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Enhancement of Electro-Kinetic Remediation of Contaminated Soil for Removal of A Hazards Metal Ions

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Abstract

An electrokinetic investigation was conducted to examine the influence of heavy metal content, voltage gradient, and pH on the energy usage and efficiency of removing combined heavy metals (Cr and Cd) from polluted soil. Fifteen (15) studies were performed using the Box-Behnken Design, with each experiment spanning five days. The data were used to estimate the removal efficiencies of heavy metals and the energy consumed during the process using Minitab. Numerical Optimization indicates an optimal usage of energy of 156.3 kWh/m³ of treated soil, with removal efficiencies for Cd and Cr determined at 95.31% and 96.01%, respectively, under operating conditions of heavy metal concentrations of 100, 200, and 300, voltage gradients of 20, 25, and 30, and pH levels of 4, 6.5, and 9. The rise in heavy metal content was observed to diminish removal efficiency, attributed to the increased current generated throughout the experiment, resulting from the enhanced soil electrical conductivity. Increases in voltage gradient were seen to enhance the efficiency of removal. The rise in both heavy metal content and voltage gradient was observed to increase energy usage; nonetheless, energy usage is substantial at low pH magnitudes and low heavy metal contents, as well as at low voltages. Conversely, energy consumption increases with rising pH at high voltages and high concentrations of heavy metals.

Keywords: Electro-kinetic soil remediation; Cr; Cd; EDTA; Removal efficiency; Energy consumption

1. Introduction

Soil pollution is a significant environmental issue that is increasing worldwide. In several cases, industrial utilization of land contributes to soil pollution. Numerous environmental policies and rules establish the appropriate pollution cap, depending on the risk evaluation at a given location. To satisfy the legal criteria, polluted land must undergo mitigation before it can be utilized for another purpose. In particular, the use of recreational, industrial, residential, and commercial properties demands that humans are exposed to hazardous compounds and materials to a minimum, ensuring a healthy atmosphere. In the presence of high levels of metals and other compounds, both inorganic and organic, toxicity may be established. Oil-based hydrocarbon derivatives, Heavy metals, and solvents, as well as industrial pollutants, are among the most hazardous toxins. Due to their toxic nature, heavy metals pose a significant public health issue and are generated by various sources [1][2]. They were remarkably stable and did not break

down into other chemicals. Heavy metals can concentrate in the liver and other organs, potentially building up to harmful levels if absorbed or ingested over a prolonged period, even in small quantities.

An in-situ process that can be utilized to handle finer soils and soils with changeable charge minerals, such as kaolinite contaminated with toxic substances and/or polar organic materials, is electrokinetic treatment. In a soil matrix created by adding a direct current between electrodes, electro-kinetic processes require an electric field. Due to the electric differential, three major pathways are activated by pollutant ions or molecules, allowing them to move across the soil to electrodes: electrophoresis, electroosmosis, and electromigration [3]. Researchers have investigated the potential of certain additives to enhance contaminant mobility, thereby increasing the effectiveness of the traditional EK treatment method. Since the mid-1990s, numerous chemicals have been examined during the EK treatment phase, including chelating agents and surfactants, to promote the movement of contaminants in the soil. Surfactants were commonly utilized to wash biological compounds from the surface of soil particles owing to their amphiphilic properties. Bhattacharya (1996) introduced surfactants using the EK method to cure soil polluted with gasoline efficiently. On the other hand, in the EK treatment method, Yeung et al. (1996) and Wong et al. (1997) introduced a chelating agent, EDTA, to enhance the removal of heavy metals from soil, as noted by Kim et al. (2011).

In this study, the feasibility of Cr and Cd for contaminated soil was investigated through electromagnetic flow and electric migration, with optimal conditions identified for effective treatment and the selection of disinfectant agents to absorb contaminated species. The Box-Behnken method was also applied to remove heavy metals from the soil.

2. Materials and Method

2.1. Contaminant

The solutions with heavy metal (100 mg/L each) specifications have been established from their salts in this analysis, both of which are analytical grades, namely Cr(NO3) 2 · 3H2O and Cd(NO3) 2 · 6H2O. To produce 100 mg kg-1 of Cr and Cd in the soil, a primary moisture amount of 40% was used. For this, 20 ml of Cr standard solution was taken, and the same amount from the Cd standard solution was diluted to 400 ml with purified water and added to 1 kg of dry soil. In the current research, three simulated Cr and Cd polluted soil specimens with concentrations of 100, 200, and 300 mg kg-1 have been produced for investigation.

2.2. Soil Samples

At this point, one type of soil (clay) is used as a model to experiment. The samples of soil were collected from a depth range of 30 to 50 cm under the surface of the ground in an agricultural area of the Al Syahi precinct, south of Babil province. It was cleaned by removing any stones and plant roots and then further sieved through a 2mm sieve to achieve an acceptable regularity. The soil properties and their compositions are illustrated in Table 1.

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Table 1. The soil properties and compositions

Properties	Magnitude
particles size Distribution	
Sand (%)	21.20
Silt (%)	39.12
Clay (%)	36.61
Gravel (%)	0
Atterberg limit (ASTM D 2487)	
Liquid limit (%)	42.22
Plastic limit (%)	28.46
Plasticity index (%)	14.51
Compaction text	
Max dry density (gm/cm^3)	1.73
pH	7.8
$CaCO_3$ (%)	23

2.3. Tests of Electro-kinetic

2.3.1.Setting up of Reactor

The electrokinetic research setup utilized for this analysis is illustrated in Figure 1 and 2. Two compartments with electrodes, a battery source, and a multimeter. The internal size of the glass electro-kinetic cell is (400 x 80 x 100) mm. The actual length of this cell's soil sample is equivalent to 200 mm. Graphite electrodes were used as both the anode and cathode. To add a steady voltage to the electrodes, a DC source was utilized, and a multimeter was used throughout the test to track the voltage and determine the current flow through the soil specimen.

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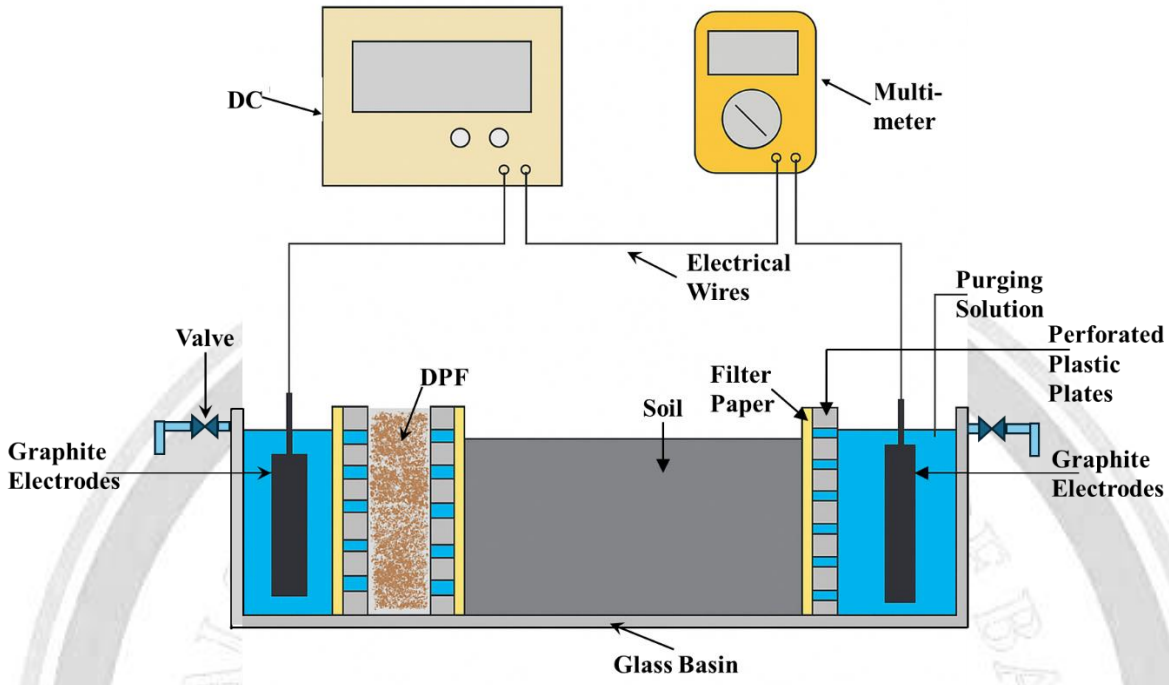

Figure1. Schematic diagram of the Electro-Kinetic Cell.

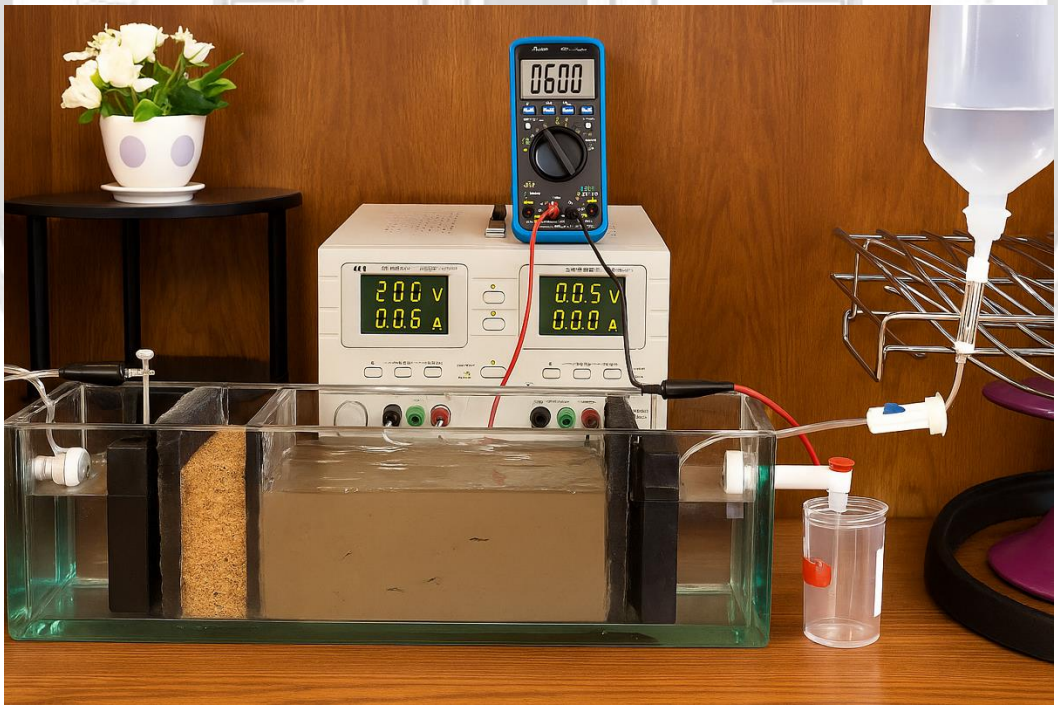

Figure 2. Trial system of EK chamber utilized in this work.

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2.4. Procedure of Experiments

With Cr and Cd combined, a soil specimen of approximately 1 kg is artificially injected. To achieve homogeneity of the heavy metal delivery in the soil, it has been blended well with the aid of a mechanical mixer. With the aid of purified water. Both tests are conducted utilizing (0.1 M) Ethylene Diamine Tetra acetic Acid such as catholyte throughout the analysis to save this OH^{-} ion as well as holding a tiny three pH and (0.1 M) of (E D T A) as anolyte to increase the distribution of H+ ion during the soil bed, thereby enhancing the operation of these elements and graphite electrodes dipped into these chambers and utilized for producing. Eventually, depending on the experimental plan, the procedure was initiated each time with the required test conditions (pH, voltage gradient, and amount). Every experiment takes five days and is conducted at the room's normal temperature. The current of electricity, as well as the depth of electroosmotic flow and the pH and conductivity of the electrolyte, are specifications measured on a 6-hour basis to account for current variance over time. Additionally, these measurements are used for energy consumption analysis, including the electroosmotic volume produced and the deterioration rate of process fluids. Soil samples have been taken after each test to measure soil pH, electrical conductivity, moisture content, and residual amounts of pollutants.

2.5. Experimental Design

Experiments have been planned to utilize Reaction Surface Methods (RSM) as they generate tremendous data from a limited number of experiments conducted. Along with other RSM methods, Box Behnken Designing (BBD) was utilized for second item model design for simulation, enhancement, and analysis of findings even with its benefits over others, taking account of deformation (nonlinear existence) of answers that are beyond the skill of the first design and is economically feasible since this needs less studies [4]. Version 18 of Minitab was the mathematical program used to accomplish these goals. Fifteen tests have been designed with three parameters (independent parameters) utilizing the BBD method: pH magnitude, heavy metal content, and voltage gradient.

The test number sufficient to support the spectrum of parameters was calculated using the Box-Behnken matrix, as described in Formula (1) [5].

$$N = 2k(k-1)+r \qquad (1)$$

Whereas:

N is the test number,

k is the parameter number,

Moreover, r is the number of replicated central points.

The approach suggested that the levels of the parameters modified at just three levels (+1, 0, -1) were identical, and the intervals between these levels were similar. The overall experiment number, calculated by Formula (1) for the 3-Box Behnken model parameters, is 12, in addition to three central point replicates. Therefore, the total would be Fifteen experiments to determine the impact of independent parameters on the removal process. Corresponding to the experimental design approach of Box Wilson, 27 tests were required to cover three independent machine parameters.

Table 2. Independent (controllable) variables and their levels.

Parameters (unit)	Character		Level		
	Coded	Actual	-1	0	1
Concentration(ppm)	x_1	X_1	100	200	300
Voltage (volt)	x_2	X_2	20	25	30
pH	x_3	X_3	4	6.5	9

Table 2, demonstrates X3, X2, and X1, the actual parameters (factor) selected for designing the 3-levels high= (+1), intermediate=(0), and low (-1) magnitudes. The coded parameters (x3, x2, and x1) have been connected to parameters by Formula

$$Xi = \frac{Xi - Xo}{\Delta Xi} \; ; \quad i = 1,2,3 \qquad (2)$$

Whereas:

The independent variable absolute magnitude at the central level= X0 and the interval magnitude= ΔX.

Table 3. Box-Behnken design matrixes.

Run	Design parameters		
	x_1	x_2	x_3
1.0	-1.0	-1.0	0.0
2.0	1.0	-1.0	0.0
3.0	-1.0	1.0	0.0
4.0	1.0	1.0	0.0
5.0	-1.0	0.0	-1.0
6.0	1.0	0.0	-1.0
7.0	-1.0	0.0	1.0
8.0	1.0	0.0	1.0
9.0	0.0	-1.0	-1.0
10.0	0.0	1.0	-1.0
11.0	0.0	-1.0	1.0
12.0	0.0	1.0	1.0
13.0	0.0	0.0	0.0
14.0	0.0	0.0	0.0
15.0	0.0	0.0	0.0

Table 3 indicates the Box Behnken matrixes are the experimental discovery organized at random orders to maximize the heavy metal removal mechanism in terms of estimating the impact of amount, voltage, and pH on the performance of removal of heavy metals [6]. The findings obtained for the impact of pH, voltage, and amount on removing performance could be modeled by Minitab as a second-order polynomial, which can be utilized to estimate the optimum values for the three parameters, as shown in Formula (3) [7].

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$$y = \beta 0 + \sum \beta i\, xi + \sum \beta ii\, x^2 i + \sum \beta ij\, xi\, x\, j + \varepsilon \qquad (3)$$

Whereas:

The response of estimating is *y*,

The coefficient of intercept is $\beta 0$,

The linear influence (slope) of input parameter *xi is* βi,

The linear interaction influenced by linear between two input parameters *xi is* βij,

Moreover, βii is squared influence.

Analysis of variation In order to find variations in the rate of success of the variables tested, ANOVA is a mathematical tool for decision-makers, at which a total of square and F-statistics have been utilized to explain the relative significance of analyzed data processing and error and unregulated parameter estimation.

Table 4. Experiment Details and Consequences for Behnken Box System (BBD)

Trials	Variables			(Removing efficacies and Energy usage) Responses		
	amount	voltage	pH	Cr%	Cd%	Energy usage (kWh)
1	100	20	6.5	95.84	92.45	0.2
2	300	20	6.5	82.49	80.20	0.3
3	100	30	6.5	96.01	95.31	0.59
4	300	30	6.5	92.57	90.54	0.6
5	100	25	4	95.88	93.77	0.413
6	300	25	4	85.89	83.43	0.5
7	100	25	9	79.18	77.52	0.36
8	300	25	9	71.69	70.40	0.31
9	200	20	4	88.99	86.65	0.27
10	200	30	4	90.15	88.61	0.69
11	200	20	9	72.04	71.14	0.23
12	200	30	9	85.80	83.74	0.7
13	200	25	6.5	90.10	89.50	0.28
14	200	25	6.5	90.10	89.50	0.28
15	200	25	6.5	90.10	89.50	0.28

3. Results And Discussion

3.1. Removing Efficacies Toxic Metals

At the duration end of the fifth day of operating, depending on the experimental plan, the consequences shown in Figures 3 and 4 demonstrate the average removal efficacies of the toxic chemicals. As a consequence of the experimental situations, the reported differences within each toxic metal. It can be observed from Figures 3 and 4 that Cr ions have the most effective removal efficacy, while Cd ions have the lowest removal efficacy. The results showed that the majority of Cr removed from the soil is the most portable, followed by Cr, which is the most portable metal,

and Cd. The optimum interventions are achieved throughout the range Cd< Cr, using EDTA as a complexing agent. Overall, the best-removing efficacies of heavy metals occurred when the pH at the anode and cathode partitions was 6.5 in EX-3, where 96.01% and 95.31% removals of Cr and Cd, respectively, were achieved due to M-EDTA^2 being the primary type under neutral pH conditions. Consequently, negative charges in M-EDTA structures have been transferred by chemical oxidation to the anode [8]. Therefore, EDTA may be known to be a comparatively highly impactful processing fluid that acts to extract metals. The steadiness constants are far greater for M-EDTA complexes than for other complexes. In addition, EDTA may be added to a metal ion up to 6 positions as a form of chelator, allowing minerals to be desorbed from the surface particles of the matrix and controlling the speed of metal ion movement in the substance [9]. The removal efficacies have been determined depending on the residual and initial pollutant amount in the soil. The removing efficacies are given by Eq (4):

$$\eta\ \% = \frac{\text{Initial conc.} - \text{Residual conc.}}{\text{Initial conc.}} * 100 \quad (4)$$

Whereas:

η % : Removing Efficacy

From Figures 3 and 4, the removing efficacies for Cr and Cd are 95.84, and 92.45 %, respectively in EX-1 with the use of initial amount 50 mg/kg for each contaminant in soil have been greater than the removing efficacies of Cr and Cd are 82.49, and 80.2% respectively in EX-2, where the initial amount of each contaminant is 150mg/kg, due to the flow of electroosmotic was reduced with the increasing of initial amount of heavy metal, hence the increase in pollutant removing and migration. The removal efficacies of lead and copper are 90.15% and 88.61%, respectively, in EX-10 when the applied voltage is 30 V. In contrast, the removal efficacies of Cr and Cd are 88.99% and 86.65%, respectively, in EX-9 under the same conditions but at 20 V.

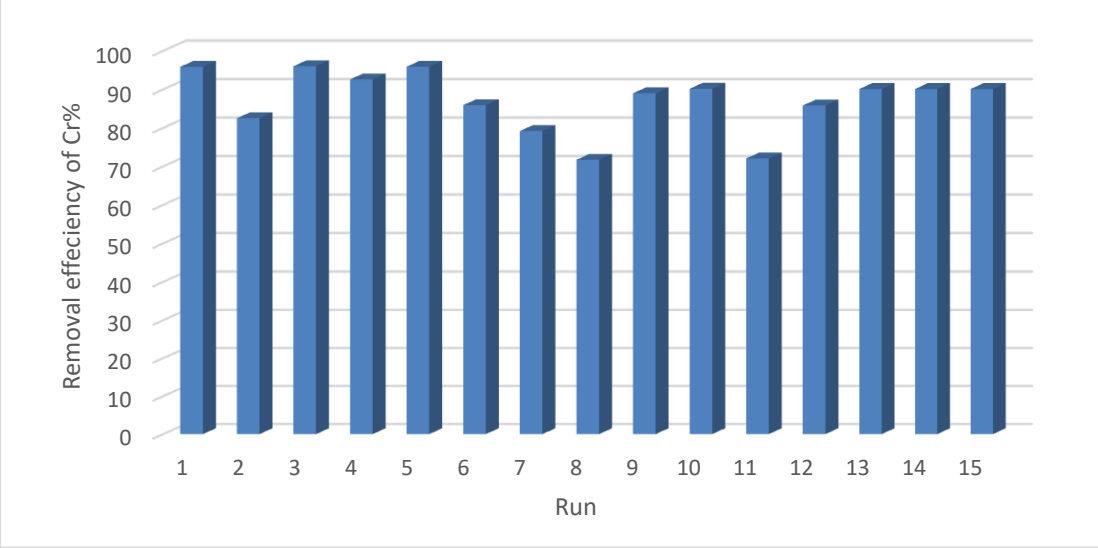

Figure 3. percent of removing efficacy of Cr

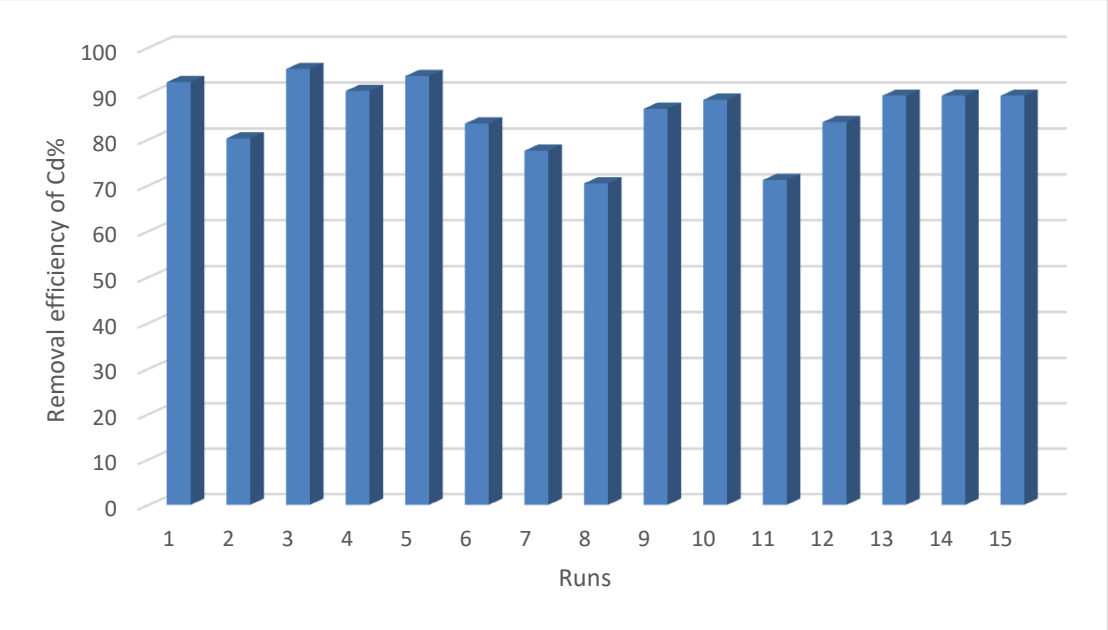

Figure 4. percent of removing efficacy of Cd

3.2. Energy Usage

Figure 5 shows the energy usage difference over the five days of remediation for the 15 investigational tries; it could be detected from R1&R2 That energy consumption increases with the increase in the amount of toxic metals due to increasing in the current generated throughout the experiment due to increase in soil electrical conductivity. As for the voltage, the utilized energy increases with the increase in the voltage. It has been noticed throughout R1 1and R12 experiments that the greater the voltage, the greater the energy utilized. In terms of Ph, the energy utilized up is significant at small pH magnitudes and in the occurrence of low amounts of heavy metals, as well as the occurrence of low voltages, while the energy utilized up increases with an increase in the pH at significant amounts of heavy metals, as well as at great voltages. In the next part, the 3D surface reaction graphs provide a simple differentiation of these energy usage variables.

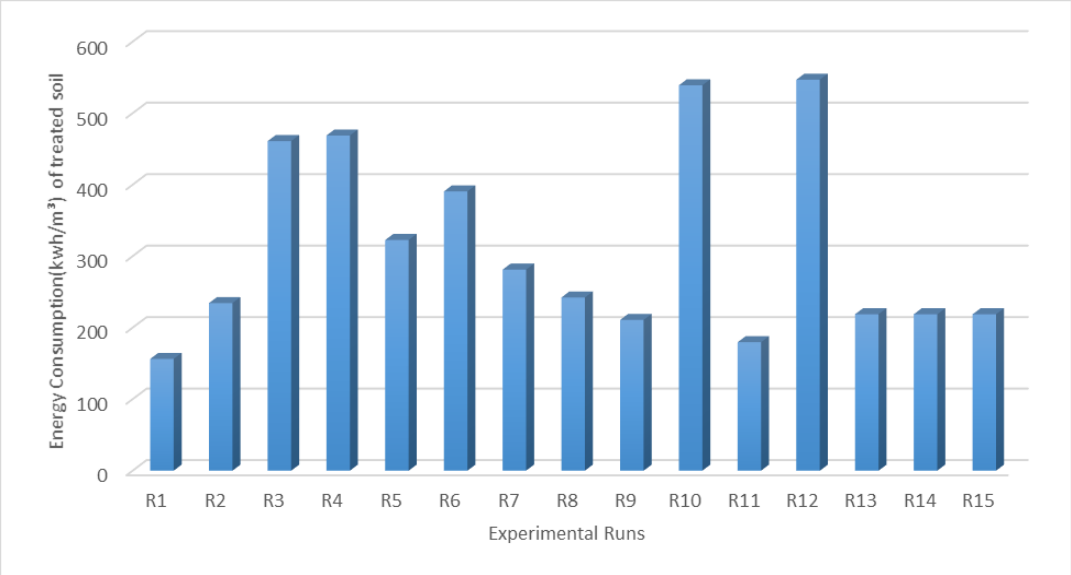

Figure 5. the differentiation of energy usage

The energy consumption is given by Eq (4.2):

$$E = \int_0^t VI\, dt \qquad (5)$$

4. Surface Response for 3D-draws Demonstrates the impact of responses on the parameters

The models are created based on experimental evidence and have been demonstrated to be true within a 95 percent confidence interval by both statistical tests and hypotheses, providing a degree of confidence depending on the facts acquired from these plots. These graphs enable us to analyze the data further and appreciate the impact of the independent variables of concern (heavy metal amount, induced voltage, and pH) on the reactions in this analysis, ranging from heavy metal removal efficacy to energy usage.

4.1. Removing efficacy of Heavy metal

The 3D contour and surface response diagrams demonstrating the impact of pH, applied voltage, and amount on the removing efficacies of heavy metals dependent on the Fifteen experimental findings over five days of remediation period are seen in figures 6-9. The results indicate that raising the voltage that is used from 20 to 30 V boosts removal efficacy, likely due to an increase in the mobility of heavy metal ions resulting from heightened potential variance. The increase in pH of the purification process solution resulted in a diminished efficacy for the removal of all heavy metals. Additionally, the transport of heavy metal ions from the cathode to the anode, also the quantity of these ions increased with a decrease in pH. This is due to the heightened tendency of metal ions to adsorb onto soil particles as pH rises [10]. Precipitation and ion exchanges [11, 12] are other possible factors that diminish removal effectiveness. The data indicates the presence of heavy metals in both scenarios.

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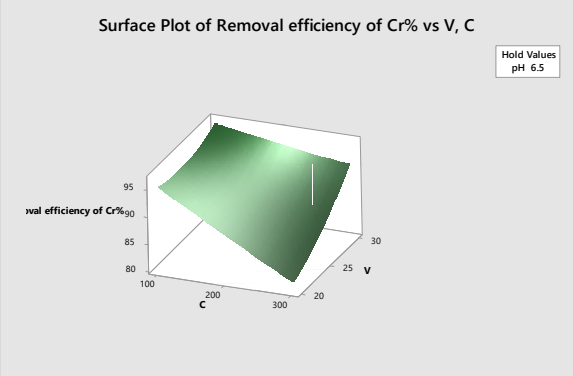

Figure 6. Effects of concentration and Voltage gradient on Cr Removal.

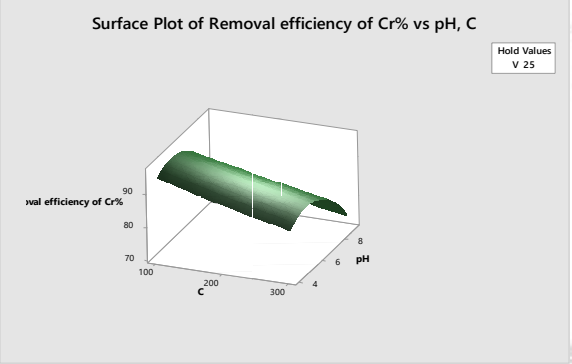

Figure 7. Effects of concentration and pH on Cr Removal.

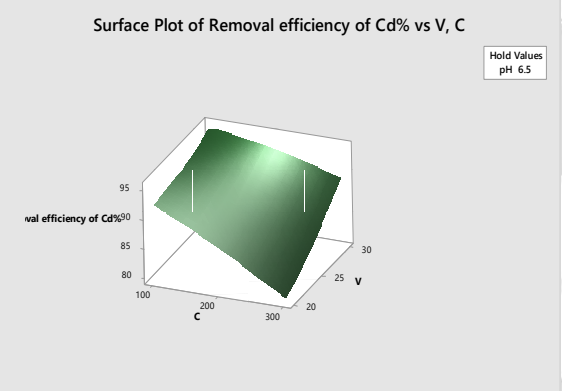

Figure 8. Effects of concentration and V gradient on Cd Removal

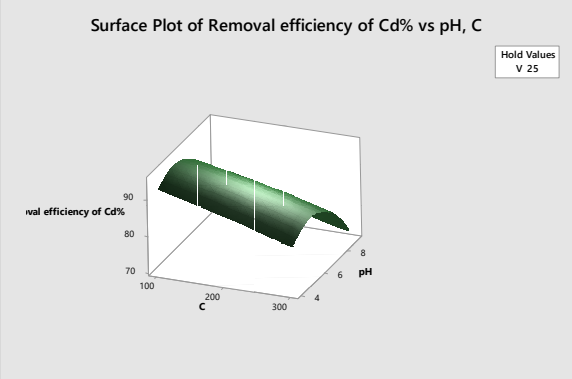

Figure 9. Effects of concentration and pH on Cd Removal.

4.2 Energy consumption

Figures 10 and 11 demonstrate the variance of the three energy usage variables, which could be easily demonstrated from the deformation of Figure 10, which demonstrates the rise in the applied voltage from 20 to 30 raises the energy, that is attributable to the reality that the rise in the applied voltage improves the voltage as well as the consuming of energy and current, and is essentially the consequence of the two. Furthermore, It has been noted that the elevation of heavy metal amounts leads to increased energy use. The usage of energy is substantial at low pH levels and minimal heavy metal concentrations, and at low voltages. Conversely, energy consumption escalates with rising pH levels in the presence of substantial heavy metals amounts and high voltages.

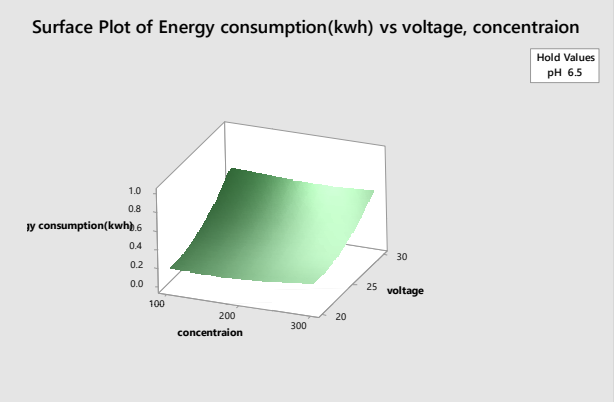

Figure 10. effect of concentration and voltage gradient on Energy consumption.

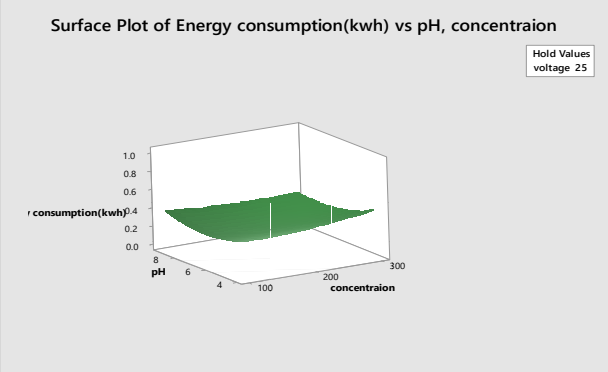

Figure 11. Effects of concentration and pH on Energy consumption.

5. Statistical analysis and Models' Fitting

Depending on the experiment's nature, the consequences provided in Table 4 are the experiment's outcomes. It was supplied to the Minitab. Tables 5-7 present the variance analysis for all the responses modeled, which involve (Cr and Cd) removal, and Energy usage. As identified in the variance analysis tables at the 5 percent significance stage, the surface reaction models built have been validated with all the required likelihood and statistical tries. A possibility magnitude (p-magnitude) < 0.05 indicates that a model is statistically effective in estimating a reaction to ensure that almost all established models in their projections were very relevant. The formula has been returned several times with every model created to eliminate the negligible terms before a final refines model has been developed in which all the terms were relevant depending on <0.05 p-magnitude. The final formulas, derived from fitting the experiment's outcomes, are presented in Formulas 6 to 8.

Removal efficiency of Cr% = 155.1 - 0.1938 C - 4.71 V + 5.59 pH + 0.000027 C*C +0.0542 V*V - 1.154 pH*pH + 0.00495 C*V + 0.00250 C*pH + 0.2520 V*pH (6)

Removal efficiency of Cd% = 117.6 - 0.1349 C - 2.82 V + 7.48 pH - 0.000056 C*C + 0.0276 V*V - 1.225 pH*pH + 0.00374 C*V + 0.00322 C*pH + 0.2128 V*pH (7)

Energy consumption(kwh) = 2.536 + 0.00088 concentration - 0.1772 voltage - 0.1836 pH + 0.000003 concentraion*concentraion + 0.004385 voltage*voltage + 0.01326 pH*pH - 0.000045 concentraion*voltage - 0.000137 concentraion*pH + 0.00100 voltage*pH (8)

Table 5. Analyzing the variance table (ANOVA)for Cr removing

Source	DF	Adj SS	Adj MS	F-Magnitude	P-Magnitude
Model	9	839.751	93.306	32.61	0.001
Linear	3	566.6	188.867	66.01	0
C	1	146.804	146.804	51.31	0.001
V	1	79.191	79.191	27.68	0.003
pH	1	340.605	340.605	119.05	0
Square	3	207.346	69.115	24.16	0.002
C*C	1	0.272	0.272	0.09	0.77
V*V	1	6.792	6.792	2.37	0.184
pH*pH	1	192.008	192.008	67.11	0
2-Way Interaction	3	65.805	21.935	7.67	0.026
C*V	1	24.552	24.552	8.58	0.033
C*pH	1	1.562	1.562	0.55	0.493
V*pH	1	39.69	39.69	13.87	0.014
Error	5	14.306	2.861		
Lack-of-Fit	3	14.306	4.769	*	*
Pure Error	2	0	0		
Total	14	854.057			

Table 6. analyzing of variance table (ANOVA)for Cd removing

Source	DF	Adj SS	Adj MS	F-Magnitude	P-Magnitude
Model	9	820.54	91.171	44.88	0
Linear	3	553.2	184.4	90.78	0
C	1	148.609	148.609	73.16	0
V	1	96.327	96.327	47.42	0.001
pH	1	308.264	308.264	151.75	0
Square	3	222.457	74.152	36.5	0.001
C*C	1	1.179	1.179	0.58	0.481
V*V	1	1.758	1.758	0.87	0.395
pH*pH	1	216.366	216.366	106.51	0
2-Way Interaction	3	44.882	14.961	7.36	0.028
C*V	1	13.988	13.988	6.89	0.047
C*pH	1	2.592	2.592	1.28	0.31
V*pH	1	28.302	28.302	13.93	0.014
Error	5	10.157	2.031		
Lack-of-Fit	3	10.157	3.386	*	*
Pure Error	2	0	0		
Total	14	830.696			

Table 7. analyzing of variance table (ANOVA)for Energy usage

Analyzing of Changes					
Sources	DF	SS Adj	MS Adj	F-Magnitude	P-Magnitude
Model	9	0.397731	0.044192	19.49	0.002
Linear	3	0.324067	0.108022	47.64	0
concentration	1	0.002701	0.002701	1.19	0.325
voltage	1	0.31205	0.31205	137.62	0
pH	1	0.009316	0.009316	4.11	0.098
Square	3	0.066322	0.022107	9.75	0.016
concentration*concentration	1	0.003991	0.003991	1.76	0.242
voltage*voltage	1	0.044373	0.044373	19.57	0.007
pH*pH	1	0.02536	0.02536	11.18	0.02
2-Way Interaction	3	0.007342	0.002447	1.08	0.437
concentration*voltage	1	0.002025	0.002025	0.89	0.388
concentration*pH	1	0.004692	0.004692	2.07	0.21
voltage*pH	1	0.000625	0.000625	0.28	0.622
Errors	5	0.011337	0.002267		
Lack-of-Fit	3	0.011337	0.003779	*	*
Error of Pureness	2	0	0		
Total	14	0.409068			

The coefficients of correlation models are as obtainable in Table (8) with R^2 magnitudes of 0.9832, 0.9878, and 0.9723 arrived at for Cr removing, Cd removing, and Energy usage models' respectively. Although R2 is considered skewed [13,14], a stronger coefficient of correlation is also utilized, which is less skewed and more reliable for determining the adequacy of the modified model, named R2. For example, the elimination of the Cr model of R2 of 0.9832 has an appropriate and good agreement of < 0.2 variations between the modified R2 of 0.9531 and the expected R2 of 0.732 means that there is no anomaly in the data, which suggests that the variables in the experiment studied can be related to 95.31 percent (adjusted R2) of the overall variance in the elimination of Cr and around 0.5 percent possibility that perhaps the difference of the surface reaction model could be attributable to noise (experimental error), which indicates that the model's estimation potential falls below the 95 percent trust limit. An SD of 1.69 has been observed, reinforcing the model's high efficiency. It is necessary to remember that as the modified R2 magnitude tends towards unity, the SD contributes to a lower magnitude. The number of squares projected provides a measurement of the model-built model-building process suited for the design points. Similarly, the surface reaction models for Cd removing have significantly modified R2 magnitudes for energy use and are in good alignment with the respective expected R2, as demonstrated in Table (8). The other model adequacy checks were considered to be of a comparable type to the elimination of Cr. All testing conducted shows the models to be of a great standard and perfectly adequate to manage the spaces' design for the projects, thereby forming accurate inferences. Much of the fit's models indicate some reliability based on the statistical assessment done.

Nevertheless, for high-performing versions, medium R2 magnitudes with R2(pred) magnitudes of 0.5566 can be called moderate R2 magnitudes. However, even though all other predictive assessments are satisfactory, these models may have reaction actions attributable to the variables examined. [13,14].

Table 8. Surface reaction models with the coefficients of correlation magnitudes for reaction

Reactions	SD	R2	R2(adj)	R2(pred)
Cr removing	1.69149	98.32%	95.31%	73.20%
Cd removing	1.42525	98.78%	96.58%	80.44%
Energy usage	0.047618	97.23%	92.24%	55.66%

Conclusion

This research examined the impact of pH, voltage gradient, and heavy metal amounts on the efficacy of removal of Cr and Cd, as well as the energy usage of the electrokinetic remediation process. Models were created to forecast the parameters within acceptable anticipated R values. An elevation in the amount of heavy metals was seen to diminish the efficacy of removal of both Cr and Cd. An elevation in voltage gradient correspondingly enhanced the removal efficiencies of both Cr and Cd. A rise in pH results in a reduction in the removal efficiency of both Cr and Cd. The usage of energy escalates with the rising content of heavy metals, attributable to the augmented current created throughout the experiment because of increased soil electrical conductivity. The energy used escalates with an increase in voltage. The energy expenditure is significant at low pH levels, particularly with minimal quantities of heavy metals and low voltages. On the other hand, energy consumption increases with rising pH levels with increased amounts of heavy metals and high voltages.

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تعزيز المعالجة الكهروحركية للتربة الملوثة لإزالة أيونات المعادن الخطرة

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الخلاصة

تم إجراء دراسة كهروحركية لفحص تأثير محتوى المعادن الثقيلة، وتدرج الجهد، ودرجة الحموضة (pH) على استهلاك الطاقة وكفاءة إزالة مزيج من المعادن الثقيلة (الكروم Cr والكادميوم Cd) من التربة الملوثة.**

وقد تم تنفيذ خمس عشرة (15) تجربة باستخدام تصميم بوكس–بينكن (Box–Behnken Design)، امتدت كل تجربة لمدة خمسة أيام. استخدمت البيانات لتقدير كفاءة إزالة المعادن الثقيلة والطاقة المستهلكة أثناء العملية باستخدام برنامج "مينيتاب" (Minitab).

تشير نتائج التحسين العددي إلى أن الاستخدام الأمثل للطاقة بلغ **156.3 كيلوواط ساعة لكل متر مكعب من التربة المعالجة**، مع تحقيق كفاءة إزالة للكادميوم والكروم بلغت **95.31% و96.01%** على التوالي، وذلك ضمن ظروف تشغيل تشمل تراكيز معادن ثقيلة بمقادير 100، و200، و300 ملغم/كغم، وتدرجات جهد تبلغ 20، و25، و30 فولت/سم، ومستويات pH عند 4، و6.5، و9.

لوحظ أن زيادة محتوى المعادن الثقيلة تؤدي إلى انخفاض في كفاءة الإزالة، ويُعزى ذلك إلى زيادة التيار الكهربائي المتولد أثناء التجربة، الناتج عن زيادة التوصيلية الكهربائية للتربة. ومن ناحية أخرى، تبين أن زيادة تدرج الجهد تُحسن من كفاءة الإزالة.

كما لوحظ أن ارتفاع كل من محتوى المعادن الثقيلة وتدرج الجهد يؤدي إلى زيادة استهلاك الطاقة؛ ومع ذلك، فإن استهلاك الطاقة يكون مرتفعًا أيضًا عند انخفاض قيم pH ومحتوى المعادن الثقيلة، وكذلك عند تدرجات الجهد المنخفضة. وعلى العكس من ذلك، فإن استهلاك الطاقة يزداد مع ارتفاع قيم pH عند وجود تدرجات جهد عالية وتراكيز مرتفعة من المعادن الثقيلة.

الكلمات الدالة:– المعالجة الكهروحركية للتربة؛ الكروم(Cr) ؛ الكادميوم(Cd) ؛EDTA ؛ كفاءة الإزالة؛ استهلاك الطاقة.