University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 32 Number 11 November 2026



Eco-Friendly Zinc Extraction from Sandy Soils via Electrokinetics Assisted by Tartaric Acid and Agricultural Waste

Ali Omran Al-Sulttani [1,*], **Stella Robert Jameel** [2], **Laith Hamdan Hawal** [2], **Amimul Ahsan** [3,4]

[1]Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
[2]Environmental Engineering Department, Al-Mustansiriyah University, Baghdad, Iraq
[3]Department of Civil and Environmental Engineering, Islamic University of Technology, Gazipur, Bangladesh
[4]Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

ABSTRACT

The contamination of agricultural sandy soils by zinc (Zn) presents not only a risk for the quality of crops but also a problem for the quality of groundwater. Common enhancing agents used in electrokinetic remediation (EKR) of heavy metals, such as EDTA, present persistence in the environment. This work evaluates an EKR technique that involves a biodegradable chelating agent, tartaric acid, and a barrier of untreated rice husk installed in front of the cathode. The experimental design includes a sandy soil (93.4% sand) artificially contaminated with 300 mg/kg Zn and treated for 5 days under the voltage gradient of 1 V/cm. Besides three experiments without enhancement, where the purging solutions were tap water adjusted to pH 3, 7 and 11, there was one experiment with tartaric acid at pH 3 as the anolyte. All experiments were done once. The removal of Zn decreased from 77.8% at pH 3 to 69.7% at pH 7 and 53.2% at pH 11 due to the higher desorption and electromigration of Zn in acidic conditions and the precipitation of Zn as $Zn(OH)_2$ in neutral and alkaline conditions. In all experiments, the residual amount of Zn decreased along the direction from the anode to the cathode. The removal of Zn in the tartaric acid-enhanced experiment was the highest (90.8%), which corresponds to 13 percentage points more than in the experiment without enhancement at pH 3, with the residual amount of Zn being 15–43 mg/kg in the soil column. This fact is due to the formation of soluble Zn-tartrate complexes and buffering action of tartaric acid that maintained soil pH within 4.2–5.7. The amount of Zn retained in the rice husk barrier was up to 38 mg/kg. Therefore, the EKR enhanced by biodegradable tartaric acid can be considered a potentially useful technique for the remediation of Zn-contaminated sandy soils. Replicate tests, the cost evaluation, the effect of the technique on soil quality and quantification of the barrier contribution are needed.

Keywords: Electrokinetic remediation, Zinc removal, Sandy soil, Tartaric acid, Rice husks.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2026.11.10
This is an open access article under the CC BY 4 license (http://creativecommons.org/licenses/by/4.0/).
Article received: 27/07/2026
Article revised: 28/10/2026
Article accepted: 29/10/2026
Article published: 01/11/2026

1. INTRODUCTION

Soil contamination with heavy metals due to industrial practices, insufficient waste management, and misuse of agrochemicals poses a serious environmental problem across the globe **(Masindi and Muedi, 2018)**. Zinc (Zn) is a micronutrient, but its excess concentrations are toxic. This is usually caused by sewage sludge application, electroplating and mining wastes, and over-fertilization with Zn **(Park et al., 2011; Alloway, 2013)**. The excess concentration of Zn impairs the enzymatic activity and nutrient uptake, reduces crop productivity and could leach to the groundwater **(Nagajyoti et al., 2010; Hołtra and Zamorska-Wojdyła, 2020)**. Electrokinetic remediation (EKR) is an in-situ method that uses low-intensity direct current for contaminant removal through electromigration, electroosmosis, and electrophoresis, and water electrolysis creates an acidic front near the anode and an alkaline front near the cathode **(Acar and Alshawabkeh, 1993; Hansen et al., 2016; Reddy et al., 2019).** In sandy soil, high permeability and low cation exchange capacity provide good conditions for ions migration; however, the lack of buffer ability leads to precipitation of metal hydroxides near the cathode, which is the main drawback of the process **(Virkutyte et al., 2002; Yeung and Gu, 2011).**
Enhancement agents are used to ensure that metals remain soluble and mobile **(Rozas and Castellote, 2012; Jamshidi-Zanjani and Khodadadi Darban, 2017; Gomes and Bustos, 2021)**. While the man-made chelators like EDTA work efficiently, they are not readily biodegradable and can remain in the soil and groundwater **(Pan et al., 2024)**. Thus, there is a search for alternatives with high biodegradability. Reported removals of Zn include 95.05% by sodium alginate **(Wang et al., 2021)** and 63.9–94.5% by citric acid in soft clay **(Sun et al., 2023, 2024)**. Environmentally-friendly enhanced electrokinetic remediation (EKR) was used for contaminated with cobalt soil **(Hawal and Al-Sulttani, 2024)**. Tartaric acid, the naturally occurring hydroxy-dicarboxylic acid, forms soluble complexes with Zn^{2+} ions **(Wasay et al., 1998a; 1998b)** but has not been studied sufficiently as an EKR enhancer. Meanwhile, cheap lignocellulosic waste like rice husk can act as sorptive barriers **(Nguyen et al., 2013),** and sawdust was recently used to enhance EKR for mercury capture in sandy soil **(Jameel and Jawad, 2025).** Nevertheless, the majority of Zn-EKR studies were conducted on fine-grained soils. Enhancement agents and reactive barriers were also studied independently. The combination of tartaric acid with a rice husk barrier for Zn-contaminated sandy soil has rarely been examined. Thus, the goals of the current study are: (i) investigation of the impact of purging-solution pH (3, 7, and 11) on migration and removal of Zn, (ii) assessment of the contribution of tartaric acid and (iii) evaluation of rice husk barrier ability to capture Zn around the cathode.

2. MATERIALS AND METHODS

2.1 Soil Sample

A sample soil was collected from a farm area and classified as sandy soil. About 20 kg of bulk soil was collected using a stainless-steel auger to prevent metallic interference. After collection, the soil was spread on clean polyethylene sheets and air-dried for 48 hours to remove moisture and ensure good homogenization, and large organic materials (roots, leaves, stones, etc.) were removed manually. The dried soil was then passed through a 2 mm sieve to ensure uniform particle size. The size distribution of particles was analyzed based on **(ASTM D422-63, 2007)**, while the other physicochemical characteristics were tested using the techniques described in **Table 1**. These baseline properties are important in

determining the electrokinetic behavior of the soil during remediation, because ion migration, electroosmotic flow, and adsorption capacity are affected by particle size, porosity, cation exchange capacity, and organic content **(Virkutyte et al., 2002)**.

Table 1. Physical and chemical properties of the sandy soil and the standard methods used.

Property	Value	Standard / method
Sand (%)	93.37	**(ASTM D422-63, 2007)**
Silt (%)	3.24	**(ASTM D422-63, 2007)**
Clay (%)	3.39	**(ASTM D422-63, 2007)**
Texture classification	Sand	USDA textural triangle
Specific gravity (Gs)	2.65	**(ASTM D854, 2014)**
Organic matter content (%)	0.06	**(ASTM D2974, 2014)**
Initial pH	7.2	ASTM D4972-19 (1:2.5 soil–water)
Cation exchange capacity (meq/100 g)	3.1	**(USEPA, 1986)** Method 9081
Porosity, n (%)	39.4	Calculated from Gs and dry density

2.2 Rice Husks (RH)

The rice husks used in this study were collected from a local rice processing plant. The husks were washed using distilled water to remove dust and other contaminants, dried under solar irradiation for 48 hours, and then milled to particle sizes ranging from 1–2 mm. The husks did not undergo any chemical pre-treatment but were used as raw rice husks. Raw rice husks can be able to absorb metal ions through the hydroxyl and carboxyl groups that are present in the lignocellulosic matrix of the rice husks and also the silanol groups in biogenic silica **(Ahmaruzzaman and Gupta, 2011; Nguyen et al., 2013).** For raw rice husk, **(Zhang et al., 2013)** obtained a maximum adsorption capacity of zinc of 12.41 mg/g.

2.3 Zinc Contaminant

The solution simulating zinc contamination consisted of 5.7926 g of zinc nitrate [$Zn(NO_3)_2$] having a molecular weight of 189.36 g/mol. Dissolved in 1000 ml of deionized water, the concentration of zinc turned out to be 2000 mg/L. Then the calculated volume of this solution was added to 5 kg of dry soil, and thus a contamination rate of 300 mg/kg was obtained **(Cameselle et al., 2020).** The selection of this concentration is based on the upper limit for zinc in agricultural soils set by the EU Sewage Sludge Directive 86/278/EEC (150-300 mg/kg **(Yunta et al., 2024)**, and therefore, it is the concentration of the soil at the remediation threshold.

2.4 Tartaric Acid

Tartaric acid ($C_4H_6O_6$) was employed as a biodegradable chelating enhancing agent since it was known for its excellent chelation capacity of divalent metal ions like Zn^{2+}. With the help of the functional groups – COO^- and – OH, tartaric acid can easily complex with metal ions and form water-soluble metal-ligand complexes that improve the mobility of zinc ions in the soil under electrokinetic treatment **(Cameselle et al., 2021; Ge et al., 2022).** A 5 M stock solution of tartaric acid was made by dissolving 750 g of tartaric acid (MM = 150.09 g/mol) in deionized water and diluting to a volume of 1000 mL. A 0.1 M working solution was

prepared by diluting the stock solution with deionized water. In EX-4, the working solution was slowly added to the tap water in the anode chamber until the anolyte pH became 3, without adding any HCl in this experiment. The amount of the working solution added was not measured; however, based on the dissociation constants of tartaric acid, the concentration of tartaric acid at pH = 3 is around 2 mM.

3. ELECTROKINETIC TEST SETUP

Three-dimensional schematic representation of the electrokinetic cell employed in the present investigation is presented in **Fig. 1**. Dimensions of the glass cell were 60 cm length, 15 cm width, and 15 cm height. Soil chamber was packed with 30 cm long soil sample **(Al-Hamdan and Reddy, 2005)**. A rice husk barrier (15 cm high and 6 cm thick), consisting of approximately 220 g of untreated rice husk packed in a fine cotton cloth (cheesecloth) bag, was placed between the soil and the cathode chamber.
Dimension of each electrode chamber was 12 cm x 15 cm x 15 cm and there existed a valve located 10 cm above its bottom for regulating fluid flow. Graphite electrodes were cylindrical in shape (10 cm height and 6 cm diameter) with perforations in the top end for the electrical contact. Perforated plastic sheets (15 cm x 15 cm) were used to separate the rice husk separator from both soil and cathode chambers. Plastic sheet contained circular holes of 7 mm diameter at 1 cm interval and there was a placement of Whatman Grade 40 filter paper in the front surface of each sheet. DC source (LDESTAR, LP 3005D) of constant voltage was used for energizing the electrodes and electric current through the soil was measured with a multimeter.

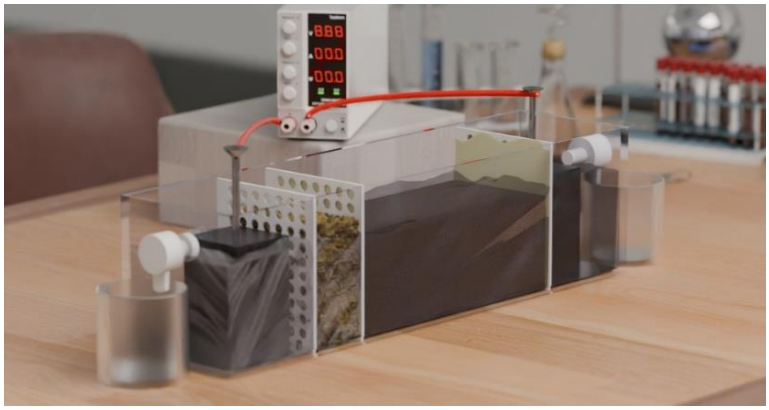


Figure 1. 3D schematic diagram of the electrokinetic remediation cell.

4. EXPERIMENTAL WORK

Prior to the testing, the electrokinetic cell was washed with distilled water, and filter papers were placed between the soil chamber and the electrode chambers. After that, the polluted soil was introduced to the soil chamber up to the designed height, leveled, and compacted by means of a special tool; then, it was left untouched for 24 hours before the beginning of the tests **(Hawal and Al-Sulttani, 2024).** During the course of experiments, the level of the solution in both electrode chambers was maintained the same in order to exclude any hydraulic gradient in the soil. The electrodes were introduced into the electrode chambers and connected to a constant voltage source, supplying a voltage gradient of 1 V/cm **(Reddy**

and Chinthamreddy, 2003). The electrolyte, with the exception of the enhanced test, was ordinary tap water. Four types of electrokinetic tests were carried out to evaluate the influence of pH and the addition of tartaric acid on the effectiveness of zinc extraction. In the case of EX-1, EX-2, and EX-3, tap water with pH of 3, 7, and 11, correspondingly, was used as the purging solution. The electrical conductivity of these solutions was between 565 and 620 μS/cm. In the test of EX-4, tartaric acid solution was used as the anolyte in order to observe the effect of tartaric acid on the process of mobilization and removal of zinc. All the other parameters, such as the initial concentration of zinc (300 mg/kg), voltage, soil, and duration of the treatment, remained the same in all four experiments. The purging solutions for EX-1, EX-2 and EX-3 were prepared by adjusting tap water to pH 3, 7 or 11 by adding 1 M HCl or NaOH solution, as required. During the tests, water electrolysis made the anolyte increasingly acidic and the catholyte increasingly alkaline; therefore, the pH and EC of both electrolytes were monitored throughout the 5-day period, and HCl or NaOH was added as needed to return each electrolyte to its target pH **(Faisal et al., 2022)**. In EX-4, the anolyte was acidified with tartaric acid instead of HCl (Section 2.4) **(Faisal et al., 2022)**. After completion of each test, the soil specimen was separated into five equal parts along the length of the cell. The soil samples from each part were extracted in polyethylene containers marked for further zinc determination via AAS. Besides that, the rice husk barrier was also removed and analyzed for adsorption of zinc. To measure the pH and EC of the soil after treatment, 5 grams of each sample were added to 12.5 mL of deionized water (soil-to-water ratio is 1:2.5); then, the soil-water mixture was thoroughly stirred and left untouched for 1 hour; after that, the pH and EC were measured **(ASTM D4972-19, 2019).** Due to the long duration (5 days) of each test and the large size of the cell, each electrokinetic test was carried out only once. Since each test was done only once, the results are provided in a descriptive form. For each test, the efficiency of removal was estimated based on the average residual concentration of Zn in the five soil samples, while SD of these samples was used to estimate the spatial variability of Zn in the soil sample column. No inferential statistics were applied to compare the tests. Operational conditions of the tests are described in **Table 2** below.

Table 2. Operational conditions for each experiment.

EX. No.	Zinc Concentration (mg/kg)	Tartaric Acid	Rice Husk	Voltage (V/cm)	pH of Solution	Objective of the Experiment
EX-1	300	No	Yes	1	3	Baseline/Acidic
EX-2	300	No	Yes	1	7	Baseline/Neutral
EX-3	300	No	Yes	1	11	Baseline/Alkaline
EX-4	300	Yes	Yes	1	3	Effect of Tartaric Acid

5. ANALYTICAL METHODOLOGY

Soil samples were digested using an adapted acid digestion procedure that was based on USEPA Method 3050B (USEPA, 1996). Contrary to Method 3050B that employs HNO_3, H_2O_2 and HCl, digestion was conducted using a combination of concentrated acids of nitric, perchloric and hydrochloric acids in a ratio of 5:1:3, as proposed by **(Fabunmi et al., 2014).** The method involved adding 5 mL of the acid solution into 1 g of dried soil samples that was left overnight. The sample was then heated to near dryness on a hot plate and left to cool down. After that, deionized water was added to the samples and filtered to obtain a digest which was made up to a final volume of 25 mL. Determination of zinc was done using flame

atomic absorption spectrometry (AAS; Shimadzu AA-7000, Japan) using the wavelength 213.9 nm using calibration standards made from Zn stock solution. Analytical quality-control data (procedural blanks, replicate measurements and spike recoveries) were not available from the original laboratory records; this is acknowledged as a limitation of the analytical data.

6. RESULTS AND DISCUSSION

6.1. Influence of pH on Zinc Removal Efficiency

As for Zn removal efficiency, the influence of the purging solution pH is obvious **(Fig. 2).** Five days after electrolysis began, Zn removal was 77.8% in EX-1 (pH 3), 69.7% in EX-2 (pH 7) and 53.2% in EX-3 (pH 11), i.e., with an increase in pH, removal becomes less efficient **(Han et al., 2021; Ge et al., 2022).** In each of the three tested scenarios, residual Zn concentrations in the soil drop monotonically from the anode side toward the cathode side: from 98 to 35 mg/kg in EX-1, from 114 to 60 mg/kg in EX-2, from 171 to 110 mg/kg in EX-3 (X/L = 0.1 to 0.9), at all points following the order EX-1 < EX-2 < EX-3. Considering the low cation exchange capacity (CEC) (3.1 meq/100 g) and negligible amounts of organic matter (0.06%) **(Table 1)** in this soil, Zn is retained mainly by cation exchange and surface complexation on the limited clay and oxide surfaces. With low pH levels, hydrogen ions compete for available ion-exchange sites, resulting in Zn desorption in form of free Zn ions that can further undergo transport toward the cathode through electromigration **(Acar and Alshawabkeh, 1993; Virkutyte et al., 2002)**.

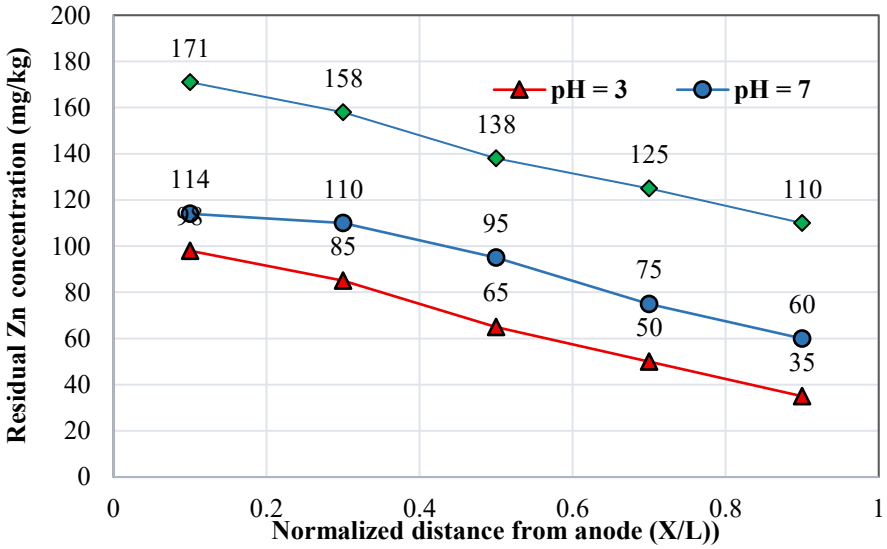


Figure 2. Residual zinc concentration under different pH values.

At neutral and alkaline pH values, the hydrolysis of Zn^{2+} takes place ($ZnOH^{+}$), and the formation of zinc hydroxide ($Zn(OH)_2$) begins, thus removing Zn from the mobile phase **(Reddy and Chinthamreddy, 2003; Faisal et al., 2022).** The decreasing concentrations of Zn in soil from the anode toward the cathode mean Zn transport to the cathode region and leaving Zn from the soil at the cathode side while slowest Zn removal occurred in the anode region. There are two reasons explaining this trend: first, Zn desorbed near the anode must migrate through the whole soil column before it leaves the soil, whereas Zn near the cathode needs to travel only a short distance. Furthermore, residual concentration of Zn also includes

the portion of Zn that has not yet left the soil but dissolved in the pore solution. Second, EC was highest near the anode **(Fig. 4)**; since the same current passes through every cross-section of the column, the local electric field, and therefore the electromigration velocity of Zn^{2+}, is lowest in the anode region **(Acar and Alshawabkeh, 1993; Virkutyte et al., 2002).** In EX-3, alkaline purging solution (pH 11, regulated by addition of NaOH) neutralizes the acidity at the anode side produced by hydrogen ions, thus no acid front enters the soil from the anode and the pH in this area remains near 7.1 **(Fig. 3);** hence, Zn desorption does not occur but its partial precipitation as $Zn(OH)_2$ took place, which results in the highest residual concentration in this scenario (171 mg/kg) **(Yeung and Gu, 2011).**

The obtained pH profiles **(Fig. 3)** correlate well with electrolysis reactions occurring at the electrode. Water electrolysis reactions at the anode ($2H_2O \rightarrow O_2 + 4H^+ + 4e^-$) and the cathode ($2H_2O + 2e^- \rightarrow H_2 + 2OH^-$) lead to the formation of H^+ and OH^- ions **(Acar and Alshawabkeh, 1993)**.

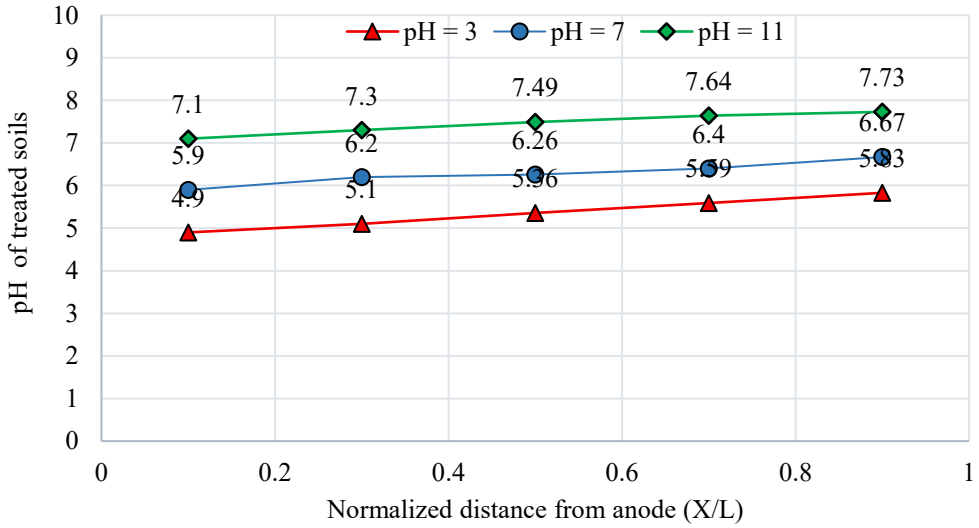


Figure 3. Soil pH distribution in soil profiles under different pH values.

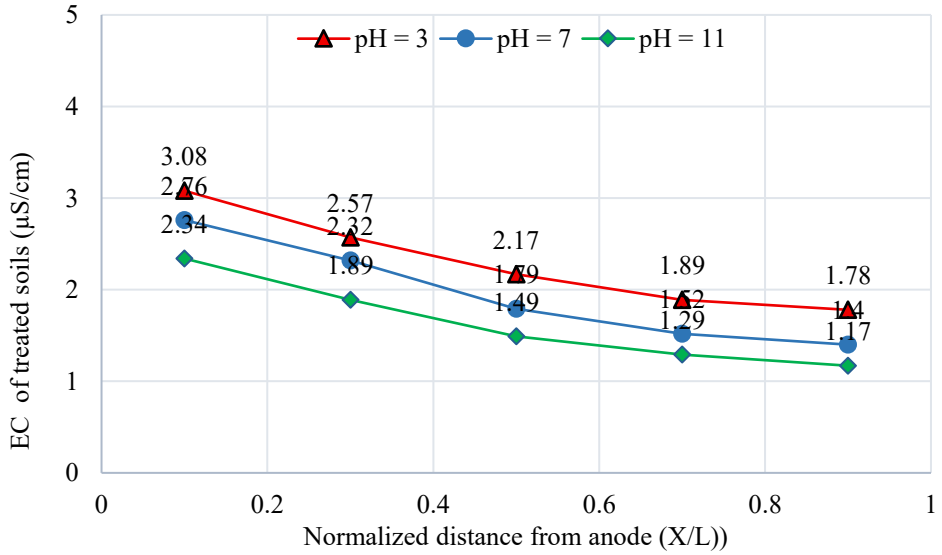


Figure 4. EC distribution in soil profiles under different pH values.

In the case of uncontrolled electrolysis reactions, due to the higher ionic mobility of H^+ compared with OH^- (about 1.8 times higher) the acid front would progress from the anode side across most of the soil, while the basic front is formed near the cathode. However, in this research the pH value of the electrolyte was maintained at a target level due to additional additions of HCl and NaOH. This resulted in neutralization of the produced H^+ and OH^- ions in great quantity, thus neither strongly acidic nor strongly alkaline zones are formed. Therefore, the soil pH in all scenarios rises slowly from the anode to the cathode region: from 4.9 to 5.83 in EX-1, from 5.9 to 6.67 in EX-2 and from 7.1 to 7.73 in EX-3. The overall pH level of each profile followed the order of the purging-solution pH, indicating that the purging solution, rather than electrolysis alone, controlled the soil pH. Hence, the lower Zn removal efficiency in the EX-2 and EX-3 cases is caused by the near-neutral and alkaline conditions (pH 5.9 – 7.73) favoring Zn sorption, hydrolysis and precipitation **(Faisal et al., 2022; Hawal and Al-Sulttani, 2024; Bokde et al., 2025).**

According to the graphs **(Fig. 4),** the EC values in all three samples without enhancement decreased from the anode to the cathode and varied from 3.08 to 1.78 µS/cm in EX-1, from 2.76 to 1.40 µS/cm in EX-2 and from 2.34 to 1.17 µS/cm in EX-3. There were two reasons for that trend: 1) anions (NO_3^-, which is added with the contaminant, and Cl^-, which is added with HCl for pH correction) migrated to the anode and accumulated there; 2) the low pH near the anode **(Fig. 3)** prevented ion precipitation, while high pH near the cathode caused sorption and precipitation of Zn and other ions. At every position, EC followed the order EX-1 > EX-2 > EX-3, i.e. it decreased as the soil pH increased, in agreement with the order of removal efficiency. This once again confirms that the amount of Zn remained in solution was the key factor determining the removal **(Virkutyte et al., 2002).**

6.2 Effect of Tartaric Acid as an Enhancer

Incorporating tartaric acid into the anolyte (EX-4) yielded the highest removal efficiency, 90.8%, which is 13 percentage points higher than that of the control treatment at identical purging-solution pH (EX-1, 77.8%). The residual Zn levels dropped from 43 mg/kg at the anode to 15 mg/kg at the cathode **(Fig. 5),** in the same order as in the other treatments, but at the markedly lower levels, whereas the soil pH increased from 4.2 at the anode to 5.66 at the cathode, keeping the entire profile acidic **(Fig. 6).** As the experiment was conducted only once, the result needs to be verified via replicated tests.

This improvement could be due to the following three mutually connected mechanisms. (i) Proton supply and pH buffering: the tartaric acid is a diprotic acid ($pKa_1 = 2.98$, $pKa_2 = 4.34$). Being supplied to the soil, the acid releases protons that desorb Zn from exchange and surface sites, whereas the buffer $H_2T/HT^-/T^{2-}$ system regulates the soil pore solution acidity around its pKa and neutralizes OH^- arriving from the cathode side, thus maintaining the entire profile acidity below the value when the precipitation of $Zn(OH)_2$ occurs. (ii) Complexation: within the investigated pH range (4.2–5.66), tartrate is predominantly presented as HT^- and T^{2-} that complex with Zn^{2+} via their carboxyl and α-hydroxyl groups forming soluble Zn-tartrate complexes **(Wasay et al., 1998a; Cameselle et al., 2021).** The complexation lowers the activity of free Zn^{2+} and prevents its adsorption onto soil surfaces and precipitation and keeps it dissolved in the form of the complex, enabling its migration both as the free ion by electromigration and as the complexed form by electroosmosis. (iii) Increase in the ionic strength: the dissociation of tartaric acid and dissolved Zn raises the ionic strength of the pore fluid, evidenced by its electrical conductivity values of 6.9 µS/cm at the anode and 5.9 µS/cm at the cathode **(Fig. 7),** 2–3 times higher than those for EX-1. The

increase in conductivity lowers the soil electrical resistance, enabling the larger current and, consequently, higher electromigration flux at identical voltage gradient **(Virkutyte et al., 2002).**

As tartaric acid is the natural biodegradable organic acid, it is expected to have a lower environmental impact compared to the persistent synthetic chelators like EDTA **(Pan et al., 2024).** However, the effects of tartaric acid on soil fertility and vegetation and fates of the remaining tartrate in the treated soils were not assessed during the present study and require further research.

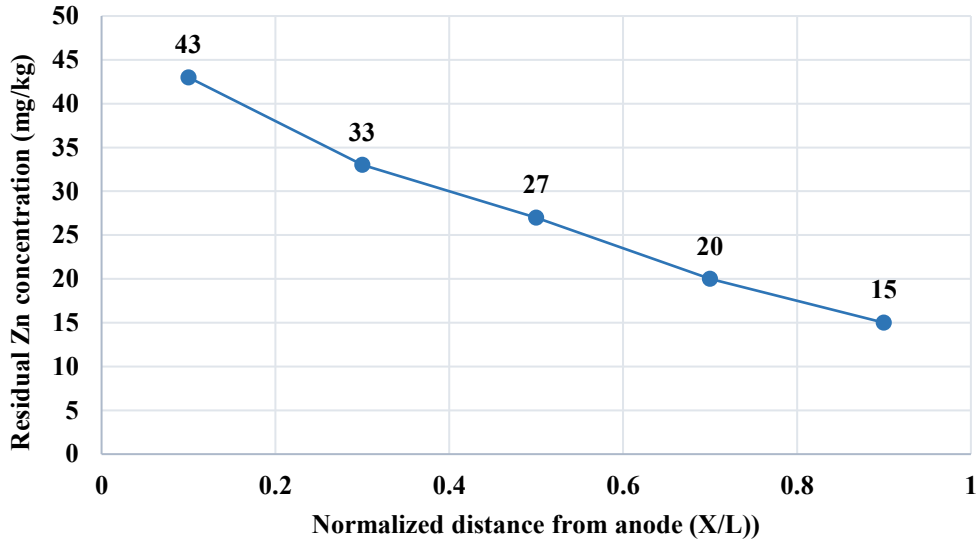


Figure 5. Residual zinc concentration (mg/kg) after enhancement conditions.

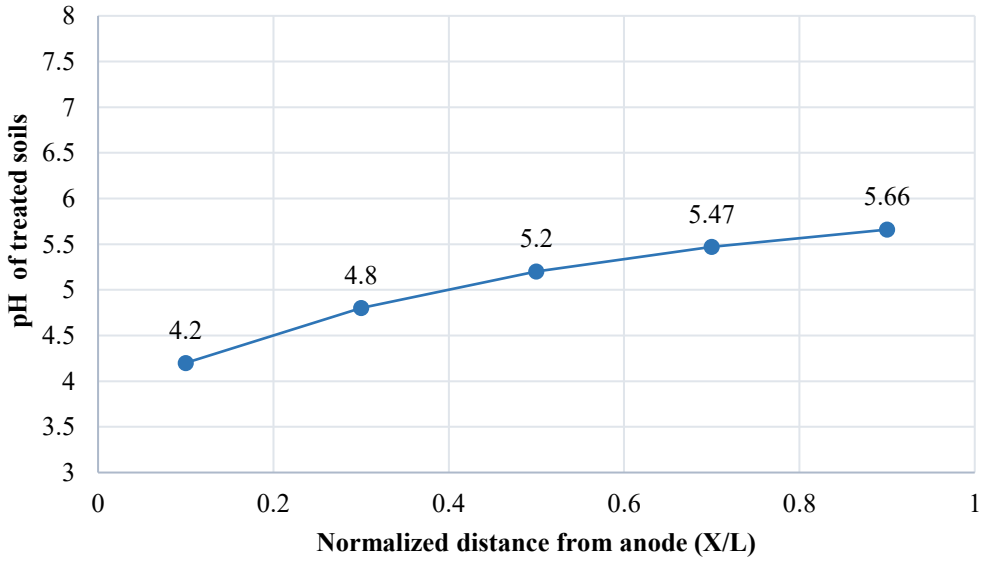


Figure 6. Soil pH distribution in the soil profile after enhancement conditions.

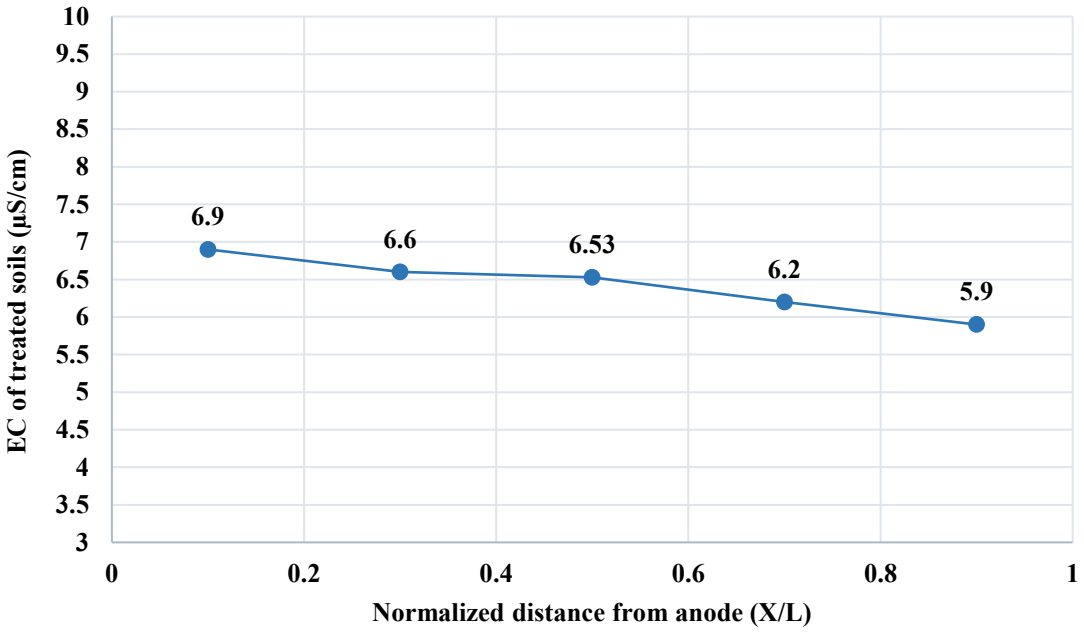


Figure 7. EC Distribution in the soil profile after enhancement conditions.

6.3 Zinc Adsorption by Rice Husks

The rice husk barrier acted as a physical partition separating the soil and the cathode chamber and as a sorbent for the Zn arriving at the cathode side. In all experiments, Zn was detected in the barrier, with a maximum concentration of 38 mg/kg. Given a barrier mass of approximately 220 g, this corresponds to at most about 8.4 mg of Zn retained in the barrier. Sorption sites of rice husk include hydroxyl and carboxyl groups of its lignocellulosic matrix and silanol groups of its biogenic silica **(Ahmaruzzaman and Gupta, 2011; Li et al., 2026)**. Zn^{2+} can be bound to these groups by ion exchange and surface complexation. Such processes are strongly dependent on the pH value: at an acidic pH value, the protonation of functional groups and competition with H^+ ions decrease the capacity of Zn sorption, while zinc bound in tartrate complexes is less available for sorption than Zn^{2+} ions. It can thus explain the low value of measured retention (38 mg/kg, i.e. 0.038 mg/g) compared with the maximum capacity of untreated rice husk reported in batch experiments (12.41 mg/g) **(Zhang et al., 2013)**. Since Zn was not measured in the catholyte and no mass balance was made in this experiment, the role of the barrier in the reduction of Zn transfer to the catholyte cannot be estimated in this study. The current results therefore provide only evidence that some amount of the mobilized Zn was retained by the barrier, and the main part of Zn removal is connected with its transport from the soil. The effect of the barrier on the catholyte needs further investigation including the measurement of Zn in the electrolytes and barrier.

7. EFFICIENCY OF ZINC REMOVAL

The percentage of zinc removed in each experiment was calculated using the formula **(Brahmi et al., 2015):**

$$\eta\ (\%) = \frac{Ci - Cr}{Ci} \times 100\% \quad (1)$$

Where:

- C_i is the initial zinc concentration (mg/kg),
- C_r is the final residual concentration (mg/kg).

As shown in **Fig. 8**, acidic conditions (pH 3) gave higher Zn removal than neutral and alkaline conditions, and the highest removal (90.8%) was obtained in EX-4, where tartaric acid was used as the anolyte at pH 3. These results show the strong influence of pH and of a biodegradable organic mobilizing agent on Zn mobility and removal from the soil.

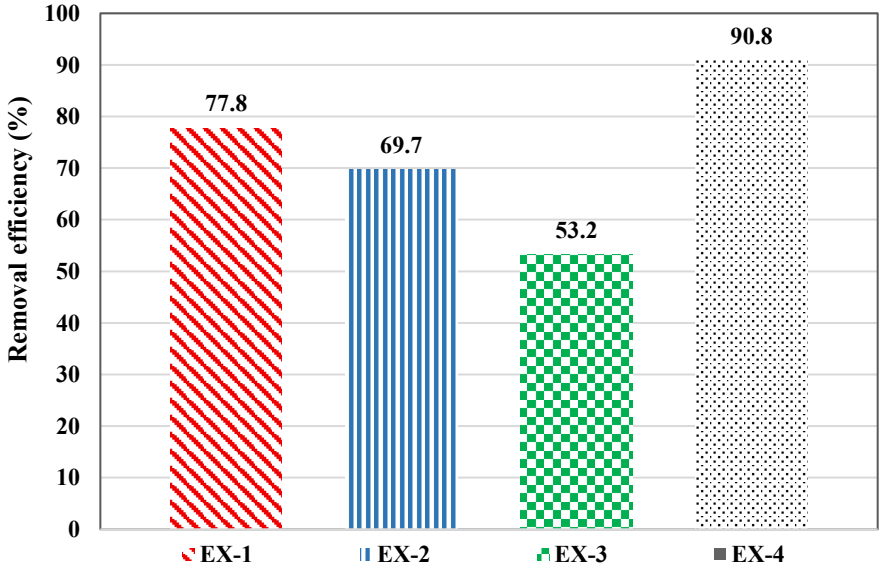


Figure 8. Removal efficiency for each experiment.

Table 3 shows the residual Zn concentrations of the five soil columns of each experiment. The average residual concentrations were 66.6 ± 25.5, 90.8 ± 23.0, 140.4 ± 24.6 and 27.6 ± 11.0 mg/kg for EX-1, EX-2, EX-3 and EX-4, respectively (average ± standard deviation of the five soil columns). The standard deviation is an indicator of the variation of Zn concentrations along the soil column in each experiment, and it is smallest in EX-4, which demonstrates a uniform removal of Zn along the soil column in the case of tartaric acid addition.

Table 3. Residual Zn concentrations in the five soil sections of each test (mean ± SD of five sections from a single test).

Test	Purging solution / anolyte	Mean residual Zn ± SD (mg/kg)	Range along the column (mg/kg)	Removal efficiency (%)
EX-1	Tap water, pH 3	66.6 ± 25.5	35–98	77.8
EX-2	Tap water, pH 7	90.8 ± 23.0	60–114	69.7
EX-3	Tap water, pH 11	140.4 ± 24.6	110–171	53.2
EX-4	Tartaric acid, pH 3	27.6 ± 11.0	15–43	90.8

7.1 Comparison with Previous Studies

Table 4 provides a comparison between the efficiency of zinc (Zn) removal in the present study and those obtained from various studies on electrokinetic remediation (EKR) process. The efficiency of Zn removal obtained in the experiment without any enhancement (77.8%) lies within the reported range of citric acid enhanced EKR treatment of Zn contaminated soft clay (63.9 – 83.5%), **(Sun et al., 2024)**. However, the efficiency of Zn removal using tartaric acid (90.8%) is very close to the maximum value reported for other biodegradable enhancers, such as citric acid 94.5%, **(Sun et al., 2023)** and sodium alginate 95.05%, **(Wang et al., 2021)**, and much higher than that of EDTA 38.2%, **(Sun et al., 2023)**. Due to the differences in the type of soil, the initial Zn concentration, applied voltage and duration of the treatments, the results cannot be directly compared to each other. Nevertheless, it can be concluded that the same efficiency of Zn removal can be reached in a 5-day period in the sandy soil using the proposed method.

Table 4. Comparison of Zn removal efficiency with recent electrokinetic studies.

Reference	Soil type	Enhancing agent / configuration	Initial Zn (mg/kg)	Zn removal (%)
(Sun et al., 2023)	Soft clay	0.2 M citric acid (anolyte and catholyte)	≈3175	94.5
(Sun et al., 2023)	Soft clay	EDTA	≈3175	38.2
(Sun et al., 2024)	Soft clay	Citric acid (0.2–1.0 M)	500–1000	63.9–83.5
(Wang et al., 2021)	Contaminated soil	Sodium alginate (2 wt%)	–	95.05
This study (EX-1)	Sandy soil	Tap water, pH 3 + rice husk barrier	300	77.8
This study (EX-4)	Sandy soil	Tartaric acid, pH 3 + rice husk barrier	300	90.8

7.2 Limitations and Field-Scale Applicability

Several issues are associated with the current study. Each test was performed only once; therefore, the results are presented descriptively, and the SD of the five soil sections represents spatial variability rather than experimental reproducibility. The tests were carried out under laboratory conditions using artificial soil of sand composition with a single Zn concentration (300 mg/kg) and a short incubation period (5 days). The mobility of Zn in real-life contaminated soils might have aged and been partially bound to carbonates, oxides, and organic matter, along with other metals that would compete with the enhancing agent. Therefore, the removal efficiencies observed in this study cannot be directly translated to soils containing larger amounts of clay, carbonate, or organic matter. To use the technique at a field scale, certain factors need to be taken into account: the configuration and spacing of electrodes, energy usage, soil heterogeneity, electrolyte pH control, consumption of tartaric acid, and recycling of used rice husks with Zn content. Future studies should include replicate tests and different soils and Zn concentrations, field-contaminated and multi-metal soils, and longer treatment times.

8. CONCLUSIONS

The effectiveness of electrokinetic remediation (EKR) of zinc contaminated sandy soil (300 mg/kg) using tartaric acid, a degradable chelating agent, combined with an untreated rice husk barrier placed in front of the cathode, was tested. EKR treatments were carried out for

5 days with 1 V/cm of voltage gradient and tap water (pH 3, 7, 11) as the purging solution and tartaric acid (pH 3) as the anolyte in a one-time test for each condition. The main outcomes of the research are described as follows: 1. The purging solution pH determined the level of Zn removal, which varied from 77.8% (pH 3) to 69.7% (pH 7) and 53.2% (pH 11), due to the precipitation of $Zn(OH)_2$ and a low rate of desorption with higher pH of the medium. With any treatment regime, residual amounts of zinc decreased with the distance from the anode to the cathode. 2. Tartaric acid increased Zn removal to 90.8%, 13 percentage points higher than in the control test with the same purging solution pH due to the formation of soluble complex of Zn-tartrate and soil pH stabilization at 4.2–5.7. 3. The amount of zinc retained in the rice husk barrier reached 38 mg/kg (at most about 8.4 mg of Zn); its impact on Zn transfer to the catholyte was not assessed. There were the following limitations in the test: single laboratory-scale tests were made under fixed conditions for one soil type, spiked contamination of soil with one metal (zinc), voltage gradient and treatment time. For future research, replicates of laboratory tests and measurements, field-contaminated and multi-metal polluted soils, measurement of zinc concentration in electrolytes for making a mass balance, evaluation of the cost and impacts of tartaric acid on the soil quality should be considered.

Acknowledgments

We express our sincere thanks and gratitude to the College of Engineering, University of Baghdad, and the Environmental Engineering Department, Al-Mustansiriyah University, for their support.

Credit authorship contribution statement

Ali Omran Al-Sulttani: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - original draft; and Writing - review and editing. Stella Robert Jameel: Resources; Funding acquisition; Software; Roles/Writing - original draft; and Writing - review and editing; Supervision; Validation; Methodology. Laith Hamdan Hawal: Resources; Funding acquisition; Software; Roles/Writing - original draft; and Writing - review and editing; Supervision; Validation; Methodology. Amimul Ahsan: Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Visualization; Writing - review and editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Acar, Y. B., and Alshawabkeh, A. N., 1993. Principles of electrokinetic remediation. *Environmental science and technology*, 27(13), pp. 2638-2647. https://doi.org/10.1021/es00049a002

Ahmaruzzaman, M., and Gupta, V. K., 2011. Rice husk and its ash as low-cost adsorbents in water and wastewater treatment. *Industrial and Engineering Chemistry Research*, 50(24), pp. 13589–13613. https://doi.org/10.1021/ie201477c

Al-Hamdan, A. Z., and Reddy, K. R., 2005. Surface speciation modeling of heavy metals in kaolin: Implications for electrokinetic soil remediation processes. *Adsorption*, 11(5), pp. 529-546. https://doi.org/10.1007/s10450-005-5611-6

Alloway, B. J., 2013. Trace metals and metalloids in soils and their bioavailability. *Heavy Metals in Soils*, 22, pp. 4-18. https://doi.org/10.1007/978-94-007-4470-7

ASTM D422-63, 2007. Standard test method for particle-size analysis of soils. Annual Book of ASTM Standards.

ASTM D1125-14, 2014. Standard test methods for electrical conductivity and resistivity of water. *Annual Book of ASTM Standards*. ASTM International, West Conshohocken, PA.

ASTM D2974-14, 2014. Standard test methods for moisture, ash, and organic matter of peat and other organic soils. *Annual Book of ASTM Standards*. ASTM International, West Conshohocken, PA.

ASTM D4972-19, 2019. Standard test methods for pH of soils. *Annual Book of ASTM Standards*. ASTM International, West Conshohocken, PA.

Bokde, A. A., Subash, A., Gholap, V., and Kandasubramanian, B., 2025. Electrokinetic soil-water remediation: a comprehensive exploration. *Separation and Purification Reviews*, pp. 1-22. https://doi.org/10.1080/15422119.2025.2537073

Brahmi, K., Bouguerra, W., Hamrouni, B., and Loungou, M., 2015. Removal of zinc ions from synthetic and industrial Tunisian wastewater by electrocoagulation using aluminum electrodes. *Desalination and Water Treatment,* 56(10), pp. 2689-2698. https://doi.org/10.1080/19443994.2014.981414

Cameselle, C., Gouveia, S., and Cabo, A., 2020. Analysis and optimization of Mn removal from contaminated solid matrixes by electrokinetic remediation. *International journal of environmental research and public health*, 17(6), P. 1820. https://doi.org/10.3390/ijerph17061820

Cameselle, C., Gouveia, S., and Cabo, A., 2021. Enhanced electrokinetic remediation for the removal of heavy metals from contaminated soils. *Applied Sciences*, 11(4), P. 1799. https://doi.org/10.3390/app11041799

Faisal, A. A., Alkhateeb, R. W., Al-Hashimi, O. A., Shubbar, A., and Saleh, B., 2022. Removal of zinc, lead and nickel from contaminated soil by electro-kinetic technology under the influence of washing and buoyance forces with different purging solutions. *Separation Science and Technology*, 57(8), pp. 1290-1303. https://doi.org/10.1080/01496395.2021.1976208

Ge, X., Xie, J., Song, X., Cao, X., Wang, Y., Xu, Z., Wang, Y. and Hou, X., 2022. Electrokinetic remediation of cadmium (Cd), copper (Cu) and nickel (Ni) co-contaminated soil with oxalic acid, acetic acid or citric acid as the catholyte. *International Journal of Electrochemical Science*, *17*(4), P. 220444. https://doi.org/10.20964/2022.04.48

Gomes, H. I., and Bustos, E. B., 2021. Combined use of remediation technologies with electrokinetics. *Electrokinetic Remediation for Environmental Security and Sustainability*, pp. 61-84. https://doi.org/10.1002/9781119670186.ch3

Han, D., Wu, X., Li, R., Tang, X., Xiao, S., and Scholz, M., 2021. Critical review of electro-kinetic remediation of contaminated soils and sediments: mechanisms, performances and technologies. *Water, Air, and Soil Pollution*, 232(8), P. 335. https://doi.org/10.1007/s11270-021-05182-4

Hansen, H.K., Ottosen, L.M. and Ribeiro, A.B., 2016. Electrokinetic soil remediation: an overview. *Electrokinetics across disciplines and continents: new strategies for sustainable development*, pp. 3-18. https://doi.org/10.1007/978-3-319-20179-5_1

Hawal, L. H., and Al-Sulttani, A. O., 2024. Decontamination of Cobalt-Polluted Soils Using an Enhanced Electro-kinetic Method, Employing Eco-friendly Conditions. *Water, Air, and Soil Pollution*, 235(3), P. 204. https://doi.org/10.1007/s11270-024-07007-6

Hołtra, A., and Zamorska-Wojdyła, D., 2020. The pollution indices of trace elements in soils and plants close to the copper and zinc smelting works in Poland's Lower Silesia. *Environmental Science and Pollution Research*, 27(14), pp. 16086-16099. https://doi.org/10.1007/s11356-020-08072-0

Fabunmi, I., Olumodeji, O., Uyimadu, J. P., and Adeleye, A., 2014. Evaluation of the Effectiveness of Different Acid Digestion on Sediments. *IOSR Journal of Applied Chemistry*, 7(12), pp. 39–47. https://doi.org/10.9790/5736-071213947

Jameel, S. R., and Jawad, F. W., 2025. Enhanced electrokinetic removal of mercury from sandy soil using thioglycolic acid and lignocellulosic sawdust at acidic conditions. *Ecological Engineering and Environmental Technology*, 26(9), pp. 72–80. https://doi.org/10.12912/27197050/209380

Jamshidi-Zanjani, A., and Khodadadi Darban, A., 2017. A review on enhancement techniques of electrokinetic soil remediation. *Pollution*, 3(1), pp. 157-166. https://doi.org/10.22059/poll.2017.59583

Kumar, U., and Bandyopadhyay, M., 2006. Sorption of cadmium from aqueous solution using pretreated rice husk. *Bioresource Technology*, 97(1), pp. 104–109. https://doi.org/10.1016/j.biortech.2005.02.027

Li, X., Wang, M., Jin, M., and Wu, W., 2026. Advances in bio-based composites for soil heavy metal remediation: a comprehensive review. *International Journal of Phytoremediation*, 28(4), pp. 579-604. https://doi.org/10.1080/15226514.2025.2577827

Masindi, V., and Muedi, K. L., 2018. Environmental contamination by heavy metals. *Heavy metals*, 10(4), 115-133. https://doi.org/10.5772/intechopen.76082

Nagajyoti, P. C., Lee, K. D., and Sreekanth, T. V. M., 2010. Heavy metals, occurrence and toxicity for plants: a review. *Environmental chemistry letters*, 8(3), pp. 199-216. https://doi.org/10.1007/s10311-010-0297-8

Ndazi, B. S., Karlsson, S., Tesha, J. V., and Nyahumwa, C. W., 2007. Chemical and physical modifications of rice husks for use as composite panels. Composites Part A: *applied science and manufacturing*, 38(3), pp. 925-935. https://doi.org/10.1016/j.compositesa.2006.07.004

Nguyen, T. A. H., Ngo, H. H., Guo, W. S., Zhang, J., Liang, S., Yue, Q. Y., and Nguyen, T. V., 2013. Applicability of agricultural waste and by-products for adsorptive removal of heavy metals from wastewater. *Bioresource technology*, 148, pp. 574-585. https://doi.org/10.1016/j.biortech.2013.08.124

Pan, Z., Wang, G., Liang, J., and Cang, L., 2024. Enhancing electrokinetic remediation of soil contaminated with As, Cd, Cu, and Pb using the biodegradable chelator GLDA: A pilot study. *Journal of Soils and Sediments*, 24(6), pp. 2361-2376. https://doi.org/10.1007/s11368-024-03824-8

Park, J. H., Choppala, G. K., Bolan, N. S., Chung, J. W., and Chuasavathi, T., 2011. Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant and soil*, 348(1), pp. 439-451. https://doi.org/10.1007/s11104-011-0948-y

Reddy G, K., Yarrakula, K., and Lakshmi U, V., 2019. Reducing agents enhanced electrokinetic soil remediation (EKSR) for heavy metal contaminated soil. *Iranian Journal of Chemistry and Chemical Engineering*, 38(3), pp. 183–199. https://doi.org/10.30492/ijcce.2019.37187

Reddy, K. R., and Chinthamreddy, S., 2003. Sequentially enhanced electrokinetic remediation of heavy metals in low buffering clayey soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(3), pp. 263-277. https://doi.org/10.1061/(asce)1090-0241(2003)129:3(263)

Rozas, F., and Castellote, M., 2012. Electrokinetic remediation of dredged sediments polluted with heavy metals with different enhancing electrolytes. *Electrochimica Acta*, 86, pp. 102-109. https://doi.org/10.1016/j.electacta.2012.03.068

Sun, Z., Tan, W., Gong, J., and Wei, G., 2023. Electrokinetic remediation of Zn-polluted soft clay using a novel electrolyte chamber configuration. *Toxics*, 11(3), P. 263. https://doi.org/10.3390/toxics11030263

Sun, Z., Geng, J., Zhang, C., and Du, Q., 2024. Electrokinetic remediation of Cu- and Zn-contaminated soft clay with electrolytes situated above soil surfaces. *Toxics*, 12(8), P. 563. https://doi.org/10.3390/toxics12080563

USEPA, 1986. Method 9081: Cation-exchange capacity of soils (sodium acetate). United States Environmental Protection Agency, Washington, DC.

USEPA, 1996. Method 3050B: Acid digestion of sediments, sludges, and soils. United States Environmental Protection Agency, Washington, DC.

Virkutyte, J., Sillanpää, M., and Latostenmaa, P., 2002. Electrokinetic soil remediation—critical overview. *Science of the Total Environment*, 289(1–3), pp. 97–121. https://doi.org/10.1016/S0048-9697(01)01027-0

Wang, Y., Han, Z., Li, A., and Cui, C., 2021. Enhanced electrokinetic remediation of heavy metals contaminated soil by biodegradable complexing agents. *Environmental Pollution*, 283, P. 117111. https://doi.org/10.1016/j.envpol.2021.117111

Wasay, S. A., Barrington, S. F., and Tokunaga, S., 1998a. Organic acids to remediate a clay loam polluted by heavy metals. *Canadian Agricultural Engineering*, 40(1), pp. 9-16.

Wasay, S. A., Barrington, S. F., and Tokunaga, S., 1998b. Remediation of soils polluted by heavy metals using salts of organic acids and chelating agents. *Environmental Technology*, 19(4), pp. 369-379. https://doi.org/10.1080/09593331908616692

Yeung, A. T., and Gu, Y. Y., 2011. A review on techniques to enhance electrochemical remediation of contaminated soils. *Journal of Hazardous Materials*, 195, pp. 11–29. https://doi.org/10.1016/j.jhazmat.2011.08.047

Yunta, F., Schillaci, C., Panagos, P., Van Eynde, E., Wojda, P., and Jones, A., 2024. Quantitative analysis of the compliance of EU Sewage Sludge Directive by using the heavy metal concentrations from LUCAS topsoil database. *Environmental Science and Pollution Research*, 31, pp. 16554–16569. https://doi.org/10.1007/s11356-024-31835-y

Zhang, Y., Zheng, R., Zhao, J., Zhang, Y., Wong, P. K., and Ma, F., 2013. Biosorption of zinc from aqueous solution using chemically treated rice husk. *BioMed Research International*, 2013, P. 365163. https://doi.org/10.1155/2013/365163

استخلاص الزنك من التربة الرملية بطريقة صديقة للبيئة باستخدام التحريك الكهربائي بمساعدة حمض الطرطريك والنفايات الزراعية

علي عمران السلطاني[1]، *، ستيلا روبرت جميل[2]، ليث حمدان حول[2]، اميمول احسان[3، 4]

[1]قسم هندسة الموارد المائية، كلية الهندسة، جامعة بغداد، بغداد، العراق

[2] قسم الهندسة البيئية، الجامعة المستنصرية، بغداد، العراق

[3]قسم الهندسة المدنية والبيئية، الجامعة الإسلامية للتكنولوجيا، غازيبور ، بنغلاديش

[4] قسم الهندسة المدنية والإنشائية، جامعة سوينبرن للتكنولوجيا، ملبورن، أستراليا

الخلاصة

لا يُمثل تلوث التربة الرملية الزراعية بالزنك (Zn) خطرًا على جودة المحاصيل فحسب، بل يُشكل أيضًا مشكلة لجودة المياه الجوفية. وتُظهر عوامل التحسين الشائعة المستخدمة في المعالجة الكهروكيميائية للمعادن الثقيلة، مثل EDTA، ثباتًا في البيئة. تُقيّم هذه الدراسة تقنية المعالجة الكهروكيميائية التي تتضمن عاملًا مُخلِّبًا قابلًا للتحلل الحيوي، وهو حمض الطرطريك، وحاجزًا من قشور الأرز غير المُعالجة مُثبَّتًا أمام المهبط. يتضمن التصميم التجريبي تربة رملية (93.4% رمل) مُلوَّثة صناعيًا بـ 300 ملغم/كغم من الزنك، ومُعالَجة لمدة 5 أيام تحت تدرج جهد كهربائي قدره 1 فولت/سم. بالإضافة إلى ثلاث تجارب بدون تحسين، حيث كانت محاليل التنقية عبارة عن ماء الصنبور مُعدَّل الرقم الهيدروجيني إلى 3 و7 و11، كانت هناك تجربة واحدة باستخدام حمض الطرطريك عند الرقم الهيدروجيني 3 كمحلول إلكتروليتي. أُجريت جميع التجارب مرة واحدة. انخفضت نسبة إزالة الزنك من 77.8% عند درجة حموضة 3 إلى 69.7% عند درجة حموضة 7، ثم إلى 53.2% عند درجة حموضة 11، وذلك نتيجةً لزيادة امتزاز الزنك وهجرته الكهربائية في الظروف الحمضية، وترسيبه على هيئة هيدروكسيد الزنك $Zn(OH)_2$ في الظروف المتعادلة والقلوية. في جميع التجارب، انخفضت كمية الزنك المتبقية باتجاه المصعد نحو المهبط. وكانت أعلى نسبة إزالة للزنك في التجربة المُعززة بحمض الطرطريك (90.8%)، أي بزيادة قدرها 13 نقطة مئوية عن التجربة غير المُعززة عند درجة حموضة 3، حيث تراوحت كمية الزنك المتبقية بين 15 و43 ملغم/كغم في عمود التربة. ويعود ذلك إلى تكوّن معقدات طرطرات الزنك الذائبة، وإلى تأثير حمض الطرطريك المُخفف الذي حافظ على درجة حموضة التربة ضمن نطاق 4.2–5.7. بلغت كمية الزنك المحتجزة في حاجز قشور الأرز 38 ملغم/كغم. لذا، يُمكن اعتبار تقنية استخلاص الزنك المعزز بحمض الطرطريك القابل للتحلل الحيوي تقنيةً واعدةً لمعالجة التربة الرملية الملوثة بالزنك. ويلزم إجراء اختبارات متكررة، وتقييم التكلفة، ودراسة تأثير هذه التقنية على جودة التربة، وتحديد كمية مساهمة الحاجز.

الكلمات المفتاحية: المعالجة الكهروكيميائية، إزالة الزنك، التربة الرملية، حمض الطرطريك، قشور الأرز.