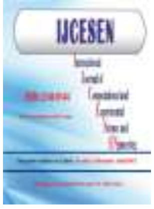
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)
Vol. 11-No.1 (2025) pp. 1261-1269
http://www.ijcesen.com
ISSN: 2149-9144



Research Article

Eco-friendly Assessment of Anode Hexagonal Configuration on the Migration of Metal Ions

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Article Info:

DOI: 10.22399/ijcesen.1047
Received : 01 December 2024
Accepted : 17 February 2025

Keywords :

Cadmium,
Hexagonal,
Electrokinetic,
Remediation,
Acidified Soil.

Abstract:

The remediation process used to extract different types of contaminants from the contaminated soil by applying an electrical field is the electro-kinetic technique. Experiments were performed under unenhanced, enhanced, and acidified conditions: the enhancement condition used 1 M acetic acid in the cathode chamber as a catholyte solution with pH regulated between 3 and 4, while distilled water served as the anolyte solution. The unenhanced condition used distilled water in the cathode chamber as the catholyte solution, without pH control, and distilled water as the anolyte solution, together with acidified contaminated soil. The highest removal efficiency rate of cadmium was recorded in the acidified soil with enhanced conditions (EK-9), reaching 65.26%, compared to the experiment with acidified contaminated soil with unenhanced conditions (EK-8), which reached 59.38%. Following that the removal efficiency of the cadmium ion obtained was equal to 56.65% in the experiment when using contaminated soil without acidification with enhanced conditions (EK-6). The lowest removal efficiency rate in this study was in the case without acidification contaminated soil with unenhanced conditions (EK-3), gaining 26.03%. This work also measured the pH and showed a significant decrease in the acidified soil conditions at enhanced conditions reaching 4.2, 5.2, and 6.1 for the samples of points measured at 3.3, 6.6, and 10 cm distances from the anode electrode for EK-9, respectively. Its highest value was reached in the experiments for contaminated soil (without acidification) at operating unenhanced conditions (EK-3), reaching 8.7, 10, and 10.7 for samples of points A1, A2, and A3, respectively.

1. Introduction

Soil pollution from heavy metals (HMs) is a significant environmental issue. Agricultural, industrial, and military operations are the primary contributors to heavy metal pollution [1]. The risks associated with heavy metal soil contamination are multifaceted and pose severe threats to both human health and the integrity of the ecosystem. These risks become evident by various routes such as direct consumption or contact with polluted soil, soil-to-plant-to-human, soil to plant to animal to human cycle (the food chain), consumption of contaminated ground water, phytotoxicity, which reduces food quality and utilization by making the soil unproductive for agricultural use hence posing food insecurity, and other problems associated with land ownership and tenure [2]. Electrokinetic treatment is an advanced physical technique for remediating heavy metals, employing direct current power on both sides of the soil to generate a potential gradient that facilitates the migration of pollutants to the soil column's end via diffusion, electrophoresis, electromigration, and electroosmotic flow. In addition, electrokinetic treatment to being effective in low-permeability soil, this remediation is also economic friendly cost-effective due to its simplicity of installation and operation [3]. In the EKR process, the electrolysis of water results in the segmentation of soil regions into an acidic zone ($H_2O \rightarrow 2 H^+ + 1/2 O_2 + 2 e$) and an alkaline zone ($2 H_2O + 2 e^- \rightarrow 2 OH^- + H_2$). The hydrogen ($H^+$) ions generated from water oxidation facilitate the desorption of metal cations from the soil surface. The hydroxyl (OH^-) ions generated in the alkaline zone adversely affect metal transport [4]. To enhance electrokinetic (EK) soil remediation using the cation exchange membrane (CEM), the region near the anode, the higher are the H^+ concentrations and the redox potentials. Both low pH and elevated redox potential facilitate the acceleration of Cd electro-migration, enabling the rapid remediation of soils next to the anode [5]. Soil pH is considered a critical variable influencing the concentration of the metals in the soil solution, the mobility and availability of these metals to plants. The elevation of hydrogen ion concentration influences the mobilization intensity of heavy metals. In extremely acidic soils, the mobility of metallic elements significantly exceeds that in soils with neutral and alkaline reactions [6]. The maximum extraction of aluminum from drinking water treatment sludge occurred when acetic acids were used as a conditioning cathode solution to neutralize the cathodic reaction throughout the process. In this instance, up to 80% of the original aluminum could be retrieved in the cathode chamber when 0.1 M acetic acid was used [7]. This research goals are to observe the impact of arranging anode electrodes in hexagonal form using an electrokinetic treatment process on removing metal ions in the two conditions: enhancement and un-enhancement, and to enhance the efficacy of metal removal by acidifying the contaminated soil. The second part of the paper describes the materials and methods, followed by the result and discussion in the third part. Finally, the conclusions are stated in the fourth part.

2. Materials And Methods

2.1 Soil Preparation and Characterize

The soil employed in the current study was obtained from agricultural location, Hilla city of Iraqi country. It was obtained from the site soil, which is approximately 30-50 cm subsurface depth. It was cleaned, dried and well sorted with an additional sieving for achieving satisfying uniformity. Therefore, In order to obtain soil that was artificially contaminated with cadmium ($Cd(NO_3)_2.4H_2O$) to a concentration of about 655 mg/kg, the soil sample had been pressed inside the reactor cell to attain equilibrium.. After three days, the cadmium-contaminated soil was allowed to sit in the electrokinetic cell [8]. The main physicochemical characteristics of the native soil, where the soil texture consists according to particle size distribution test as 50% silt, 10% sand, and 40% clay. The initial amount of chloride ions (mg/l) and the percentage of calcium carbonate (%) were 1.124 and 11.847, respectively. The cation exchange capacity of the native soil was 8.25 (meq/ 100 g). The organic content was 0.57%. The concentration of cadmium in an initial sample was 655 mg/Kg. According to the practical method adopted by [9] to acidify Cd-contaminated dry soil in the present study by adding 0.6 liters of acetic acid at a concentration of 3 M per 1 kg of soil, subsequently stored in a container until it was ready to be placed in an electro-kinetic cell. Consequently, the pH of the acidified soil (6.8) was lower than that of the initial soil (8.8). Conversely, the electrical conductivity of the acidified soil (6.13 mS/cm) was greater than that of the initial soil (5.43 mS/cm). Acidified soil contained a lower percentage of calcium carbonate (3.95%) than its initial value of 4.32%.

2.2 Experimental Work

In the current study, Figure 1 explains the EK experiment setup, also Figure 2 shows the schematic representation for the shape of arranging six anode electrodes in a hexagonal form around the cathode electrode that is placed in the center of the chamber. This arrangement of the electrodes and practical method used in the present study as the same [10] where electrodes are configured in triangular, quadrangular, and hexagonal designs to provide electrochemical remediation of polluted soil using a self-constructed testing apparatus. Cylindrical graphite (99.9% purity) serves as the cathode, while stainless steel is used for the anode. The diameters of the cathode and anode are 1 cm. The chamber of the cathode electrode contained a 0.1 mol/L citric acid solution, which used as the cathode electrolyte. In the three-electrode configuration, the distances between the cathode and anode are uniformly 14.5 cm, resulting in control voltage gradients of 2 V/cm, with power-on durations consistently set at 120 hours. The present study's experiment contains a rectangular chamber (15 cm depth*30 cm width* 30 cm length), seven electrode compartments, the power supply, and seven electrodes. The anode compartments were arranged in hexagonal form, which is composed of plexiglass in diameter measuring 3.5 cm and height of 13 cm, these six anode electrodes were arranged around the cathode electrode that set in the center of the chamber. Both the cathode and anode made use of seven chemically inert cylindrical graphite electrodes; the anode electrodes measured 15 by 1.8

cm in length and diameter, respectively, while the cathode electrodes were 15 by 2.5 cm in length and diameter, respectively. The inert electrodes inhibit the entry of extraneous chemical species that may complicate the electrochemical processes during operation, their use is especially important at the anode, since the oxidation process has a significantly corrosive impact on the electrode [11]. The actual selected length of the soil specimen in this cell was ten centimeters, according to pervious study [12]. The gasses was produced during electrolysis were released from the upper sections of both the anode and cathode chambers [13]. The DC power source was employed to apply a consistent voltage to each electrode through power cables that were affixed to the electrode's top [14]. Throughout the test, a multimeter was employed to observe the voltage and determine the current flow through the soil sample. In this investigation, a voltage gradient of 1.5 V/cm was implemented in all experiments, in accordance with the methodology employed [15]. Three sampling points have been defined (A1, A2, and A3) along the path distance between an anode and cathode, with a distance of 3.3 cm, 6.6 cm, and 10 cm from the anode, respectively, in accordance with the arranged sample point shapes for extracting the soil specimen [16]. Following the 100-hour operation of the EK, soil samples were collected at the designated locations using a hand auger. Then, the samples were dried, crushed, and used for determining soil pH and concentration of cadmium in the soil. Three sample locations were designated (A1, A2, and A3). After drying, 5 grams of soil that taken from A1, A2, and A3 sampling points were mixing with 12.5 milliliters of distilled water. The solids were allowed to settle for one hour after manual agitation for several minutes. The pH of the supernatant was subsequently measured to depict the soil's pH [17]. The procedure for the acidic digestion of the soil [18] was used to extract cadmium ions from samples of points (A1, A2, and A3) to determine the concentration of cadmium. Table 1 presents a summary of the experimental scope regarding the impact of the arrangement of six anode electrodes in the hexagonal form around the cathode electrode, and acidification of contaminated soil through the electro-kinetic remediation experiments. In EK-8 & EK-9 test attained the objective of this work, which was to show the effect of acidification of contaminated soil through an electro-kinetic treatment process on the characteristics of the treated soil, was achieved by adding (600 ml) of 3 M acetic acid per one kilogram of dry contaminated soil, as a practical method for acidification of sludge adopted by [9], subsequently, it is stored in the container for a duration to prepare it for placement in an electrokinetic chamber. For the EK-8 test two compartments (anode and cathode) was filled in the distilled water, while the EK-9 test the anode and cathode compartments were filled with distilled water as anolyate solution and 1 molar AA as a catholyte solution, respectively. Test for EK-6 was accomplished under the same conditions as EK-3 except in the cathode compartment where filled with 1 molar acetic acid as catholytic solution, In EK-3 test (unenhanced conditions: The leaching solution used in both the anode and cathode chambers is distilled water, without a pH control in the cathode chamber) &EK-6 test (enhanced conditions: the anode chambers are filled with distilled water as the leaching solution, while acetic acid (AA) is utilized as the catholyte solution with a regulated pH ranging from 3 to 4)), which was used spiked the soil with the contaminant (cadmium) (without acidification).

Figure 1. *Electrokinetic chamber experimental configuration, which consists of hexagonal-shaped anode electrodes arranged around the cathode electrode*

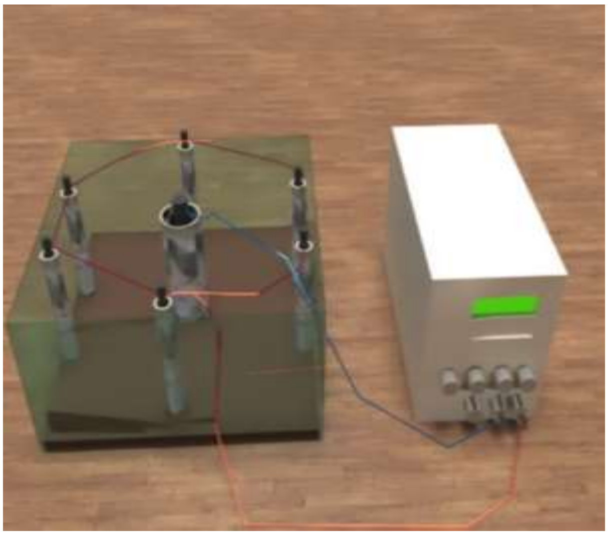


Figure 2. *Schematic graphic of the hexagonal arrangement of electrodes in electrokinetic experiment.*

Table 1. *Details of electro-kinetic remediation experiments in the present study.*

Series	**Experiment Designation**	**Target Contaminant (Con., mg/kg)**	**Distance between electrodesn(cm)**	**Time (hours)**	**(pH)**	
					Anode	**Cathode**
Series I (Unenhanced)	EK-3	Cd(655)	10	100	DW	DW
Series II (enhanced)	EK-6	Cd(655)	10	100	DW	1M AA (~3)
Series III (acidify)	EK-8	Cd (655)	10	100	DW	DW
	EK-9	Cd (655)	10	100	DW	1M AA (~3)

Note: DW: Distilled water; AA: Acetic Acid; M: Molar; Cd: cadmium**;** con.: concentration**.**

3. Results and Discussion

3.1 The Impact of Hexagonally Arranged Anode Electrodes

The purpose of this experiment was to determine the impact of placing six anode electrodes in a hexagonal arrangement to the cathode's placement in the chamber cell's middle on the extraction of cadmium ion from artificially contaminated soil for the EK-3 test utilized distilled water as the catholyte solution without pH regulation, while distilled water using served as the anolyte solution. In the EK-6 test, distilled water was used as the anolyte solution, and 1 Molar Acetic Acid was employed as the catholyte solution within a pH-controlled range of 3-4. In all tests in the current study, A potential gradient of 1.5 V/cm was used [19], which cited that the more voltage, the higher the current in the soil system. The migration rate of pollutants can be enhanced by high voltage, but it may also result in an increase in power consumption. Consequently, it is crucial to identify an appropriate voltage gradient. Distribution of the pH and the residual concentration of cadmium for the treated soil at the end of the treatment period, which was equal to 100h, for EK-3 and EK-6 experiments, as a function of the distance from anode to cathode chamber illustrated in Figure 3 with Table 2. It was noticeable that the pH at (A1, A2, and A3) for EK-3 was higher than its preliminary value for original soil. Contrarily, the pH of the soil in each section of the EK-6 after the end of the electrokinetic treatment period was less than its preliminary value of the regional soil. A pH values for the treated soil at distances of 3.3, 6.6, and 10 cm from the anode chamber during the EK-3 test were recorded as 8.7, 10, and 10.7, respectively. These values exceeded those of the corresponding sample points for treated soil in the EK-6 test, which were 6.2, 7.1, and 7.5, respectively. It was observed from the same Figure 3 that the treated soil pH at A3 for EK-6 was equal to 7.5, i.e., the neutral pH environment, this is due to the adding of the 1 M acetic acid to help control the solution pH and keep it within the range 3-4 in the cathode chamber, which helped to decrease soil pH in the sample of a point near the cathode region as compared to the same point for EK-3 (the soil pH at A3 was equal to 10.7). Also, Figure 3 shows the comparison of the amount of the residual (Cd (II)) in each sample point of the treated soil between EK-3 and EK-6, in the case that arranged the anode electrodes in the form hexagonal. In the EK-3 test, the concentration of (Cd (II)) in the samples for the remediate soil which was equal to 438.15, 497.8 and 517.45 mg/kg, respectively, corresponding to removal efficiency of 33.10%, 24% and 21%, as compared to its initial concentration of cadmium in the contaminated soil which was equal to 655 mg/kg, were higher than those of the samples points for the EK-6 test, which was 256.85, 283.54, and 311.27 mg.kg^{-1}, respectively, which corresponding the removal efficiency of 60.7%, 56.71% and 52.47%, respectively. The residual cadmium concentration for EK-3 and EK-6 decreased from the initially concentration of 655 mg/kg. It was observed that the concentration of cadmium ions in point sample A1 was lower than it was in point A3 for each test of EK-3 or EK-6. The results of this research are consistent with the earlier work [20] that copper dissolved into the pore solution as Cu^{2+} ions as the acid front advanced at the anode, and those ions were subsequently transported to the cathode. Nevertheless, the alkaline pH front at the cathode impeded the electromigration of Cu^{2+}, resulting in Cu accumulation in the soil section adjacent to the cathode. Also it was found that the speciation and mobilization of the contaminating metals in soil are significantly influenced by the pH profile of the soil [21]. In Sections 1 to 3 the mobilization of Cd, Cu, and Zn have occurred. In sections 4-6, particularly in sections 5 and 6, the pH levels caused the metals to precipitate in the soil and produce the corresponding metallic hydroxide. Figure 4 a-c display the SEM (scanning electron microscope) and EDS spectra of sample points A1 and A3 for EK-3 (when distilled water is used as the anolyte and catholyte solutions) were magnified to a 10 μm.

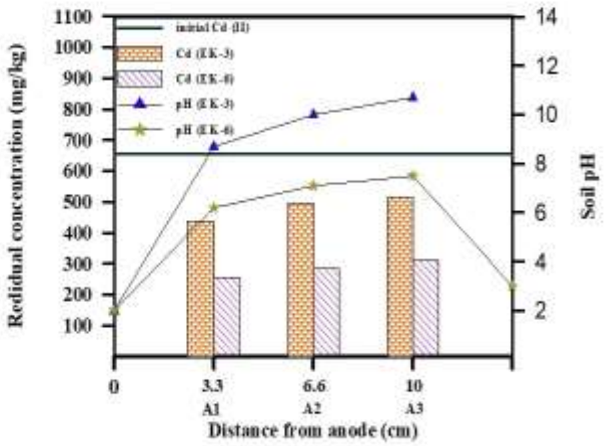
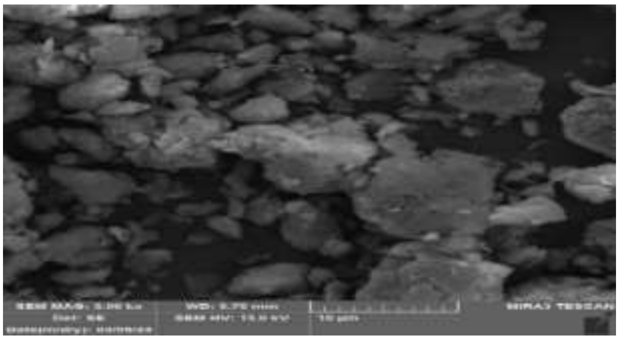


***Figure 3.** Cadmium and the pH values after treatment soil during the electrokinetic processes for the EK-3 and EK-6 experiments.*

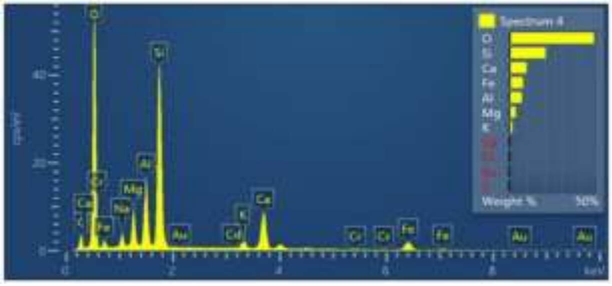
***Table 2.** Residual cadmium (II) concentrations and percentage of calcium carbonate for each section of treated soil for EK-3 and EK-6 testing.*

Exper-iments	**Parameters**	**Sample points**		
		A1	**A2**	**A3**
EK-3	Initial concentration of Cd (II) (mg/kg)	655		
	Cd (II) residual concentration (mg/kg)	438.15	497.8	517.45
	Reduction (%)	33.10	24	21
	Average reduction (%)	26.03		
EK-6	Cd (II) residual concentration (mg/kg)	256.85	283.54	311.27
	Reduction (%)	60.78	56.71	52.47
	Average reduction (%)	56.65		

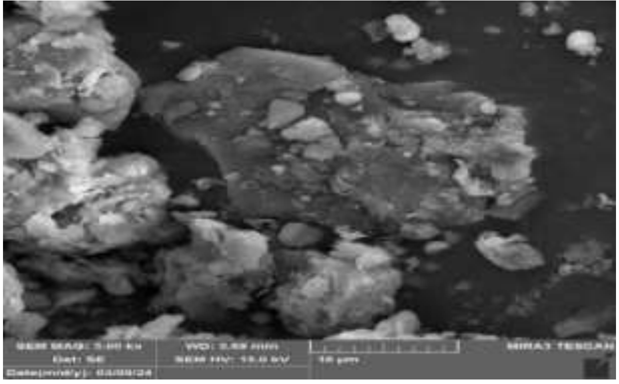
Figure 4a illustrates that the form of the soil's surface in A1, whereas the pore spacing between soil particles for the region near the anode was larger as compared with it's in the region near the cathode (sample point A3), as shown in Figure 4 c. This indicated that the stacks of substantial platy soil particles with big voids were processed using a calcium-distilled water system. The covering materials were dissolved due to the acidic environment or other chemical processes occurring around the anode. Conversely, the extensive interconnected soil particles in the background, and the randomly distributed tiny nodules in the front near the cathode [22]. Figure 4 b and d elucidates the sequence of arrangement of the predominant element in the composition for point of sample A1 as follows: Oxygen (O), silicon (Si), calcium (Ca), iron (Fe), aluminum (Al), magnesium (Mg), potassium (K), carbon (C), cadmium (Cd), antimony (Au), and chromium (Cr). While the elements in the composition of sample A3(near the cathode region) are arranged in order as follows: Oxygen (O), silicon (Si), calcium (Ca), iron (Fe), aluminum (Al), magnesium (Mg), potassium (K), cadmium (Cd), chromium (Cr), antimony (Au) and carbon (C). The SEM (scanning electron microscopy) pictures of the specimen at sample points A1 and A3 for EK-6 (use 1 molar AA as the catholyte solution) are shown in Figure 5a and 5b. The images were magnified to a 200 µm scale. The form of the soil surface in A1 is shown in Figure 5a, which refers to



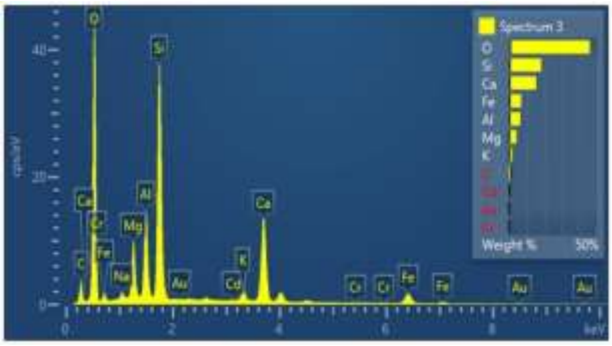
(a)SEM images of the A1 (near the anode)



(b) EDS spectra of the A1 (near the anode)

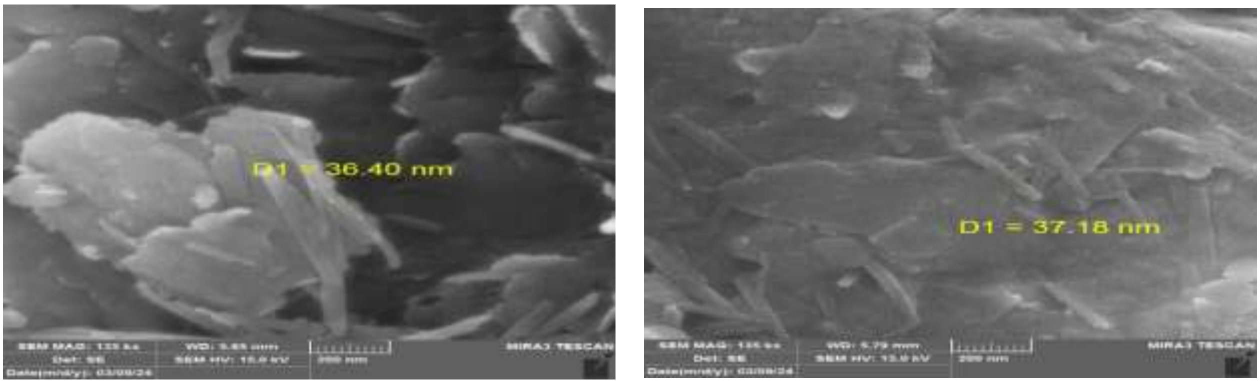


(c) SEM of the A3 (near the cathode)



(d) EDS spectra of the A3 (near the cathode)

***Figure 4.** EDS spectra and SEM for the EK-3 test*



(a) at A1 (near the anode region) (b) at A3 (near the cathode region)

Figure 5. *SEM of the treated soil at A1 and A3 section for EK-6*

the presence of pores between soil particles for the region near the anode, it also found that the particle size was 36.4 nm. Figure 5b, shows the shape of particles in the cathode region (point of sample A3) with a smooth surface and white points adhering to the surface, this led to an increase in particle size to become 37.18 nm due to reduced pores between soil particles. It was shown that the surface of soil particles exhibited increased smoothness as compared with the initial one, after soil treatment using an electrokinetic technique [23]. Citric acid and sodium chloride are the most common complexes formed with calcium ions. Ultimately, complexes moved to cathode wells by the processes of electromigration and electroosmotic flow. The scanning electron microscope (SEM) image showed the presence of powder sediment in the cathode, which was deposited by needle-shaped crystals. Also it was reported that the qualitative assessment of copper and cadmium migration in the soil treated with EK was also conducted using scanning electron microscope (SEM) pictures [24]. The photographs of the soils on the anode side show reduced metal concentrations and appear brighter. In contrast, the cathode-end soils treated with EK have a darker appearance, indicating a greater concentration of the corresponding metals.

3.2 Effect acidifies of contaminated soil

Unenhanced conditions

Figure 6 with Table 3 represents the distribution concentration of Cd (II) and pH after 100 hours of electrokinetic remediation for EK-3 and EK-8 experiments, at three distances from the anode of sample points A1, A2, and A3: 3.3, 6.6, and 10 cm, respectively. It was noticed that the soil pH before acidification (8.8) was higher than the value after acidification of the contaminated soil (6.9). The soil pH profiles in the EK-3 at point of sample A1 was lower than the original contaminated soil (8.8), with the exception of points A2 and A3, which were more than the preliminary values of 10 and10.7, respectively. In the EK-8 experiment (acidification of contaminated soil), the initial soil pH after acidifying the contaminated soil, i.e., before carrying out the electrokinetic process remediation became 6.9. The soil pH at sampling point A1 is lower than the initial value after acidifying the contaminated soil (5.9) while, the soil pH at A2 and A3 was higher than the initial values of acidification of the contaminated soil 7.5, and 7.9, respectively. In EK-8 experiment found a decrease in soil pH at all points of samples more than the experiment EK-3 (without acidified contaminated soil). In the EK-8 test, the removal efficiency of Cd (II) decreased with increasing distance from the cathode, with the values at these points of samples A1, A2, and A3 equal to 62.58%, 58.20%, and 57.37% respectively. The corresponding residual amount of cadmium was 245.1, 273.77, and 279.2 mg/kg, While the removal efficiency of cadmium ions for the EK-3 experiment at sections A1, A2, and A3 (33.10%, 24%, and 21% respectively) lower as compared to the same points of samples in the EK-8 experiment.

The concentrations of the cadmium in these points for EK-3 test were equal to 438.15, 497.8, and 517.45 mg/kg, respectively. The reason for this is that the soil pH in the parts of samples was lower in the EK-8 experiment as compared to the EK-3 experiment.

This point can be interpreted in accordance with the documentation provided by [25] reported that the dissolution of heavy metal ions associated with mineralized surfaces may be facilitated by a decrease in pH.

This was due to the fact that the concurrent release of metal ions was increased by H+ on the mineral surface through the cation exchange process. Additionally, the reduction in pH resulted in the protonation of the soil mineral surface, hence enhancing the desorption of metal ions. The efficacy of removal for Cd, Zn, Pb, and Cu were higher in a relatively low pH environment compared to a relatively high pH environment.

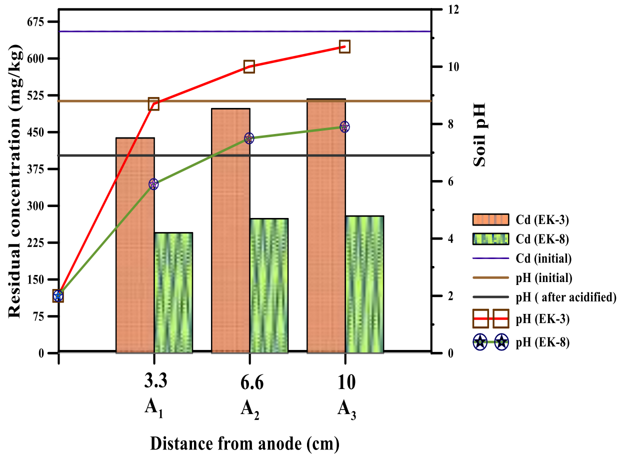


Figure 6. *Cadmium and pH values in the treated soil through electrokinetic technique for EK-3 and EK-8 tests*

Table 3. *Cadmium ion removal efficiency (R) from sample sites through the electrokinetic cell.*

Test		**A1**	**A2**	**A3**
EK-3	R(%)	33.10	24	21
	Average (%)	26.03		
	Initial soil pH	8.8		
	Soil pH	8.7	10	10.7
EK-8	R(%)	62.58	58.20	57.37
	Average (%)	59.38%		
	Initial soil pH after acidified	6.9		
	Soil pH	5.9	7.5	7.9

Enhanced Conditions with Acidification

By comparing the experimental findings of EK-6 and EK-9, the effects of applying contaminated soil (without acidification conditions) and soil contaminated (with acidification conditions). For the EK-6 and EK-9 (enhanced conditions with acidification contaminated soil) experiments, the distribution of pH and residual cadmium concentration for the treated soil at the end of the treatment duration, which was equal to 100 hours, as a function of the distance between the anode and cathode chamber is shown in Figure 7 together with Table 4. Notably, the pH of the soil values at (A1, A2, and A3) for EK-6 were equal to 6.2, 7.1, and 7.5, respectively. On the other hand, the pH of the soil in every part of the EK-6 was inferior to the original value of the native soil (8.8). Additionally, the pH of the treated soil was observed at 3.3, 6.6, and 10 cm distances from the anode electrode for EK-9 (4.2, 5.2, and 6.1), respectively. It is also less than the initial pH value after acidifying contaminated soil before treatment (6.9). This decrease in the pH value is due to the increase in positive hydrogen ions in the soil due to be acidifying contaminated soil before applied electrokinetic process and the use of acetic acid as a solution in the cathode chamber. Figure 7 compares the amount of residual Cd^{+2} in each sample point of the treated soil between the EK-6 experiment and the EK-9 experiment. In the EK-6 test, the concentration of Cd^{+2} in the A1, A2, and A3 for the treated soil, which was equal to 256.85, 283.54, and 311.27 mg/kg, respectively, corresponding to removal efficiency of 60.1%, 56.71% and 52.47%, respectively, as compared to its initial concentration of cadmium in the contaminated soil, which was equal to 655 mg/kg. The lowering amount of residual concentration of the cadmium was obtained in the EK-9 experiment with three points of samples, which was 168.99, 228.59, and 284.9 mg/kg, respectively, which corresponding the removal efficiency was equal to 74.2%, 65.1% and 56.5%, respectively.

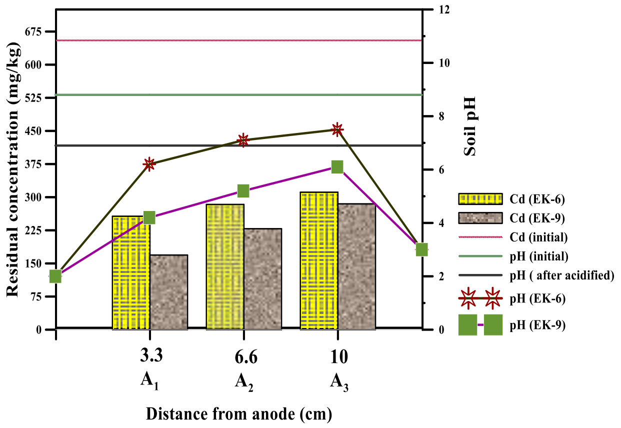


Figure 7. *Cadmium and pH values in treated soil during electrokinetic method for EK-6 and EK-9 tests.*

Table 4. *Cadmium removal efficiency (R) from sample sites through the electrokinetic cell.*

Test		**A1**	**A2**	**A3**
EK-6	R(%)	60.78	56.71	52.47
	Average (%)	56.65%		
	Initial soil pH	8.8		
	Soil pH	6.2	7.1	7.5
EK-9	R(%)	74.2	65.1	56.5
	Average (%)	65.26		
	Initial soil pH after acidified	6.9		
	Soil pH	4.2	5.2	6.1

4. Conclusions

After electrokinetic treatment, the cadmium removal efficiency rate of experiment EK-3 was the lowest in the unenhanced conditions and reached 26.03%, at the same time the pH values of the three samples of points were (A1, A2 and A3) 8.7, 10,10.7 respectively, while the removal rate of cadmium ions in experiment EK-6 increased to 56.65% in the enhanced conditions and under the same operating conditions, the pH value for the three samples was (A1, A2, and A3), 6.2, 7.1and 7.5 respectively, When using acidified conditions for experiments EK-8 and EK-9, the removal efficiency rate was 59.38% and 65.26%, respectively, which is the highest removal efficiency rate in this work and the pH showed a significant decrease in the acidified soil conditions at enhanced conditions reaching 4.2, 5.2, and 6.1 for the samples of points measured at (3.3, 6.6, and 10 cm) distances from the anode electrode for EK-9, respectively. From this, we conclude that the use of acidified conditions for cadmium-contaminated soil, with the use of acetic acid as a catholyte solution inside the cathode chamber, contributed to enhancing the migration of ions in the soil, which led to an increase in the removal efficiency.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** 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
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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