ω_n (%)	16.5
Liquid limit, ω_L (%)	31.6

Plastic limit, ω_P (%)	19.5
USCS symbol	CL
Permeability (m s^{-1})	2.55×10^{-6}
Organic matter (mg g^{-1})	4.1
pH	7.8
Electrical conductivity ($\mu\text{s cm}^{-1}$)	244
BET specific surface area ($\text{m}^2 \text{g}^{-1}$)	24.1
Composition of ions	
Ca^{2+} (mg/kg)	126
Mg^{2+} (mg/kg)	40
Na^+ (mg/kg)	103
K^+ (mg/kg)	4.6

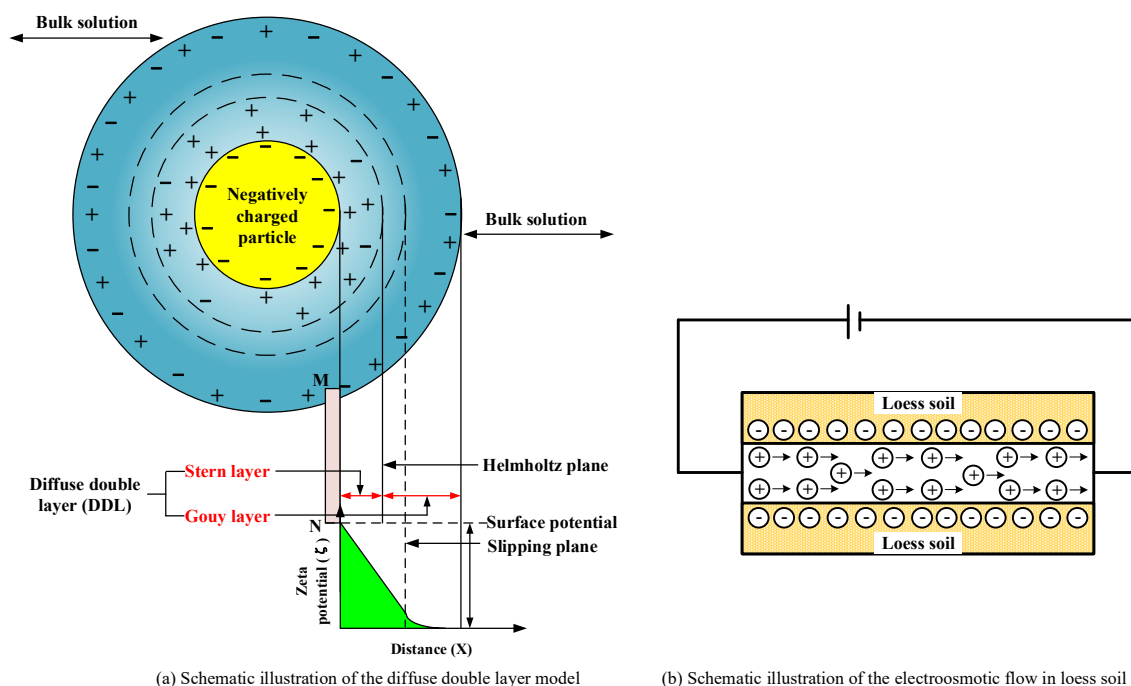


Figure 1. Schematic illustration of the diffuse double layer model and EOF in loess soil.

2.2. Electrokinetic Reactor and Experimental Design

A wide range of electrokinetic remediation systems for soils contaminated by heavy metals or organic pollutants has been reported in previous studies [8,47–52]. In general, these systems are designed based on the basic principles of electrokinetic remediation and commonly consist of a central soil chamber and two electrode chambers located at opposite ends. One electrode chamber contains the anode and the corresponding electrolyte, whereas the other contains the cathode and catholyte. Once connected to a direct-current power supply, electrolysis occurs in both chambers, producing H^+ in the anodic compartment and OH^- in the cathodic compartment. Previous studies have employed reactors of various dimensions. For example, Yuan et al. (2017) [29] used a soil chamber of $15 \text{ cm} \times 3.8 \text{ cm} \times 6 \text{ cm}$ (length $\times$ width $\times$ height) to investigate heavy-metal-contaminated black soil. Pedersen et al. (2018) [53] evaluated EK treatment of copper-contaminated tailings using a reactor with a soil chamber of $10 \text{ cm} \times 8 \text{ cm}$ (length $\times$ diameter). Millán et al. (2020) [54] constructed a device with a chamber size of $14 \text{ cm} \times 10 \text{ cm} \times 8 \text{ cm}$ (length $\times$ width $\times$ height) for studying enhanced electrokinetic remediation of herbicide-contaminated soils. Although most of these investigations were performed at laboratory scale, the soil chamber

volume in many reported systems was generally below 1000 cm³. Such small-scale reactors are valuable for clarifying the fundamental features of electrokinetic transport, but larger experimental systems have been shown to provide results that are more representative and more useful for guiding scale-up and field application [55–60]. In particular, larger specimens allow clearer observation of current response, electroosmotic flow, and temperature evolution, thereby improving the reliability of trend analysis. Guzman et al. (2015) [61] further demonstrated that the use of larger-scale models in acid-enhanced EK remediation of real contaminated soils yields results of greater engineering relevance. On this basis, a relatively large electrokinetic reactor was designed in the present study to better capture the behavior of Cu and Pb migration in loess under conditions more informative for practical application.

The experimental reactor consisted of a plexiglass soil chamber, two electrode compartments positioned on both sides of the soil chamber, two electrodes, two external electrolyte reservoirs, two peristaltic pumps, a regulated DC power supply, and a data acquisition system (Figure 2). The internal dimensions of the soil chamber were 500 × 150 × 150 mm, whereas each electrode compartment measured 100 × 150 × 150 mm. A geotextile–porous plate assembly was installed between the soil chamber and the electrode compartments to provide hydraulic separation. To monitor the spatial variation in electrokinetic behavior, the soil chamber was divided longitudinally into six sections, designated S1 to S6. A liquid-level overflow controller was used to maintain a constant electrolyte level in both electrode compartments throughout the test. The electrodes installed in the side compartments established the electric field across the soil specimen. Two external electrolyte reservoirs, each with a diameter of 150 mm and a height of 250 mm, were connected to the electrode compartments by peristaltic pumps. To regulate catholyte pH during treatment, 1.0 M NaOH and 1.0 M HCl solutions were introduced through this circulation system. For the catholyte pH-controlled tests (Exp-06 to Exp-08), 0.01 M NaNO₃ was used as a background supporting electrolyte during electrolyte circulation. The purpose of adding NaNO₃ was to maintain a comparable ionic strength and initial conductivity among the pH-controlled tests, thereby reducing the influence of conductivity fluctuation on ion transport. NaNO₃ was selected because Na⁺ and NO₃[−] do not form strong complexes or precipitates with Cu and Pb under the tested conditions, compared with complexing electrolytes such as chloride- or organic-acid-based solutions. During the tests, the catholyte pH was adjusted to 4, 7, or 9 using 1.0 M HCl or 1.0 M NaOH, while 0.01 M NaNO₃ provided the same background electrolyte condition for Exp-06, Exp-07, and Exp-08. Therefore, the catholyte pH effect was evaluated mainly by comparing these three tests under the same NaNO₃ background. During EK operation, current, electrical conductivity, pH, and electroosmotic flow in each section were recorded through the data acquisition unit. After completion of each test, the removal efficiencies of Cu and Pb were determined and compared among the different treatment conditions.

A total of eight treatments were designed to evaluate the effects of electric field strength, electrode type, and electrolyte pH regulation (Table 2). Due to the relatively large size of the EK reactor and the substantial amount of contaminated soil, electrolyte, and operation time required for each run, each treatment was conducted once in the present study. Therefore, the experimental results were mainly used to identify spatial–temporal trends and mechanistic responses under different operating conditions, rather than to perform statistical significance testing. Three electric field intensities, namely 1.0, 1.5, and 2.0 V cm^{−1}, were applied in the EK experiments. Two electrode materials, graphite and EKG, were compared, with BET specific surface areas of 1.116 and 8.900 m² g^{−1}, respectively, as determined by nitrogen adsorption. In addition, a recirculating electrolyte control system was employed to regulate solution pH during electrokinetic treatment.

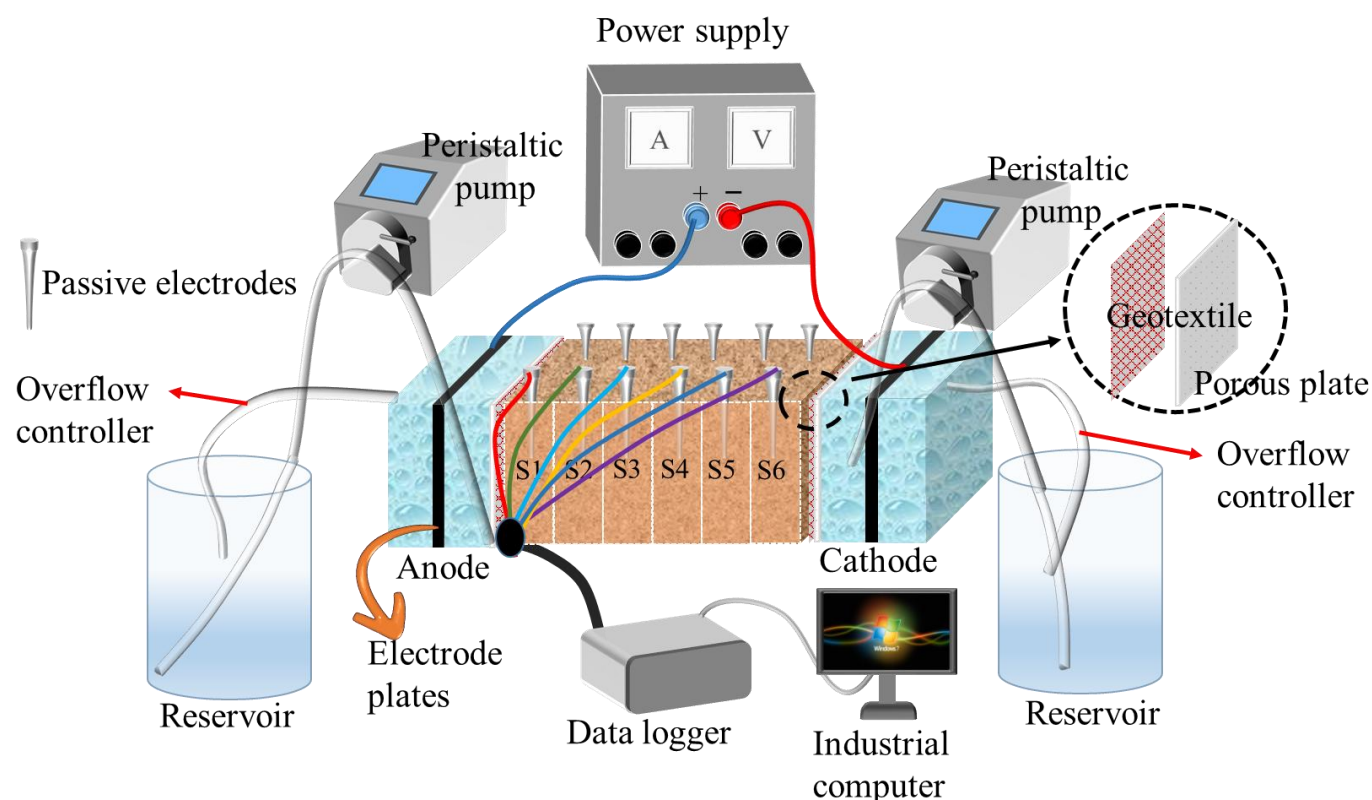


Figure 2. Schematic illustration of the electrokinetic reactor (Hu et al. (2022) and Liu et al. (2025) [4,46]). © 2022 Hu, Cheng, Wen and Kang. & © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Table 2. Experimental design of the enhanced electrokinetic remediation of copper and lead-contaminated loess.

Test	Electrode Type	Pollutant	Voltage Gradient/Vcm ⁻¹	Pretreatment	Control Catholyte pH	Duration Time/h
Exp-01	Graphite 0.125	Cu + Pb	1.0	/	/	48
Exp-02	Graphite 0.125	Cu + Pb	1.5	/	/	48
Exp-03	Graphite 0.125	Cu + Pb	2.0	/	/	48
Exp-04	Graphite	Cu + Pb	1.5	/	/	72
Exp-05	EKG 0.75	Cu + Pb	1.5	/	/	72
Exp-06	EKG 0.75	Cu + Pb	1.5	0.01 M NaNO ₃	4	72
Exp-07	EKG 0.75	Cu + Pb	1.5	0.01 M NaNO ₃	7	72
Exp-08	EKG 0.75	Cu + Pb	1.5	0.01 M NaNO ₃	9	72

Note: “/” indicates that no additional background electrolyte or catholyte pH control was applied. In Exp-06 to Exp-08, 0.01 M NaNO₃ was used as the background supporting electrolyte, and the catholyte pH was controlled at 4, 7, or 9 during EK treatment.

2.3. Analytical Procedure

After EK treatment, the soil chamber was divided into six equal sections from the anode to the cathode, denoted as S1–S6. The removal efficiency of Cu or Pb in each section was calculated according to Equation (1). The overall removal efficiency reported in this study was obtained as the arithmetic average of the six section-specific removal efficiencies. Therefore, the term “removal efficiency” in this work refers to the decrease in metal concentration in the soil phase, rather than a complete system-level metal mass balance. Since the Cu and Pb concentrations in the anolyte, catholyte, and electrode chambers were not systematically measured in the original experimental design, a complete mass balance could not be established in the present study.

After EK treatment, the soil specimens were oven-dried to a constant mass and then digested with HNO₃. It should be noted that the present study focused on the total soil-phase concentrations of Cu and Pb before and after EK treatment. Sequential extraction for distinguishing soluble, exchangeable, carbonate-bound, reducible, oxidizable, and residual fractions was not included in the original experimental design. Therefore, the discussion of metal speciation transformation in this work is based mainly on the measured pH, EC, EOF, and spatial removal patterns, together with the known alkaline and carbonate-buffering characteristics of loess. This limitation should be considered when interpreting the removal mechanism. The resulting digests were analyzed by atomic absorption spectrophotometry (Hitachi, Japan). The removal efficiency was calculated as follows:

$$\text{Removal efficiency (\%)} = (C_0 - C_f)/C_0 \times 100\% \quad (1)$$

where C_0 is initial heavy metal concentration (mg/kg) of loess, and C_f is the final concentration of heavy metals (mg/kg) after EK treatment in loess. Because each EK treatment was performed once, standard deviations, error bars, and inferential statistical comparisons were not provided. Accordingly, the following discussion focuses on the consistency of current response, pH evolution, EC variation, EOF development, and spatial Cu/Pb removal patterns. Small differences among treatments, especially for Pb removal, should therefore be interpreted as indicative trends rather than statistically verified improvements.

3. Results and Discussion

3.1. Effect of Electric Field Intensity

Electric field intensity is a key parameter controlling EK performance because it directly influences both current response and electroosmotic flow (EOF). As the applied field increased from 1.0 to 1.5 and then to 2.0 V cm⁻¹, both the current and EOF increased accordingly. In all cases, the temporal evolution showed a similar pattern, characterized by an initial increase followed by a gradual decline or stabilization (Figure 3). The increase in field strength also intensified pH polarization within the soil, resulting in lower pH values near the anode and higher pH values near the cathode (Figure 4). The electrical conductivity distribution further reflected the influence of field intensity on ion transport and precipitation behavior. The lowest conductivity was consistently observed near the cathode, and the conductivity in this region decreased from 290 to 175 μS cm⁻¹ as the electric field strength increased from 1.0 to 2.0 V cm⁻¹. This trend suggests that stronger cathodic alkalization promoted the precipitation of Cu- and Pb-bearing hydroxides, thereby reducing the concentration of dissolved ions in the pore solution. In carbonate-bearing loess, the variation in pH may also induce speciation transformation of Cu and Pb. The acid front generated near the anode can dissolve carbonate minerals and carbonate cementation, thereby releasing part of the carbonate-bound Cu and Pb into the pore solution and enhancing their subsequent electromigration. Conversely, the alkaline front near the

cathode may favor the re-precipitation of dissolved metals as hydroxide or carbonate phases. Therefore, the removal observed in the anodic and middle sections was likely associated not only with the migration of initially soluble and exchangeable species, but also with the partial mobilization of carbonate-associated Cu and Pb. The spatial distribution of metal removal did not follow a simple monotonic trend (Figure 5). In the S2–S3 sections, Cu removal at 1.5 V cm^{-1} was comparable to, and in some locations even slightly higher than, that obtained at 2.0 V cm^{-1} , while requiring a lower energy input. In contrast, beyond S3, the 2.0 V cm^{-1} condition showed a clear advantage over the lower field strengths, whereas the performance of 1.0 V cm^{-1} progressively deteriorated from S4 to S6. These results indicate that the influence of electric field intensity varied along the transport path. Therefore, the effect of field intensity involved a trade-off between enhanced mobilization and intensified cathodic precipitation. Overall, the results suggest that the optimal field strength is spatially dependent: a moderate field may provide better energy efficiency in zones close to the anode, whereas a higher field is more beneficial in downstream regions despite its greater energy demand [22].

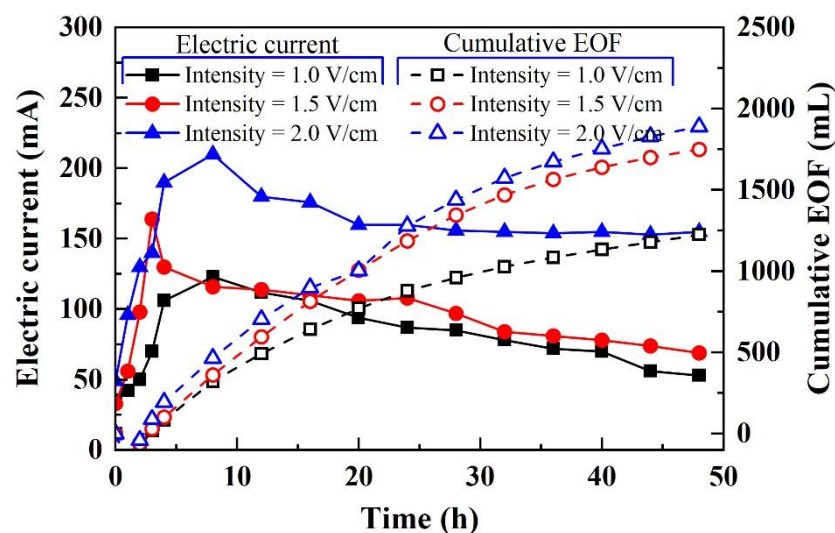


Figure 3. Relationships of electric current versus time and relationships of accumulated electroosmosis flow (EOF) versus time under the effect of electric field intensity.

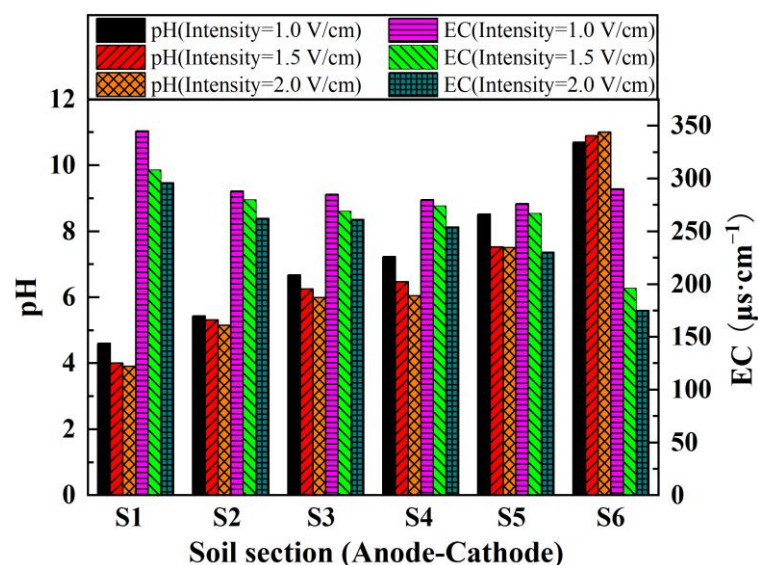


Figure 4. Variation in pH and electric conductivity (EC) against six soil sections during the electrokinetic experiment subjected to the effect of electric field intensity.

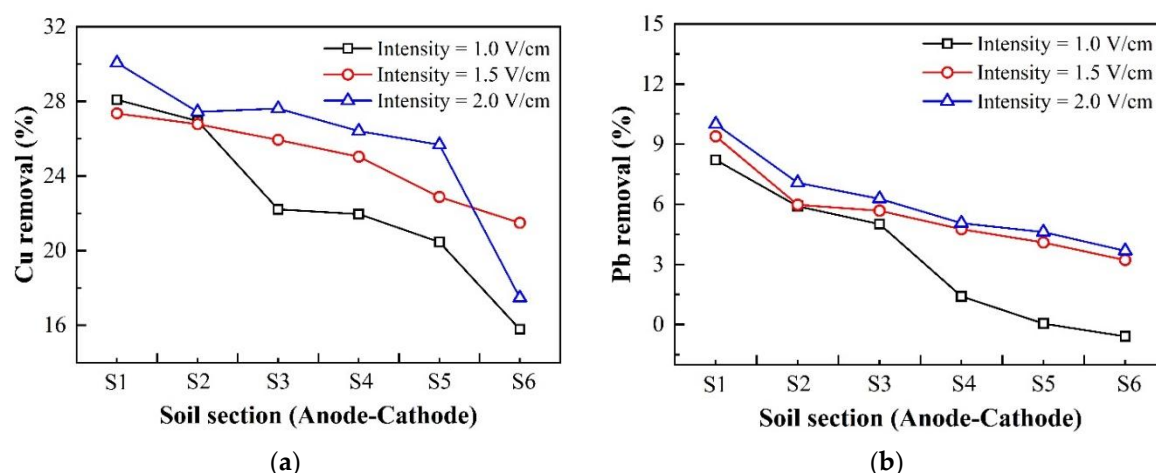


Figure 5. Removal of heavy metals across six soil sections after the EK remediation: (a) copper removal and (b) lead removal.

Extensive laboratory- and field-scale studies have demonstrated the applicability of EK remediation to a wide range of porous media, including sands, kaolin, clays, black soils, sludge, natural soils, tailings, and marine sediments. As summarized in Table 3, soil type exerts a primary influence on both contaminant removal efficiency and energy consumption. In sandy media, electrode configuration has been shown to substantially affect remediation performance. For example, Hsueh et al. (2022) reported Ni and Cr removal efficiencies of 27.3–39.3% and 6.1–30.1%, respectively, using a honeycomb electrode arrangement, whereas a square layout achieved Ni and Cr removals of 46.2–48.5% and 3.1–12.2%, but at an operating cost approximately five times higher. Telepanich et al. (2021) further showed that alginate–graphite electrodes enabled 70% Cr removal within only 0.5 h. In fine-grained systems, the contrast among different soil matrices is even more pronounced. Behrouzinia et al. (2022) obtained a Cu removal efficiency of 17.5% in kaolin using geosynthetic electrodes, whereas Yuan et al. (2017) reported 94.84% Cu removal in black soil, and Torabi et al. [56] observed only 4.59% in sludge, clearly indicating a strong matrix-dependent response. For Pb, the findings of Muazu et al. (2020) and Yuan et al. (2017) likewise confirm that intrinsic soil properties are critical determinants of EK performance. Among these properties, carbonate content plays a particularly important role, because higher calcite levels enhance soil buffering capacity, suppress acid-front propagation, and increase contaminant retention, thereby slowing metal removal [52]. Under this framework, the Cu and Pb removal efficiencies achieved in the present loess, 19.0% and 8.0%, respectively, were markedly lower than those reported for many sand- and black-soil systems. This relatively poor performance is likely associated with the high fine-particle content of loess, especially clay minerals, which strengthen metal adsorption and impede ion migration, as well as with its abundant carbonate minerals, which inhibit the advance of the acidic front [1,2]. In addition, the potential effects of particle morphology and soil fabric on ion transport in loess remain insufficiently understood and deserve further targeted investigation. Therefore, the removal efficiencies obtained in this study should be interpreted as process-level improvements under a single-stage EK treatment, rather than as final cleanup efficiencies sufficient for practical remediation.

Table 3. Comparison of studies with the research about soil type and remediation efficiency.

Electrode	Contaminants	Initial Concentration C_0 (mg/kg)	Time t (h)	Intensity (V/cm)	Soil Type	Removal Efficiency (%)	References
Aluminum electrode	Cr, Ni	186, 132	72	0.6–1.0	Sand	3.1–30.1, 27.3–48.5	Hsueh et al., 2022 [48]
Hydrogel electrode	Cr	200	0.5	4.8	Sand	70	Telepanich et al., 2021 [49]
Composite electrode	Cu	200	60	1.25	kaolin	17.5	Behrouzinia et al., 2022 [50]

Graphite	Pb	120	168	1.08	Clay	14.15	Muazu et al., 2020 [52]
Graphite	Cu, Pb	327.8 240.8	705	1.0	Black soil	94.84, 95.85	Yuan et al., 2017 [29]
/	Cu, Cd	248.4, 82	240	1.0	sludge	4.59, 30.65	Torabi et al., 2021 [51]
/	Al	16400	240	1.0	/	10–60	Ouhadi et al., 2010 [55]

3.2. Effect of Electrode Materials

When electrodes are directly connected to the power supply, they carry the full circuit current, which can readily induce polarization at the electrode–electrolyte interface due to charge-transfer limitations [40]. Compared with graphite, the EKG electrode exhibited a much larger BET specific surface area, increasing from 1.116 to 8.900 m² g^{−1}. This larger electroactive surface reduced the interfacial current density and thereby alleviated electrode polarization. As a consequence, a greater proportion of the applied voltage was effectively distributed across the soil specimen rather than being lost at the interface, resulting in a stronger effective electric field and a higher sustained current during remediation (Figure 6). The enhanced current also accelerated the generation of H⁺ at the anode and OH[−] at the cathode, which promoted ionic transport, particularly during the early stage of EK treatment. Although the more rapid production of OH[−] could intensify precipitation near the cathode, the current in the EKG system remained consistently higher than that in the graphite system during stage II, indicating lower polarization losses and less pronounced blockage at the cathodic side. A similar trend was observed for electroosmotic flow (EOF), which was also higher with EKG. The transient negative EOF values recorded at the beginning of the experiment likely reflected a short-term reversal in flow direction caused by local hydraulic or chemical gradients; nevertheless, fluid migration across the cathodic boundary was maintained even in the presence of precipitation (Figure 6).

The evolution of pH and electrical conductivity further highlights the influence of electrode material on EK performance. Along the soil column, pH gradually increased from the anode toward the cathode, whereas electrical conductivity (EC) showed the opposite trend and decreased in the same direction (Figure 7). Relative to graphite, the EKG electrode produced lower pH values throughout the loess column, indicating more effective propagation of the acidic front from the anode. This stronger acidification favored the desorption and dissolution of Cu and Pb species from soil particles, while the associated increase in ionic concentration contributed to higher EC, both of which facilitated contaminant transport and removal. The spatial distributions of metal removal clearly demonstrate the superiority of the EKG electrode (Figure 8). Both Cu and Pb removal efficiencies were higher under the EKG condition than under the graphite condition, and in all sections Cu was removed more effectively than Pb. This difference is consistent with the stronger retention of Pb in loess, which is related to its greater tendency for specific adsorption and interactions with carbonate minerals, thereby reducing its mobility compared with Cu.

From a mechanistic standpoint, the enhanced performance of the EKG electrode should be interpreted as the net result of several coupled electrochemical and electrohydraulic processes, rather than as the effect of pH or ζ potential alone. The larger BET specific surface area of the EKG electrode reduced the interfacial current density and electrode polarization, allowing a greater proportion of the applied voltage to be distributed across the soil specimen. This maintained a higher current and a stronger effective electric field, thereby enhancing electromigration and electroosmotic transport. Meanwhile, the stronger acid-front propagation in the EKG system promoted the desorption and dissolution of Cu and Pb from loess particles and carbonate-related binding phases. It should be noted that acidification may protonate negatively charged loess surfaces and reduce the

absolute value of ζ potential, which, if considered alone, would tend to decrease electroosmotic mobility. However, in the present EKG system, this potential weakening effect was offset by the higher effective electric field, increased ionic concentration, reduced electrode polarization, and less severe precipitation-induced blockage. Therefore, the observed increase in EOF under the EKG condition reflects the combined system response, while the lower pH mainly contributed to metal mobilization by enhancing desorption and dissolution.

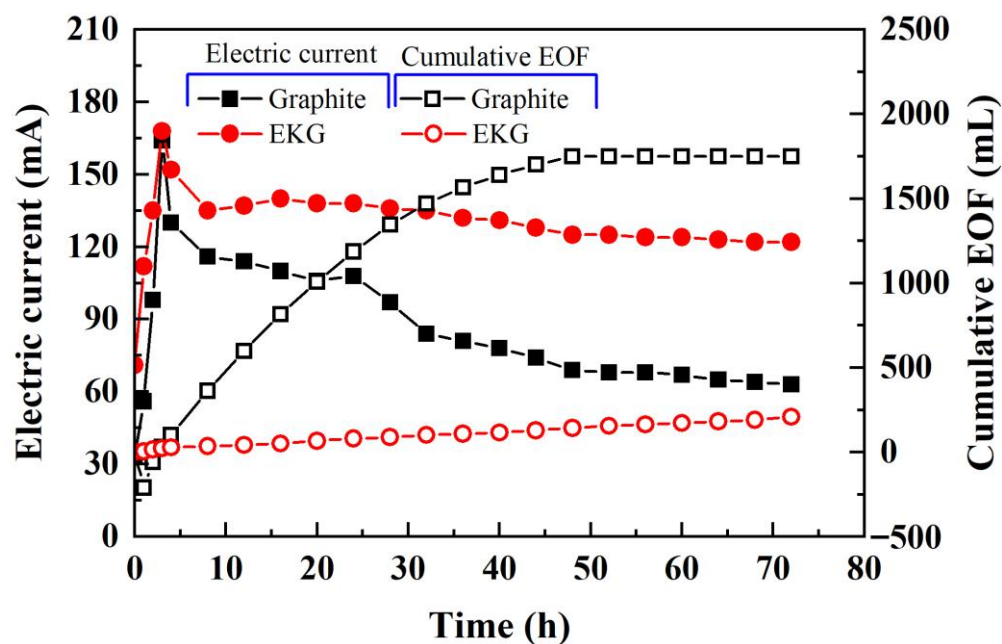


Figure 6. Variation in electric current and EOF at different time during the electrokinetic experiment subjected to the effect of electrodes.

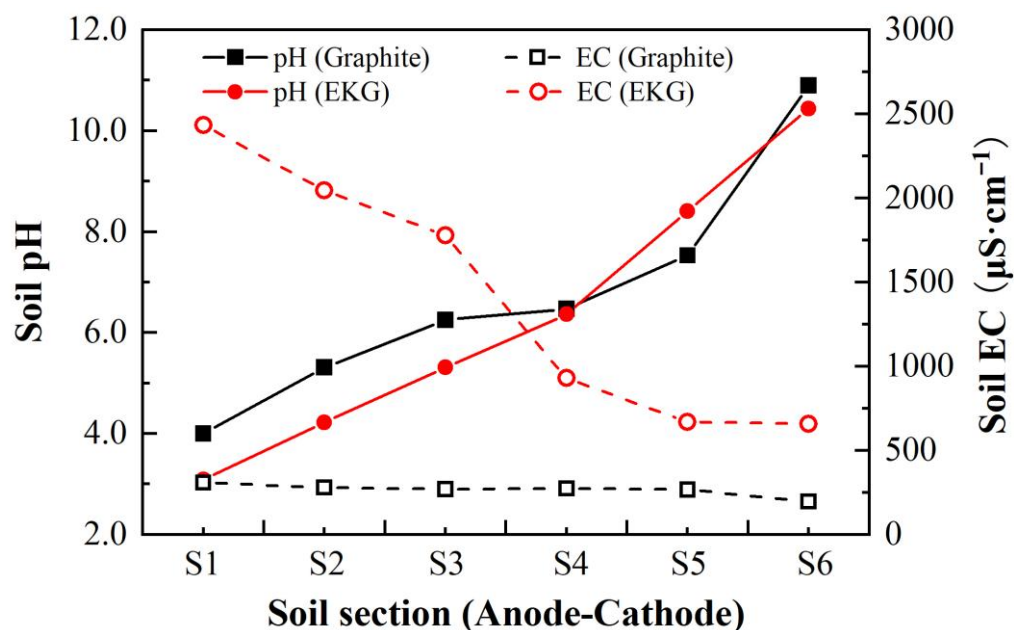


Figure 7. Variation in pH and electric conductivity (EC) at different time during the electrokinetic experiment subjected to the effect of electrodes.

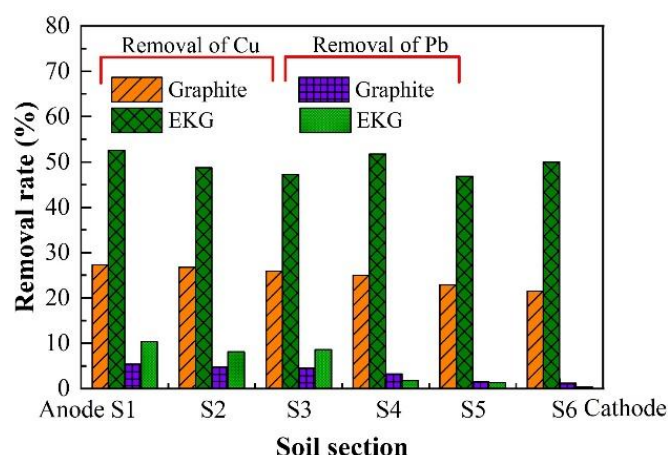


Figure 8. Removal of Cu and Pb after the electrokinetic experiment subjected to the effect of electrodes.

Overall, the EKG electrode outperformed graphite by providing a larger specific surface area, lower surface current density, weaker polarization, and a higher effective current. These characteristics promoted faster ionic transport and enhanced the removal of Cu and Pb from loess. Thus, the apparently competing effects of lower pH on metal desorption and ζ potential are not contradictory; rather, they represent different aspects of the coupled EK process. Under the EKG condition, the enhancement in effective electric field, current continuity, and contaminant mobilization outweighed the possible reduction in electroosmotic mobility caused by ζ -potential decrease. At the same time, the stronger acidification induced by EKG reduced the absolute ζ potential of loess particles, facilitated heavy metal desorption, and improved electroosmotic transport, especially in the anodic region. Together, these effects explain the superior remediation efficiency achieved with the EKG electrode. This observation is consistent with previous studies showing that increasing the electroactive surface area and improving electrode–soil contact can reduce electrode polarization and enhance current continuity in fine-grained soils. However, the improvement in loess remained lower than that reported for some sand or black-soil systems, suggesting that electrode optimization alone cannot fully overcome the transport resistance caused by fine texture and carbonate buffering.

3.3. Effect of Catholyte pH

To isolate the influence of catholyte pH, Exp-06, Exp-07, and Exp-08 were conducted under the same 0.01 M NaNO₃ background electrolyte condition. Therefore, the comparison in this section focuses mainly on the relative differences among pH 4, 7, and 9, rather than a direct comparison with the tests without NaNO₃ addition. Figure 9 illustrates the temporal evolution of electric current and EOF under different catholyte pH conditions. In EK remediation, the transport of dissolved Cu and Pb is controlled by both electromigration and electroosmotic advection, but their contributions are not equivalent. For cationic Cu and Pb species, electromigration driven by the electric field is generally the dominant transport pathway, whereas EOF mainly provides advective pore-water transport and affects hydraulic connectivity. Therefore, the remediation performance under different catholyte pH conditions should be interpreted by jointly considering current response, cumulative EOF, pH evolution, and the spatial removal profiles. In all cases, the electric current increased rapidly during the first 4 h, after which the rate of increase slowed and the current gradually approached a stable level. Among the three treatments, the system with the catholyte adjusted to pH 7 exhibited the highest current throughout most of the

experiment. After 72 h, the current continued to rise gradually in the pH 7 and pH 9 systems, whereas it tended to level off when the catholyte was maintained at pH 4. In contrast, EOF increased as the catholyte pH decreased. This behavior can be attributed to the reduction in precipitation near the cathode under more acidic conditions. Lower catholyte pH suppressed hydroxide accumulation, enhanced soil acidification, and promoted the development of a more aggregated soil structure. Such a structure likely provided wider and less tortuous transport pathways, thereby facilitating electroosmotic flow.

The spatial distributions of pH and electrical conductivity after EK treatment further demonstrate the important role of catholyte chemistry (Figure 10). With decreasing catholyte pH, the soil pH generally decreased, whereas the electrical conductivity increased. When the catholyte was controlled at pH 4, the soil pH increased from S1 to S4 and then declined from S4 to S6. This pattern suggests that OH^- released at the cathode was partly neutralized by the acidic catholyte, thereby altering the pH profile near the cathodic side. By contrast, when the catholyte pH was maintained at 7 or 9, soil pH increased progressively from the anode toward the cathode, which is consistent with the migration of OH^- from the catholyte into the soil column. The corresponding spatial removal profiles for Cu and Pb are presented in Figure 11. In all treatments, Cu removal was consistently higher than Pb removal, indicating that Pb remained more strongly retained in loess. When the catholyte pH was adjusted to 4, both Cu and Pb removal efficiencies were lowest near the anode and became higher toward the cathode. Although the pH 4 condition produced the highest cumulative EOF, it did not result in the highest Cu and Pb removal. This indicates that EOF alone was insufficient to determine metal removal. Under acidic catholyte conditions, cathodic precipitation was suppressed and pore-water flow was facilitated, which explains the relatively high EOF. However, the electric current under pH 4 was lower than that under pH 7, suggesting weaker charge transfer and a less favorable condition for electromigration. Since Cu and Pb are mainly transported as dissolved ionic species under the electric field, the reduced current likely limited the contribution of electromigration, even though electroosmotic advection was enhanced. By contrast, the pH 9 condition maintained a relatively alkaline cathodic environment, which favored OH^- accumulation and secondary precipitation of Cu- and Pb-bearing species near the cathode. This precipitation could reduce the concentration of mobile metal ions and obstruct pore-water transport, thereby weakening both electromigration and effective EOF. The pH 7 condition provided a more balanced transport environment: it maintained a higher current than pH 4, while still providing sufficient EOF and alleviating excessive cathodic precipitation compared with pH 9. Therefore, the best soil-phase removal at pH 7 can be attributed to the combined balance between electromigration, electroosmotic advection, and precipitation control, rather than to the maximum EOF alone.

Similar to previous EK studies, catholyte pH regulation changed the balance between metal mobilization and precipitation. However, in the present loess, a neutral catholyte performed better than strongly acidic or alkaline conditions, indicating that carbonate buffering and fine-pore transport constraints made the balance between current, EOF, and precipitation more important than maximizing acidification or EOF alone.

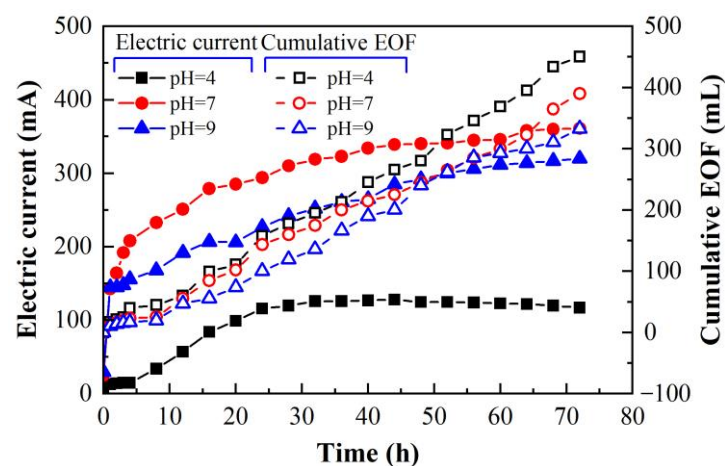


Figure 9. Variation in electric current and EOF at different soil sections after the electrokinetic experiment subjected to the effect of catholyte pH.

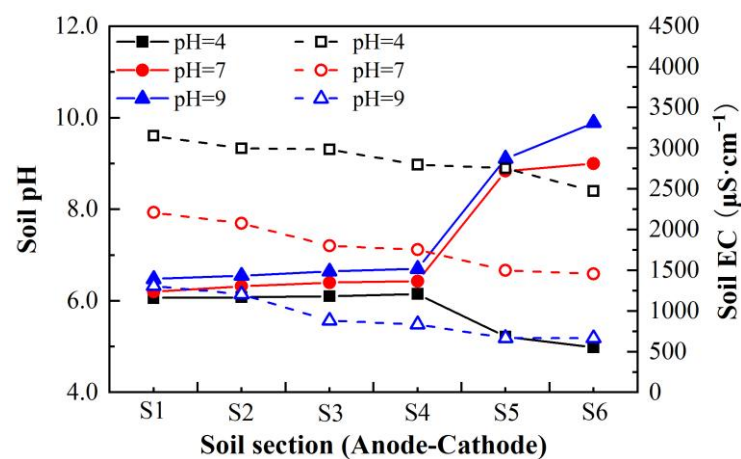


Figure 10. Variation in pH and electric conductivity (EC) at different time during the electrokinetic experiment subjected to the effect of catholyte pH.

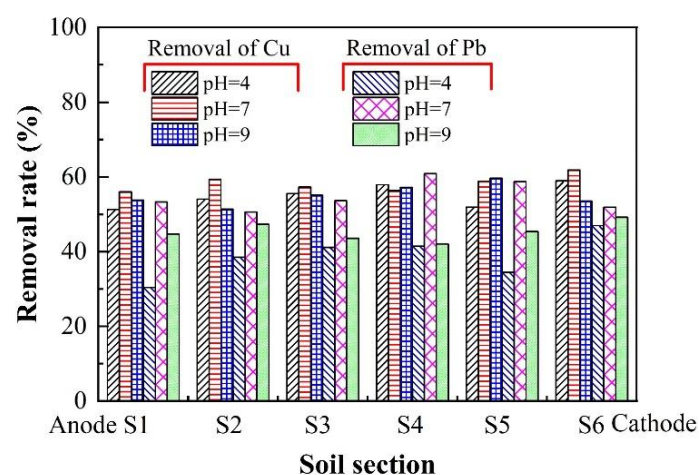


Figure 11. Removal of Cu and Pb after the electrokinetic experiment subjected to the effect of catholyte pH.

3.4. Discussion

The transport and removal of heavy metals toward the cathode during EK remediation are governed by a series of coupled physicochemical processes, including sorption,

precipitation, and dissolution reactions on loess particles, as well as diffusion, electroosmosis, and electromigration in pore water. In this study, the key EK response parameters, including electric current, EOF, pH, EC, and metal removal efficiency, were systematically evaluated to clarify the enhancement mechanisms and the limiting factors under different optimization strategies. The corresponding mechanisms controlling Cu and Pb removal are summarized in Figure 12. Although the optimized conditions improved Cu and Pb removal, the absolute overall soil-phase removal efficiencies remained modest, with maximum values of approximately 19.0% for Cu and 8.0% for Pb. These values indicate that a single-stage EK process under the present experimental duration is not sufficient to meet final remediation goals for heavily contaminated loess. However, the significance of the present study lies in identifying the main limiting mechanisms in carbonate-rich loess and demonstrating how electric field strength, electrode architecture, and catholyte pH can regulate current response, EOF, pH-front propagation, and the focusing effect. The relatively low removal efficiencies are mainly attributed to the fine-grained texture, alkaline buffering capacity, carbonate-related metal retention, and stronger immobilization of Pb compared with Cu. Therefore, the results should be regarded as mechanistic and process-optimization evidence rather than as final field cleanup performance.

For loess, the removal mechanism should be further interpreted from the perspective of metal speciation transformation. Because the tested loess was weakly alkaline and contained soluble Ca^{2+} and Mg^{2+} , Cu and Pb were likely retained through electrostatic adsorption, specific adsorption, carbonate association, and precipitation reactions. During EK treatment, the H^+ generated at the anode can decrease soil pH, dissolve carbonate cementation, and promote the transformation of carbonate-bound or weakly precipitated Cu and Pb into more mobile ionic forms. These released metal species can then migrate under electromigration and electroosmotic flow. However, when the migrated ions approach the cathodic region, the increase in OH^- concentration promotes the formation of $\text{Cu}(\text{OH})_2$, $\text{Pb}(\text{OH})_2$, or carbonate-related precipitates, causing secondary accumulation and the focusing effect. This mechanism also explains why Pb removal was generally lower than Cu removal. Pb tends to show stronger specific adsorption and carbonate-related retention in alkaline loess, and its lower solubility under alkaline conditions makes it more susceptible to precipitation and immobilization near the cathode.

The influence of anodic H^+ on the intrinsic structure of loess should also be considered. Carbonate minerals and carbonate cementation are important contributors to interparticle bonding in loess. Acidification can weaken this cementation, alter pore connectivity, and change the surface charge of soil particles. These changes may temporarily improve metal release and ionic conductivity, but excessive acidification may also induce structural disturbance, increase collapsibility risk, and reduce post-treatment mechanical stability. Therefore, although anodic acidification is beneficial for contaminant mobilization, its engineering and environmental consequences should be carefully controlled in field applications. Post-treatment pH neutralization, geotechnical stability assessment, and long-term monitoring of soil strength and permeability are recommended before large-scale application.

The results indicate that increasing the electric field strength does not necessarily lead to higher removal efficiency. Although a stronger electric field generated higher current and cumulative EOF (Figure 3), thereby promoting the migration and extraction of metal ions, an excessively high field also accelerated the formation of a strong alkaline zone near the cathode (Figure 12). This intensified the focusing effect in the cathodic region, which in turn restricted further ion transport and ultimately reduced the overall removal efficiency (Figure 5). Therefore, the influence of electric field strength reflects a trade-off between enhanced electromigration/electroosmosis and aggravated cathodic precipitation.

Compared with graphite electrodes, the EKG electrode showed lower polarization, which reduced interfacial potential loss and resulted in a higher effective current (Figure 6). The higher current accelerated the generation of both H^+ and OH^- through electrolysis and, more importantly, strengthened anodic acidification, leading to a lower pH in the S1 section of the EKG treatment (Figure 7). Because the migration rate of H^+ is approximately 1.75 times that of OH^- , the higher current also favored deeper propagation of the acidic front, which contributed to lower pH values in regions closer to the cathode (Figure 12). In addition, the stronger current produced greater EOF, and the combined effect of enhanced electromigration and electroosmotic transport improved the removal of both Cu and Pb (Figure 8). Nevertheless, although EKG clearly alleviated the focusing effect, it did not eliminate it completely, as evidenced by the relatively high pH and reduced metal removal observed in the cathodic sections.

Control of catholyte pH provided another important means of regulating the focusing effect. Previous studies have commonly used acidic catholytes to suppress cathodic alkalization, whereas the present study further compared different catholyte pH conditions. When the catholyte pH was adjusted to 9.0, OH^- generated by electrolysis accumulated more readily in the cathode compartment, resulting in a high local OH^- concentration that inhibited further OH^- release. This weakened the current in the EK system, reduced the driving force for metal migration, and lowered removal efficiency. Under this condition, the focusing effect remained pronounced near the cathode, further limiting the removal of Cu and Pb in that region (Figure 11). In contrast, when the catholyte pH was set to 4.0, the strongly acidic environment reduced the availability of anionic carriers required for electromigration toward the anode, which in turn decreased current and weakened EOF. As a result, the overall capacity for ion transport was not sufficiently enhanced, and the improvement in heavy metal removal remained limited. Among the tested conditions, a catholyte pH of 7.0 provided the most favorable balance. This condition effectively alleviated the focusing effect at the cathode while maintaining relatively high current and EOF (Figure 9), thereby promoting the migration and removal of Cu and Pb.

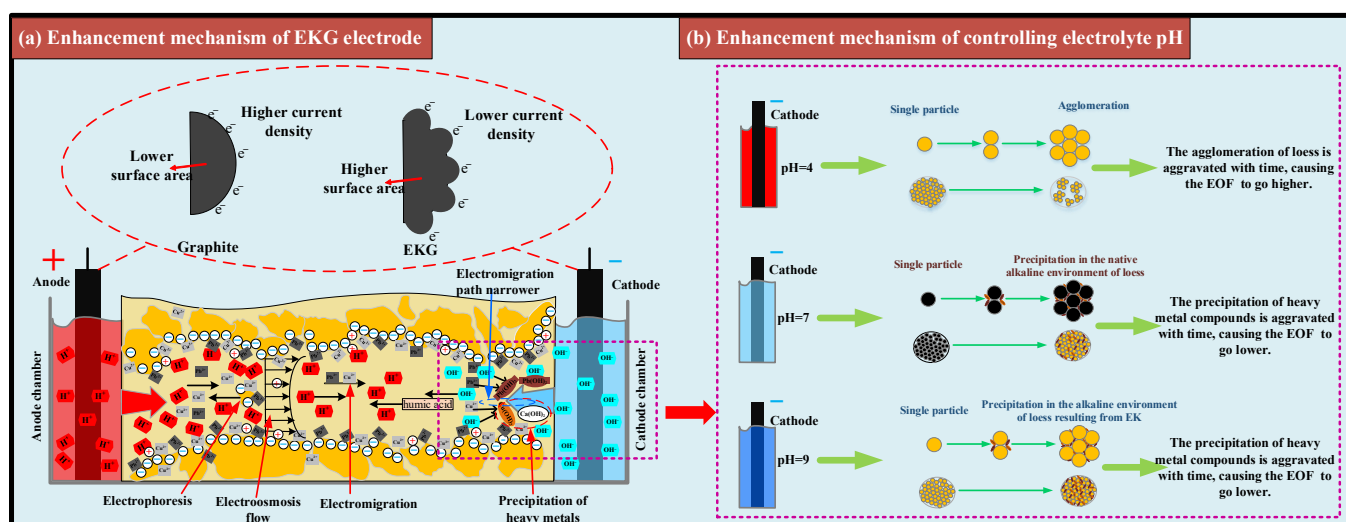


Figure 12. The main mechanisms for Cu and Pb removal in loess (modified from ref citation ([4]) © 2022 Hu, Cheng, Wen and Kang).

The relationship among current, EOF, and metal removal further indicates that the highest EOF does not necessarily correspond to the highest remediation efficiency. Electric current reflects ion migration and charge transfer in the EK system and is closely related to electromigration, whereas EOF represents the advective movement of pore water. For Cu and Pb, electromigration is particularly important because the mobile species are

mainly ionic under acidic or weakly acidic conditions. Therefore, an efficient EK process requires not only sufficient EOF to maintain pore-water transport, but also adequate current to sustain ionic migration. In the catholyte pH tests, pH 4 enhanced EOF by suppressing cathodic precipitation, but the lower current weakened the electromigration contribution. In contrast, pH 7 maintained a more favorable balance between current and EOF while reducing excessive precipitation, leading to the best overall soil-phase removal. This explains why pH 7 outperformed pH 4, even though the latter generated the highest EOF. Overall, the results demonstrate that the improvement of EK remediation in Cu- and Pb-contaminated loess depends on balancing transport enhancement against cathodic precipitation and polarization effects. Excessive electric field strength aggravates alkaline accumulation near the cathode, whereas the EKG electrode improves charge transfer and acid-front propagation but cannot fully suppress cathodic focusing. By comparison, regulating the catholyte to pH 7.0 appears to be the most effective strategy because it simultaneously weakens the focusing effect and preserves favorable electrokinetic transport conditions. For practical application, the EK treatment of Cu- and Pb-contaminated loess should be further enhanced by multi-stage or longer-duration operation, periodic polarity reversal, optimized electrode spacing, acid-buffered or chelating electrolytes, and permeable reactive barriers for capturing mobilized metals. In addition, EK remediation may be combined with stabilization/solidification or microbial mineralization to reduce residual metal mobility after partial removal. Such integrated strategies would be more suitable for meeting practical remediation targets in carbonate-rich loess than a single EK treatment alone.

4. Conclusions

This study investigated the coupled effects of electric field intensity, electrode material, and catholyte pH regulation on the EK treatment of Cu- and Pb-contaminated loess. The main conclusions are summarized as follows:

- (a) Electric field intensity controlled the balance between metal mobilization and cathodic precipitation. A stronger electric field promoted current response, EOF development, and acid-front propagation, thereby enhancing Cu and Pb migration, especially over longer transport distances. However, excessive field intensity also accelerated OH^- accumulation near the cathode and strengthened precipitation-induced focusing. Therefore, the effect of electric field intensity in loess was spatially dependent and governed by the competition between electrical driving force and cathodic immobilization.
- (b) EKG electrodes improved EK performance by reducing electrode polarization and enhancing coupled electromigration–electroosmosis transport. Compared with graphite electrodes, the larger electroactive surface area of EKG electrodes helped maintain higher current and stronger acid-front development, which promoted metal desorption and transport. Nevertheless, the improvement in Pb removal remained limited, mainly because Pb was more strongly retained by adsorption and carbonate-related precipitation in alkaline loess.
- (c) Catholyte pH regulation changed the balance among current-driven electromigration, EOF-driven pore-water transport, and precipitation control. Although pH 4 produced the highest EOF, its lower current limited the overall contribution of electromigration. In contrast, pH 9 intensified cathodic alkalization and secondary precipitation. Maintaining the catholyte at pH 7 provided a better compromise between current, EOF, and precipitation suppression, resulting in the most favorable soil-phase Cu and Pb removal among the tested pH conditions.

Overall, the results show that mitigating the focusing effect in carbonate-buffered loess requires coordinated regulation of electric field intensity, electrode architecture, and catholyte chemistry. However, the overall removal efficiencies remained modest, indicating that single-stage EK treatment is more suitable for revealing controlling mechanisms and guiding process optimization than for direct use as a standalone cleanup strategy. Future studies should combine full metal mass-balance monitoring, sequential extraction, post-treatment mechanical stability assessment, and further enhancement strategies such as longer-duration operation, polarity reversal, reactive barriers, or coupled stabilization technologies.

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References

1. Hu, W.L.; Cheng, W.C.; Wen, S.J.; Rahman, M.M. Effects of chemical contamination on microscale structural characteristics of intact loess and resultant macroscale mechanical properties. *Catena* **2021**, *203*, 105361. <https://doi.org/10.1016/j.catena.2021.105361>.
2. Mai X.R.; Tang J.; Tang J.X.; Zhu X.Y.; Yang Z.H.; Liu X.; Zhuang X.J.; Feng G.; Tang L. Research progress on the environmental risk assessment and remediation technologies of heavy metal pollution in agricultural soil. *Journal of Environmental Sciences* **2025**, *149*, 1–20.
3. Hu, W.L.; Cheng, W.C.; Wang, L.; Xue, Z.F. Micro-structural characteristics deterioration of intact loess under acid and saline solutions and resultant macro-mechanical properties. *Soil Tillage Res.* **2022**, *220*, 105382. <https://doi.org/10.1016/j.still.2022.105382>.
4. Hu, W.L.; Cheng, W.C.; Wen, S.J.; Kang, N.B. Revealing underlying mechanisms affecting electrokinetic remediation of an artificially Cu- and Pb-contaminated loess using the external regulatory system with adsorbent. *Front. Mater.* **2022**, *9*, 967871. <https://doi.org/10.3389/fmats.2022.967871>.
5. Xu, P.P.; Zhang, Q.Y.; Qian, H.; Li, M.N.; Yang, F.X. An investigation into the relationship between saturated permeability and microstructure of remolded loess: A case study from Chinese Loess Plateau. *Geoderma* **2021**, *382*, 114774. <https://doi.org/10.1016/j.geoderma.2020.114774>.
6. Xu, P.P.; Zhang, Q.Y.; Qian, H.; Hou, K. Investigation into microscopic mechanisms of anisotropic saturated permeability of undisturbed Q₂ loess. *Environ. Earth Sci.* **2020**, *79*, 412. <https://doi.org/10.1007/s12665-020-09152-7>.
7. Wang, L.Q.; Shao, S.J.; She, F.T. A new method for evaluating loess collapsibility and its application. *Eng. Geol.* **2020**, *264*, 105376. <https://doi.org/10.1016/j.enggeo.2019.105376>.
8. Cánovas, M.; Valenzuela, J.; Romero, L.; González, P. Characterization of electroosmotic drainage application to mine tailings and solid residues from leaching. *J. Mater. Res. Technol.* **2020**, *9*, 2960–2968. <https://doi.org/10.1016/j.jmrt.2020.01.046>.

9. Liu, K.H.; Guan, X.J.; Li, C.M.; Zhao, K.Y.; Yang, X.H.; Fu, R.X.; Li, Y.; Yu, F.M. Global perspectives and future research directions for the phytoremediation of heavy metal-contaminated soil: A knowledge mapping analysis from 2001 to 2020. *Front. Environ. Sci. Eng.* **2022**, *16*, 73. <https://doi.org/10.1007/s11783-021-1507-2>.
10. Liu, H.; Li, J.B.; Zhao, M.; Li, Y.B.; Chen, Y.M. Remediation of oil-based drill cuttings using low-temperature thermal desorption: Performance and kinetics modelling. *Chemosphere* **2019**, *235*, 1081–1088. <https://doi.org/10.1016/j.chemosphere.2019.07.047>.
11. Liu, T.; Yuan, X.X.; Zhang, G.; Hu, J.; An, J.; Chen, T. Stir bar sorptive extraction and automatic two-stage thermal desorption-gas chromatography-mass spectrometry for trace analysis of the byproducts from diphenyl carbonate synthesis. *Microchem. J.* **2020**, *153*, 104341. <https://doi.org/10.1016/j.microc.2019.104341>.
12. Wu, Y.J.; Santos, S.S.; Vestergård, M.; González, A.M.M.; Ma, L.Y.; Feng, Y.; Yang, X. A field study reveals links between hyper-accumulating *Sedum* plants-associated bacterial communities and Cd/Zn uptake and translocation. *Sci. Total Environ.* **2022**, *805*, 150400. <https://doi.org/10.1016/j.scitotenv.2021.150400>.
13. Ding, D.; Song, X.; Wei, C.; La, C.J. A review on the sustainability of thermal treatment for contaminated soils. *Environ. Pollut.* **2019**, *253*, 449–463. <https://doi.org/10.1016/j.envpol.2019.06.118>.
14. Du, Y.J.; Jin, F.; Liu, S.Y.; Chen, L.; Zhang, F. Review of stabilization/solidification technique for remediation of heavy metals contaminated lands. *Rock Soil Mech.* **2011**, *32*, 116–124. <https://doi.org/10.16285/j.rsm.2011.01.003>.
15. Zhou, H.D.; Liu, Z.Y.; Li, X.; Xu, J.H. Remediation of lead (II)-contaminated soil using electrokinetics assisted by permeable reactive barrier with different filling materials. *J. Hazard. Mater.* **2021**, *408*, 124885. <https://doi.org/10.1016/j.jhazmat.2020.124885>.
16. Kalantari, B.; Prasad, A. A study of the effect of various curing techniques on the strength of stabilized peat. *Transp. Geotech.* **2014**, *1*, 119–128. <https://doi.org/10.1016/j.trgeo.2014.06.002>.
17. Wang, F.; Shen, Z.T.; Liu, R.Q.; Zhang, Y.H.; Xu, J.; AL-Tabbaa, A. GMCs stabilized/solidified Pb/Zn contaminated soil under different curing temperature: Physical and microstructural properties. *Chemosphere* **2019**, *239*, 124738. <https://doi.org/10.1016/j.chemosphere.2019.124738>.
18. Muddanna, M.H.; Baral, S.S. A comparative study of the extraction of metals from the spent fluid catalytic cracking catalyst using chemical leaching and bioleaching by *Aspergillus niger*. *J. Environ. Chem. Eng.* **2019**, *7*, 103335. <https://doi.org/10.1016/j.jece.2019.103335>.
19. Lu, Y.S.; Wang, W.B.; Wang, Q.; Xu, J.; Wang, A.Q. Effect of oxalic acid-leaching levels on structure, color and physico-chemical features of palygorskite. *Appl. Clay Sci.* **2019**, *183*, 105301. <https://doi.org/10.1016/j.clay.2019.105301>.
20. Lu, C.; Hong, Y.; Liu, J.; Gao, Y.Z.; Ma, Z.; Yang, B.; Ling, W.T.; Waigi, M.G. A PAH-degrading bacterial community enriched with contaminated agricultural soil and its utility for microbial bioremediation. *Environ. Pollut.* **2019**, *251*, 773–782. <https://doi.org/10.1016/j.envpol.2019.05.044>.
21. Beyrami, H. Effect of different treatments on electrokinetic remediation of Zn, Pb and Cd from a contaminated calcareous soil. *Chin. J. Chem. Eng.* **2020**, *38*, 255–265. <https://doi.org/10.1016/j.cjche.2020.09.011>.
22. Cameselle, C. Enhancement of electro-Osmotic flow during the electrokinetic treatment of a contaminated soil. *Electrochim. Acta* **2015**, *181*, 31–38. <https://doi.org/10.1016/j.electacta.2015.02.191>.
23. Herron, J.F.; Kim, J.Y.; Upadhye, A.A. A general framework for the assessment of solar fuel technologies. *Energy Environ. Sci.* **2015**, *8*, 126–157. <https://doi.org/10.1039/c4ee01958j>.
24. Hassana, I.; Mohamedelhassanb, E.; Yanfula, E. Solar powered electrokinetic remediation of Cu polluted soil using a novel anode configuration. *Electrokinet. Acta* **2015**, *181*, 58–67. <https://doi.org/10.1016/j.electacta.2015.02.216>.
25. Jeon, E.K.; Jung, J.M.; Kim, W.S.; Ko, S.H.; Baek, K. In situ electrokinetic remediation of As-, Cu-, and Pb-contaminated paddy soil using hexagonal electrode configuration: A full scale study. *Environ. Sci. Pollut. Res.* **2015**, *22*, 711–720. <https://doi.org/10.1007/s11356-014-3363-0>.
26. Jeon, E.K.; Ryu, S.R.; Baek, K. Application of solar-cells in the electrokinetic remediation of As-contaminated soil. *Electrochim. Acta* **2015**, *181*, 160–166. <https://doi.org/10.1016/j.electacta.2015.03.065>.
27. Habibul, N.; Hu, Y.; Sheng, G.P. Microbial fuel cell driving electrokinetic remediation of toxic metal contaminated soils. *J. Hazard. Mater.* **2016**, *318*, 9–14. <https://doi.org/10.1016/j.jhazmat.2016.06.041>.
28. Habibul, N.; Hu, Y.; Wang, Y.K.; Chen, W.; Yu, H.Q.; Sheng, G.P. Bioelectrochemical chromium(VI) removal in plant-microbial fuel cells. *Environ. Sci. Technol.* **2016**, *50*, 3882–3889. <https://doi.org/10.1021/acs.est.5b06376>.
29. Yuan, L.Z.; Xu, X.J.; Li, H.Y.; Wang, Q.Y.; Wang, N.N.; Yu, H.W. The influence of macroelements on energy consumption during periodic power electrokinetic remediation of heavy metals contaminated black soil. *Electrochim. Acta* **2017**, *235*, 604–612. <https://doi.org/10.1016/j.electacta.2017.03.142>.

30. Abou-Shady, A.; Peng, C.S.; El-Araby, H.; Osman, M.A. Optimizing electrokinetic remediation for pollutant removal and electroosmosis/dewatering using lateral anode configurations. *Sci. Rep.* **2024**, *14*, 24851. <https://doi.org/10.1038/s41598-024-75060-6>.
31. Hamdi, F.M.; Ganbat, N.; Altaee, A.; Samal, A.K.; Ibrar, I.; Zhou, J.L.; Sharif, A.O. Hybrid and enhanced electrokinetic system for soil remediation from heavy metals and organic matter. *J. Environ. Sci.* **2025**, *147*, 424–450. <https://doi.org/10.1016/j.jes.2023.11.005>.
32. Naseer, U.; Du, Z.P.; Ahmad, A.; Ali, M.; Younis, A.; Yue, T.X. Advanced electrode materials in electrokinetic technology for remediation of heavy metal-contaminated soil: Recent progress and challenges. *Adv. Sustain. Syst.* **2025**, *9*, 2500197. <https://doi.org/10.1002/adsu.202500197>.
33. Yan, K.; Chai, Z.; Li, T.; Duan, B.; Xiao, C.; Liu, X.; Liu, X. Effect of voltage gradients on EK-PRB remediation: Experimental and molecular dynamics simulations. *Environ. Res.* **2024**, *252*, 119085. <https://doi.org/10.1016/j.envres.2024.119085>.
34. Yang, Z.; Tang, J.; Feng, H.; Liu, X.; Zhuang, X.; Wang, H.; Wu, Y.; Guo, Y.; Tang, L. Research progress on remediation of heavy metal contaminated soil by electrokinetic-permeable reactive barrier. *Chem. Eng. J.* **2024**, *490*, 151548. <https://doi.org/10.1016/j.cej.2024.151548>.
35. Zheng, X.J.; Li, Q.; Wang, Z.L.; Chen, M. Remediation of heavy metals contaminated soil by enhanced electrokinetic technology: A review. *Arab. J. Chem.* **2024**, *17*, 105773. <https://doi.org/10.1016/j.arabjc.2024.105773>.
36. Suzuki, T.; Kawai, K.; Moribe, M.; Niinae, M. Recovery of Cr as Cr(III) from Cr(VI)-contaminated kaolinite clay by electrokinetics coupled with a permeable reactive barrier. *J. Hazard. Mater.* **2014**, *278*, 297–303. <https://doi.org/10.1016/j.jhazmat.2014.05.086>.
37. Suzuki, T.; Niinae, M.; Koga, T.; Akita, T.; Ohta, M.; Choso, T. EDDS-enhanced electrokinetic remediation of heavy metal-contaminated clay soils under neutral pH conditions. *Colloids Surf. A Physicochem. Eng. Asp.* **2014**, *440*, 145–150. <https://doi.org/10.1016/j.colsurfa.2012.09.050>.
38. Yuan, L.Z.; Li, H.Y.; Xu, X.J.; Zhang, J.; Wang, N.N.; Yu, H.W. Electrokinetic remediation of heavy metals contaminated kaolin by a CNT-covered polyethylene terephthalate yarn cathode. *Electrochim. Acta* **2016**, *213*, 140–147. <https://doi.org/10.1016/j.electacta.2016.07.081>.
39. Wang, L.S.; Huang, L.H.; Xia, H.B.; Li, H.; Li, X.T.; Liu, X.W. Application of a multi-electrode system with polyaniline auxiliary electrodes for electrokinetic remediation of chromium-contaminated soil. *Sep. Purif. Technol.* **2019**, *224*, 106–112. <https://doi.org/10.1016/j.seppur.2019.05.019>.
40. Wang, Y.X.; Huang, L.H.; Wang, Z.X.; Wang, L.S.; Han, Y.F.; Liu, X.W.; Ma, T. Application of Polypyrrole flexible electrode for electrokinetic remediation of Cr(VI)-contaminated soil in a main-auxiliary electrode system. *Chem. Eng. J.* **2019**, *373*, 131–139.
41. Wu, J.N.; Zhang, J.; Xiao, C.Z. Focus on factors affecting pH, flow of Cr and transformation between Cr(VI) and Cr(III) in the soil with different electrolytes. *Electrochim. Acta* **2016**, *211*, 652–662. <https://doi.org/10.1016/j.electacta.2016.06.048>.
42. Fu, R.B.; Wen, D.D.; Xia, X.Q.; Zhang, W.; Gu, Y.Y. Electrokinetic remediation of chromium (Cr)-contaminated soil with citric acid (CA) and polyaspartic acid (PASP) as electrolytes. *Chem. Eng. J.* **2017**, *316*, 601–608. <https://doi.org/10.1016/j.cej.2017.01.092>.
43. Ryu, S.R.; Jeon, E.K.; Baek, K. A combination of reducing and chelating agents for electrolyte conditioning in electrokinetic remediation of As-contaminated soil. *J. Taiwan Inst. Chem. Eng.* **2017**, *70*, 252–259. <https://doi.org/10.1016/j.jtice.2016.10.058>.
44. Zhu, Z.Y.; Dennell, R.; Huang, W.W.; Wu, Y.; Rao, Z.G.; Qiu, S.F.; Xie, J.B.; Liu, W.; Fu, S.Q.; Han, J.W.; et al. New dating of the Homo erectus cranium from Lantian (Gongwangling), China. *J. Hum. Evol.* **2015**, *78*, 144–157. <https://doi.org/10.1016/j.jhevol.2014.10.001>.
45. GB/T 50123-2019; Standard for Geotechnical Test Methods. Ministry of Water Resources of the People's Republic of China: Beijing, China, 2019.
46. Liu, C.; Hu, W.; Zhu, X.; Zhang, S.; Wang, W. Removal of Cu and Pb in Contaminated Loess by Electrokinetic Remediation Using Novel Hydrogel Electrodes Coupled with Focusing Position Adjustment and Exchange Electrode. *Processes* **2025**, *13*, 2915. <https://doi.org/10.3390/pr13092915>.
47. Valenzuela, J.; Romero, L.; Acuña, C.; Cánovas, M. Electroosmotic drainage, a pilot application for extracting trapped apillary liquid in copper leaching. *Hydrometallurgy* **2016**, *163*, 148–155. <https://doi.org/10.1016/j.hydromet.2016.04.005>.
48. Hsueh, Y.S.; Cheng, X.; Dai, Y.D. Comparison of Cr/Ni removal by electrokinetic (EK) and electrochemical geooxidation (ECGO) processes: Remediation performance and economic analysis in an in-situ system. *J. Environ. Chem. Eng.* **2022**, *10*, 107018. <https://doi.org/10.1016/j.jece.2021.107018>.
49. Telepanich, A.; Marshall, T.; Gregori, S. Graphene-alginate fluids as unconventional electrodes for the electrokinetic remediation of Cr(VI). *Water Air Soil Pollut.* **2021**, *232*, 334. <https://doi.org/10.1007/s11270-021-05278-x>.

50. Behrouzinia, S.; Ahmadi, H.; Abbasi, N. Experimental investigation on a combination of soil electrokinetic consolidation and remediation of drained water using composite nanofiber-based electrodes. *Sci. Total Environ.* **2022**, *836*, 155562. <https://doi.org/10.1016/j.scitotenv.2022.155562>.
51. Torabi, M.S.; Asadollahfardi, G.; Rezaee, M. Electrokinetic removal of Cd and Cu from mine tailing: EDTA enhancement and voltage intensity effects. *J. Hazard. Toxic Radioact. Waste* **2021**, *25*, 05020007. [https://doi.org/10.1061/\(asce\)hz.2153-5515.0000579](https://doi.org/10.1061/(asce)hz.2153-5515.0000579).
52. Muazu, N.D.; Essa, M.H. Comparative performance evaluation of anodic materials for electro-kinetic removal of Lead (II) from contaminated clay soil. *Soil Sediment Contam.* **2020**, *29*, 69–95. <https://doi.org/10.1080/15320383.2019.1673698>.
53. Pedersen, K.B.; Reinardy, H.C.; Jensen, P.E. The influence of Magnafloc10 on the acidic, alkaline, and electrodialytic desorption of metals from mine tailings. *J. Environ. Manag.* **2018**, *224*, 130–139. <https://doi.org/10.1016/j.jenvman.2018.07.050>.
54. Millán, M.; Bucio Rodríguez, P.Y.; Lobato, J. Strategies for powering electrokinetic soil remediation: A way to optimize performance of the environmental technology. *J. Environ. Manag.* **2020**, *267*, 110665. <https://doi.org/10.1016/j.jenvman.2020.110665>.
55. Ouhadi, V.R.; Yong, R.N.; Shariatmadari, N. Impact of carbonate on the efficiency of heavy metal removal from kaolinite soil by the electrokinetic soil remediation method. *J. Hazard. Mater.* **2010**, *173*, 87–94. <https://doi.org/10.1016/j.jhazmat.2009.08.052>.
56. Caparrós, P.G.; Ozturk, M.; Gul, A.; Batool, T.S.; Anosheh, H.P.; Unal, B.T.I.; Altay, V.; Toderich, K.N. Halophytes have potential as heavy metal phytoremediators: A comprehensive review. *Environ. Exp. Bot.* **2022**, *193*, 104666. <https://doi.org/10.1016/j.enxepbot.2021.104666>.
57. He, T.; Xu, Z.J.; Wang, J.F.; Wang, F.P.; Zhou, X.F.; Wang, L.L.; Li, Q.S. Improving cadmium accumulation by *Solanum nigrum* L. via regulating rhizobacterial community and metabolic function with phosphate-solubilizing bacteria colonization. *Chemosphere* **2022**, *287*, 132209. <https://doi.org/10.1016/j.chemosphere.2021.132209>.
58. Zhou, R.; Liu, X.C.; Luo, L.; Zhou, Y.Y.; Wei, J.H.; Chen, A.W.; Tang, L.; Wu, H.P.; Deng, Y.C.; Zhang, F.F. Remediation of Cu, Pb, Zn and Cd-contaminated agricultural soil using a combined red mud and compost amendment. *Int. Biodeterior. Biodegrad.* **2017**, *118*, 73–81. <https://doi.org/10.1016/j.ibiod.2017.01.023>.
59. Garcia-Sanchez, M.; Kosnar, Z.; Mercl, F.; Aranda, E.; Tlustos, P. A comparative study to evaluate natural attenuation, myco-augmentation, phytoremediation, and microbial-assisted phytoremediation strategies for the bioremediation of an aged PAH-polluted soil. *Ecotoxicol. Environ. Saf.* **2018**, *147*, 165–174. <https://doi.org/10.1016/j.ecoenv.2017.08.012>.
60. Wang, Y.C.; Li, A.; Cui, C.W. Remediation of heavy metal-contaminated soils by electrokinetic technology: Mechanisms and applicability. *Chemosphere* **2021**, *265*, 129071. <https://doi.org/10.1016/j.chemosphere.2020.129071>.
61. Guzman, V.B.; Paz Garcia, J.M.; Rodriguez Maroto, J.M. Scaling up the acid enhanced electrokinetic remediation of a real contaminated soil. *Electrochim. Acta* **2015**, *181*, 139–145. <https://doi.org/10.1016/j.electacta.2015.02.067>.

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