Performance Evaluation and Optimization of Electrocoagulation for Cadmium Removal from Wastewater

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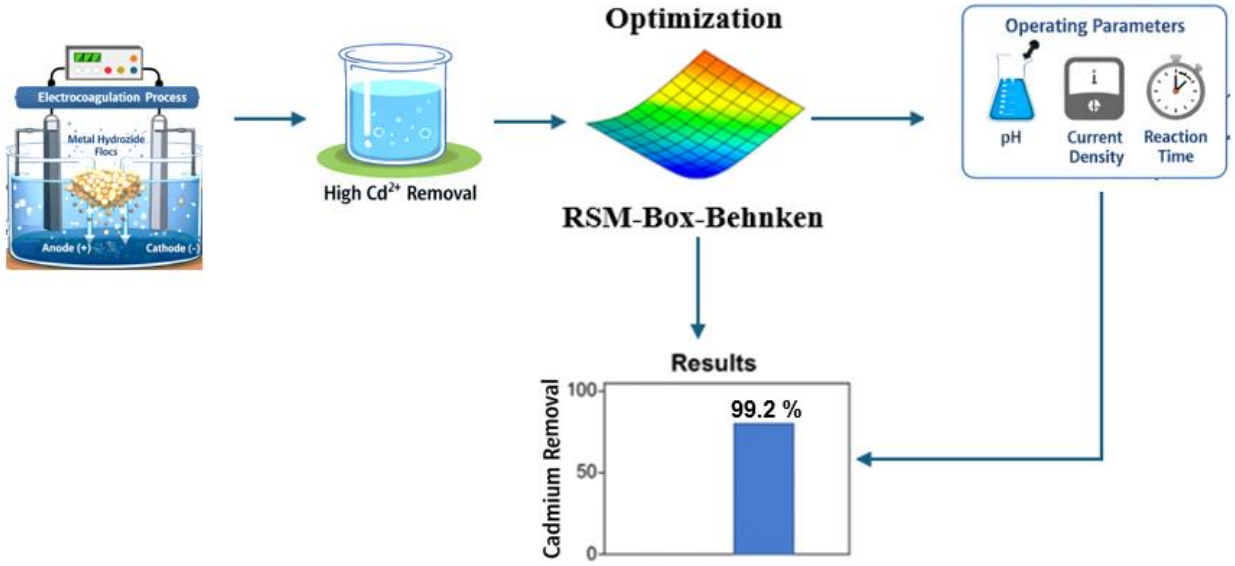
Graphical Abstract



Abstract

This study investigates the optimization of cadmium (Cd) removal from wastewater using the electrocoagulation (EC) process coupled with Response Surface Methodology (RSM). Synthetic wastewater containing 100 mg/L of Cd^{2+} was treated in a laboratory-scale reactor using aluminum and iron electrodes. Key operational parameters such as pH (4-10), current density (30-90 A/m²) and reaction time (20-60 min) were studied to investigate their influence on cadmium removal efficiency by Box-Behnken design. Cd removal efficiency ranged from 85.8-99.2% with better efficiency at neutral to slightly alkaline conditions. Statistical analysis indicated that pH was the most significant factor affecting removal efficiency followed by reaction time and current density had a minor effect. The quadratic model developed was found to be highly significant ($p < 0.0001$) with high coefficient of determination ($R^2 = 0.992$) and non-significant lack-of-fit confirming its reliability. The optimum conditions were found to be pH 8.8, current density 68.5 A/m² and reaction time 40.5 min which predicted a removal efficiency of 99.49%. Experimental validation showed removal efficiency of

97.64% with only 1.85% deviation. The results obtained suggest that EC combined with RSM is an effective and promising method for the cadmium removal from wastewater.

Keywords: Electrocoagulation, Response Surface Methodology, Water treatment, Optimization, Cadmium removal.

1. INTRODUCTION

Heavy metals' persistence, non-biodegradability, toxicity, and bioaccumulation potential in ecological and human systems have raised the issue of their contamination of water bodies to a global problem. Among the various heavy metals, cadmium (Cd) is of particular concern due to its widespread release from industrial activities such as electroplating, battery manufacturing, mining, metallurgy, and pigment production (Jaishankar et al., 2014; Fu & Wang, 2011; Qasem et al., 2021; Tchounwou et al., 2012; He et al., 2013). Once in the water bodies, cadmium can be accumulated in sediments and enter the food chain with long-term risks for aquatic ecosystems and human health (Ali et al., 2019; Jaishankar et al., 2014). Even at trace concentrations, exposure to cadmium is detrimental to human health; it has a number of adverse effects including: renal dysfunction, damage of the bone, endocrine disruption, carcinogenicity, (WHO 2017, Tchounwou et al. 2012, Nordberg et al. 2015), etc. Thus effective removal of Cd is needed.

The removal of heavy metals has been extensively studied and the conventional treatment technologies such as chemical precipitation, ion exchange, membrane filtration and adsorption have been widely applied. Despite being successfully applied on certain occasions, other treatments have some disadvantages like expensive capital and operating cost, formation of sludge, membrane fouling and low removal efficiencies with low concentrations of metal ions (Fu & Wang, 2011; Barakat, 2011; Jawad et al., 2023; Liu et al., 2019; Crini & Lichtfouse, 2019). Because of such defects and in search of alternative sustainable methods for effluent treatment electrocoagulation (EC) technology was introduced as one of the promising technology, gaining interest in the removal of many contaminants with simplicity of operation, relatively low chemical consumption, high efficiency and environmental

benefits (Mollah et al., 2001; Chen, 2004; Holt et al., 2005; Emamjomeh & Sivakumar, 2009; Nath et al., 2024). Recent studies have further demonstrated the high efficiency of electrocoagulation for toxic metalloid removal, with optimized Al- and Fe-electrode systems achieving removal efficiencies exceeding 99% under appropriately controlled pH, current density, and reaction time (Tuan et al., 2025a).

The EC process is based on the electrochemical dissolution of sacrificial metal electrodes (commonly aluminium or iron) under the effect of an applied electric current. The anodic oxidation yields metal ions which are afterwards hydrolyzed to form a variety of hydroxide and polymeric species that act as coagulants (Gomes et al., 2007; Holt et al., 2005). The in situ coagulants enhance the removal of contaminants by several mechanisms, including adsorption, charge neutralization, scavenging coagulation and simultaneous precipitation (Mollah et al., 2001; Chen, 2004). Compared to conventional coagulation, electrocoagulation presents advantages such as lower sludge production, better floc properties and no requirement of external chemical dosing (Holt et al., 2005; Emamjomeh & Sivakumar, 2009). A schematic of the electrocoagulation mechanism is shown in Figure 1.

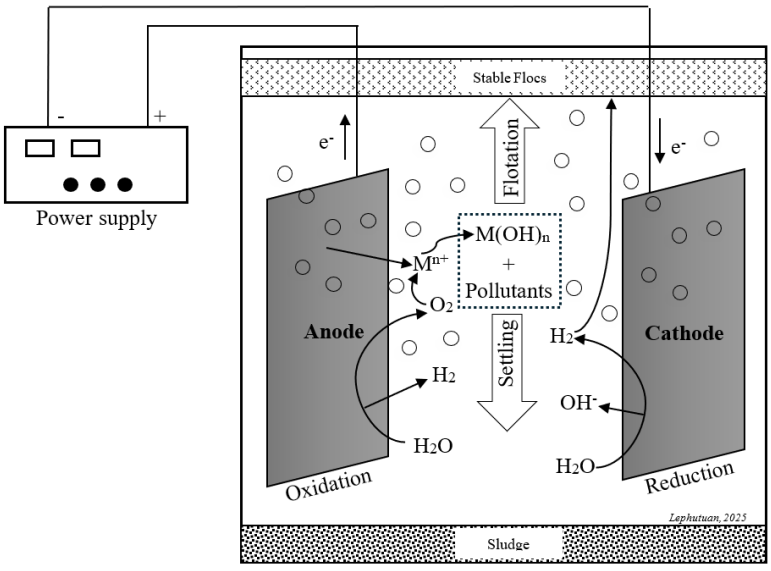


Figure 1. Mechanism of electrocoagulation process adapted from Tuan et al. (2025)

The aluminium electrocoagulation is characterized by the simultaneous electrochemical reactions on anode and cathode surfaces through the application of an electric current. Metallic aluminum at the anode is oxidized resulting in release of aluminium cations into the solution (Al^{3+}). In parallel, at the

cathode, a reduction reaction occurs, during which hydrogen gas (H_2) and hydroxide ions (OH^-) are produced. These reactions take place continuously and are crucial for the formation of coagulants in the aqueous environment.

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^- \qquad Equation\ (1)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad Equation\ (2)$$

Aluminum ions (Al^{3+}) are rapidly generated in solution and are involved in hydrolysis, and formation of a wide range of hydroxide forms and a number of different polymeric hydroxide complexes such as $Al(OH)^{2+}$, $Al(OH)_2^+$ and especially $Al(OH)_3$. These compounds exhibit very high coagulation capabilities and act as "in-situ coagulants". They assist in the removal of pollutants through a number of mechanisms. These mechanisms include: (i) direct chemical interaction with pollutants, (ii) neutralization of the electrical charge of charged colloidal particles in water and (iii) formation of large hydroxide flocs that can "capture" and bind pollutants together, thereby promoting sedimentation and removal from the solution (Mollah et al., 2001).

The general reaction in the whole system is the formation of $Al(OH)_3$ precipitate by the combination of aluminum ions and water, which is important in removing dissolved pollutants.

$$Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightarrow Al(OH)_{3(s)} + 3H^+_{(aq)} \qquad Equation\ (3)$$

$$Al^{3+}_{(s)} + OH^- \rightarrow Al(OH)_{3(s)} \qquad Equation\ (4)$$

The $Al(OH)_3$ flocs formed in the solution phase interact with pollutants (e.g., Cd) through two main mechanisms, namely, precipitation and adsorption. The flocs have a porous structure and a large surface area, which enable them to adsorb pollutant ions and "trap" the pollutant ions within the floc structure, thus effectively removing pollutants from the solution by sedimentation to the bottom or by subsequent treatment methods.

$$Al(OH)_{3(s)} + CdO^{3-}_{4(aq)} \rightarrow [Al(OH)_3 * CdO_4^{3-}]_{(s)} \qquad Equation\ (5)$$

The importance of systematic optimization has also been demonstrated in other electrochemical treatment systems, where interactions among operating variables can substantially influence treatment performance (Tuan, 2026). However, the performance of electrocoagulation is strongly

affected by operating parameters such as pH, current density and reaction time. These parameters affect the dissolution of electrodes, the formation of coagulants and mechanisms of pollutant removal (Holt et al., 2005). Therefore, the optimization of these parameters is necessary to obtain the maximum removal efficiency and process sustainability. Response Surface Methodology (RSM) is a widely employed statistical tool for modeling and optimizing complex treatment processes involving multiple interacting variables, while reducing the number of experimental runs required to develop reliable predictive models (Montgomery, 2017; Bezerra et al., 2008). Recent applications of Box–Behnken Design coupled with RSM have demonstrated high predictive performance in optimizing contaminant removal processes, including arsenic adsorption using $KMnO_4$-modified and TiO_2-impregnated laterite (Tuan et al., 2025b; Tuan & Oanh, 2025).

Although electrocoagulation has been widely investigated for removing toxic inorganic contaminants, systematic optimization for cadmium removal remains limited. In particular, the individual and interactive effects of key operating parameters, such as pH, current density, and reaction time, are not yet fully understood. Therefore, integrating experimental design with statistical modeling is essential to identify optimal operating conditions and develop reliable predictive models for efficient Cd removal from wastewater.

To fill such gaps, the present work aims to (i) evaluate the performance of electrocoagulation for cadmium removal from synthetic wastewater, (ii) study the effect of major operational parameters such as pH, current density and reaction time on removal efficiency and (iii) optimize the process using Response Surface Methodology based on Box-Behnken design. The work further aims to develop a reliable predictive model and validate its performance through statistical analysis, thus providing practical insights in the design and optimization of electrocoagulation systems for cadmium contaminated wastewater.

2. METHODOLOGY

2.1. Preparation of synthetic wastewater and analytical methods

The synthetic wastewater spiked with cadmium ions (Cd^{2+}) was generated in the laboratory in the synthetic form simulating industrial wastewater. The initial Cd^{2+} concentration was maintained at 100 mg/L prepared by dissolving analytical-grade cadmium nitrate ($Cd(NO_3)_2$) with a purity of 95% in deionized water. Sodium chloride (NaCl) was present at the concentration of 2 g/L as supporting electrolyte to enhance the electrical conductivity of the solution so as to ensure stable current during electrocoagulation. The initial pH of the solution ranged between 4 and 10, achieved by titration using both standardized 0.1 N hydrochloric acid (HCl) and 0.1 N sodium hydroxide (NaOH) since pH affect metal complexation, electrode dissolution and coagulant production. The Cd^{2+} concentration of samples was analyzed using atomic absorption spectroscopy (AAS) equipped with Shimadzu AA-7000F by following the standard analytical method.

The efficiency of cadmium removal was evaluated by comparing the initial concentration (X_0) with the concentration after a certain reaction time (X_t). The percentage of removal efficiency was calculated using the following equation:

$$Cadmium\ removal\ (\%) = ((X_0 - X_t) / X_0) \times 100 \qquad Equation\ (6)$$

where X_0 (mg/L) is the initial concentration of Cd^{2+} in the solution and X_t (mg/L) is the residual concentration at time t. This calculation approach could potentially be used for quantifying different treatments during a quantitative comparison under various conditions. pH values were measured using pH meter (calibrated, accuracy = +/- 0.1) in the pre and post the runs to determine any difference during Electrochemical treatment, from those which were recorded after treatments had run. Each experiment was performed in triplicate to ensure reproducibility and reliability of the data and the average values of the experiments were used for further analysis.

With the help of experimental design and optimization of the Process using Design-Expert software (version 13), the effects of the critical operational parameters and their interactions were

systematically studied. For the development of a predictive model and the identification of optimal operating conditions with a minimum number of experimental runs, the Response Surface Methodology (RSM) approach was used. The statistical technique is especially useful for the analysis of complex systems with multiple interacting variables and for maximizing the cadmium removal efficiency.

2.2. Experimental Procedure

The electrocoagulation (EC) system used in this study (Figure 2) was designed to meet the requirements of stable operation, uniform mixing and reproducible experimental conditions. The central part of the system was a 10 L rectangular acrylic reactor chosen for its chemical inertness, durability and transparency, which allowed to observe the formation of flocs and their settling behavior during treatment. In order to maintain homogeneous conditions in the reactor and avoid localized concentration gradients, a magnetic stirrer was installed and run at a constant speed, which ensured an effective mixing of the electrolyte, coagulants and contaminants in the course of the reaction period.

A power supply of direct current (DC) (Alexan, range of operation: 10-30 V, 0-5 A) was used to supply a stabilized and adjustable current to the electrode assembly. The electrode system consisted of parallel aluminum and iron plates (each of dimensions of 210mm × 100mm × 3mm) and was selected because of their proven effectiveness in the generation of coagulant species in electrocoagulation processes. The electrodes were placed in a monopolar system in a vertical position with a constant interelectrode distance of 20mm, which was an optimal value for the electrical resistance and the efficiency of coagulation generation of the system and minimum of energy consumption. Each electrode was immersed to a depth of about 190mm to ensure the contact with the volume of wastewater and maximum active surface area of the reaction.

The electrodes were connected to the power supply using insulated copper wires and alligator clips for accurate control and real-time adjustment of the applied voltage and current to maintain constant operating conditions for all experimental runs.

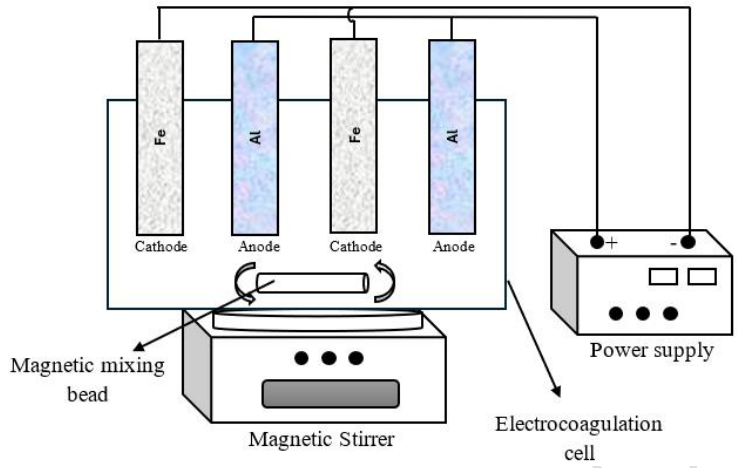


Figure 2. Electrocoagulation setup used in this study

The ranges of pH, current density and reaction time selected in this study were based on their practical applicability and well-established findings in previous electrocoagulation studies and experimental verification by the research team. The pH range is from acidic to alkaline conditions, enabling a comprehensive assessment of metal speciation, solubility and hydroxide formation which are critical for the efficiency of cadmium removal (Chen, 2004; Mollah et al., 2001). Near-neutral and slightly alkaline conditions are particularly favourable for the formation of metal hydroxide flocs that promote the adsorption and aggregation of contaminants (Garcia-Segura et al., 2017).

The selected current density range was based on the requirement of enough anodic dissolution and generation of coagulant species, but not too high that it leads to high energy consumption and passivation of electrode (Chen, 2004; Kobya et al., 2003). The selected reaction time range was based on the presence of an initial rapid removal stage, followed by a stabilization stage, which would permit hydrolysis, floc formation and aggregation of the pollutants (Mollah et al., 2001; Hakizimana et al., 2017).

The clean samples were taken from the reactor at fixed time intervals to avoid any contamination. The samples were immediately filtered, generally through standard filter paper, to remove the

suspended flocs and the residual precipitates. The filtrate was analyzed for the residual Cd^{2+} concentration by atomic absorption spectroscopy (AAS).

All experiments were carried out at ambient lab conditions, with temperature controlled between 23 and 27°C. Temperature control was important to minimize the effect of thermal changes on electrochemistry and mass transfer and to ensure reliable and comparable experimental results.

3. RESULTS AND DISCUSSION

3.1. Electrocoagulation treatment of cadmium-contaminated wastewater

A total of 19 experimental runs were performed according to the designed matrix and each experiment was performed in triplicate to ensure the reliability and reproducibility, and average values were reported subsequently. The electrocoagulation process was applied to cadmium contaminated wastewater with an initial concentration of 100 mg/L under different operational conditions. Detailed experimental parameters and the corresponding removal efficiencies are systematically presented in Table 1 and form the basis for subsequent modeling and optimization analysis.

Table 1. Box-Behnken design matrix and corresponding experimental results for cadmium removal in wastewater treatment

RUN	pH	Current density (A/m^2)	Reaction time (min)	Outflow (mg/L)	Cadmium removal (%)
1	4	30	40	13.4	86.6
2	10	30	40	2.8	97.2
3	4	90	40	13.7	86.3
4	10	90	40	2.9	97.1

5	7	30	20	1.9	98.1
6	7	30	60	1.0	99.0
7	7	90	20	5.3	94.7
8	7	90	60	1.4	98.6
9	4	60	20	12.9	87.1
10	10	60	20	3.7	96.3
11	4	60	60	11.5	88.5
12	10	60	60	1.6	98.4
13	7	60	40	0.8	99.2
14	7	60	40	1.4	98.6
15	7	60	40	1.1	98.9
16	4	30	20	14.2	85.8
17	4	90	20	13.1	86.9
18	10	90	20	3.2	96.8
19	10	30	60	1.3	98.7

Table 1 presents the experimental matrix and the corresponding treatment performance. The parameters under study were pH (4-10), current density (30-90 A/m²) and reaction time (20-60 min). The results revealed a large variation in the treatment efficiency. The cadmium removal efficiency ranged from 85.8% to 99.2%. The final cadmium concentration in the treated water decreased from

14.2 mg/L to a low value of 0.8 mg/L. This indicates the high efficiency of the electrocoagulation process.

A clear trend was observed with respect to pH. The higher removal efficiencies were obtained at neutral and alkaline conditions: e.g. at pH 10 (Runs 2, 4, 12 and 19), the efficiencies were greater than 97%. The corresponding outflow concentrations were low, generally below 3 mg/L. Conversely, the efficiencies were lower at acidic conditions (pH 4): Runs 1, 3, 9, 11, 16 and 17 showed efficiencies below 89%, with outflow concentrations relatively high (> 11 mg/L). This phenomenon can be explained by the low formation of hydroxides at low pH, which decreases the flocs formation and the removal of metals.

The effect of the current density is also evident. Increasing the current density generally improved the removal performance. Higher current densities enhance the anodic dissolution. This leads to the greater production of coagulant species. However, the effect is dependent on pH and reaction time. For example, at pH 7 and 60 min (Run 8), the removal efficiency of 98.6% was achieved at 90 A/m^2, whereas at low pH (Run 3) the performance was not significantly improved by increasing the current density.

The reaction time had a positive effect on the removal efficiency as longer contact time would lead to more complete hydrolysis and floc formation. For example, at pH 7 and 30 A/m^2, the removal efficiency increased from 98.1% (Run 5) to 99.0% (Run 6) upon extending the reaction time from 20 min to 60 min; the outflow concentration accordingly decreased. This gives evidence for the importance of sufficient contact time.

The centre point conditions (pH 7, 60 A/m^2, 40 min) were repeated in Runs 13-15. The results were consistent with removal efficiencies from 98.6% to 99.2% and outflow concentrations all below 1.5 mg/L, confirming the stability and reproducibility of the process under optimal conditions.

238 **Table 2.** Analysis of variance (ANOVA) for cadmium removal efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	508.59	9	56.51	58.92	< 0.0001	significant
A-pH	281.90	1	281.90	293.90	< 0.0001	
B-Current Density	0.6232	1	0.6232	0.6498	0.4410	
C-Reaction time	7.90	1	7.90	8.23	0.0185	
AB	0.0961	1	0.0961	0.1001	0.7589	
AC	0.0706	1	0.0706	0.0736	0.7923	
BC	0.0259	1	0.0259	0.0270	0.8732	
A^2	141.16	1	141.16	147.17	< 0.0001	
B^2	2.53	1	2.53	2.64	0.1385	
C^2	0.0000	1	0.0000	0.0000	0.9962	
Residual	8.63	9	0.9592			
Lack of Fit	8.45	7	1.21	13.42	0.0711	not significant

239 Table 2 presents the analysis of variance (ANOVA) results for cadmium removal efficiency. The
240 model is highly significant. The F-value is 58.92. The p-value is < 0.0001. This indicates that the
241 developed model adequately explains the variation in the response. Among the main factors, pH (A)
242 shows a dominant effect. The F-value of 293.90 and the p-value of < 0.0001 is very high which
243 confirms that pH is the most significant parameter affecting the cadmium removal. The strong effect
244 is in agreement with the importance of pH in the formation of hydroxides and metal precipitation.

Reaction time (C) is also significant with the F-value of 8.23 and the p-value of 0.0185 which suggests increasing the contact time improves the removal efficiency. Longer reaction time allows sufficient floc formation and pollutant aggregation. In contrast, current density (B) is not statistically significant. The p-value is 0.4410. This indicates that within the studied range, its individual effect is relatively weak compared to pH. The contribution of current density may be associated with interaction effects or combined effects. The interaction terms (AB, AC, BC) are not significant. All p-values are higher than 0.05. Therefore, the interaction effects between variables are negligible. The system is mainly controlled by individual factors rather than interactions. The quadratic term of pH (A^2) is highly significant. The F-value is 147.17 with $p < 0.0001$. This indicates strong curvature effect. It means instead of simple linear relationships there is optimum pH range. The quadratic terms of current density (B^2) and reaction time (C^2) are insignificant. The residual error is low with mean square of 0.9592. This indicates good agreement between experimental and predicted values. The lack of fit test is not significant (p=0.0711). This confirms the model fits well with the data. There is no evidence of systematic deviation. Generally, the ANOVA results show that the model is statistically robust. pH is the major controlling factor. Reaction time has a moderate effect. Current density plays a minor role within the studied range. The model is suitable for prediction and optimization of the electrocoagulation process.

The regression equation for predicting cadmium removal efficiency is presented in Equation (7). The model is expressed in terms of dimensionless coded variables. The variables are coded as A, B and C. The use of coded variables allows the comparison of factors on a common scale. It also allows the interpretation of linear, interaction and quadratic effects within the response surface framework. In this model A, B and C correspond to the operational parameters of the electrocoagulation process. In particular, A corresponds to the pH of the solution. B corresponds to the current density. C corresponds to the reaction time. Although the equation is written in coded form, each variable is related directly to its actual experimental value by standard transformation equations. The regression model provides a mathematical relationship between the input variables and the response. It allows the prediction of

cadmium removal efficiency under different operating conditions. This is useful for determining optimal conditions without the need for further experiments. In addition, the model includes both individual effects and curvature behaviour, allowing a more accurate representation of the system.

Therefore, Equation (7) is a predictive and analytical tool that can be used to assist in process optimization and to enhance the understanding of the electrocoagulation mechanism.

$$Cadmium\ Removal = \\ = 98.60 + 5.16A - 0.2425B + 0.8750C - 0.1208AB + 0.1059AC + 0.0641BC \\ - 5.80A^2 - 0.7774B^2 - 0.0024C^2 \qquad Equation\ (7)$$

Figure 3 shows the correlation between experimental results and the model predicted values for cadmium removal efficiency. There is a good agreement. The coefficient of determination is quite high (R^2 = 0.992). Thus, the model accounts for over 99% of the variability in the response. Such a high value confirms the excellent predictive capability of the developed regression model.

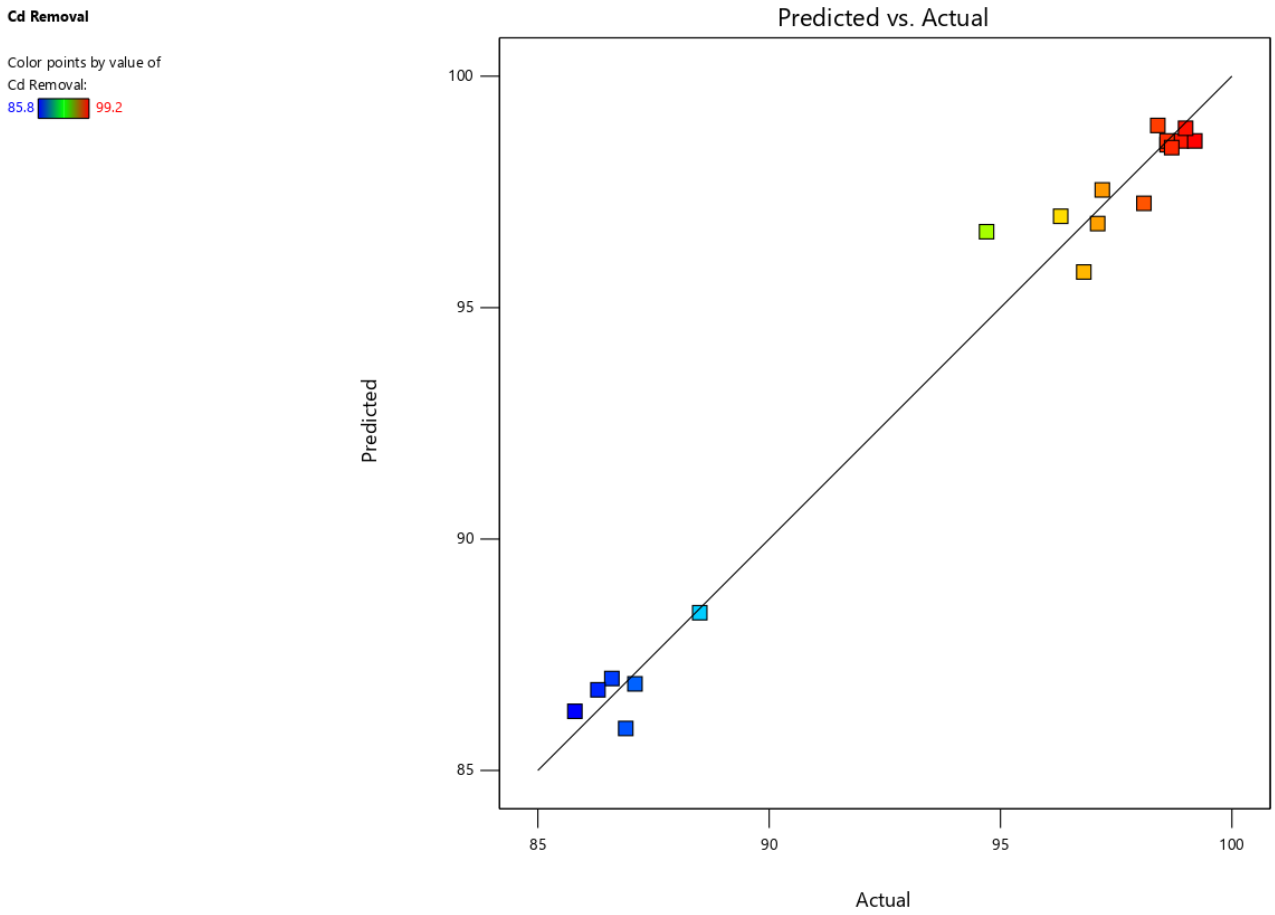


Figure 3. Comparison between experimental and model-predicted cadmium removal efficiency (%)

Figure 3 presents a direct comparison between the actual (experimental) and predicted cadmium removal efficiencies. The data points are distributed closely along the diagonal reference line (y = x). The solid line represents the line of perfect agreement between predicted and observed values. The data points lie close to the reference line suggesting a strong relationship between experimental values and modelled outcomes.

Much of the data lie close to the reference line. This suggests that the prediction errors are minimal. Only small deviations can be observed. These deviations are randomly distributed and do not show any systematic trend. This behavior confirms that the model is not biased to a great extent and works well over the entire experimental domain.

The figure also depicts a uniform agreement in the model performance for different ranges of efficiency. The color gradient representing the cadmium removal efficiency shows uniform agreement at lower and higher values. For example, predictions are accurate in the lower range (~85-88%) as well as in the higher range (~96-99%). This indicates the robustness of the model under different operating conditions.

In conclusion, Figure 3 validates the reliability and accuracy of the proposed model in describing the relationship between pH, current density and reaction time with the efficiency of cadmium removal. The good fit between experimental and predicted values emphasizes its applicability for process optimization and further studies.

3.2. Effect of operating parameters on cadmium removal efficiency

The effect of the most important operating parameters on cadmium removal efficiency was studied in a systematic way. These parameters are pH, current density and reaction time. Each of these factors plays a specific role in controlling the electrocoagulation process. Their individual and combined effects determine the overall treatment performance. Figure 4 shows the variation in cadmium removal efficiency as a function of changes in these operating conditions. The figure provides a

graphical representation of the response of the process over the experimental domain. It highlights the sensitivity of the system and the relative importance of each parameter.

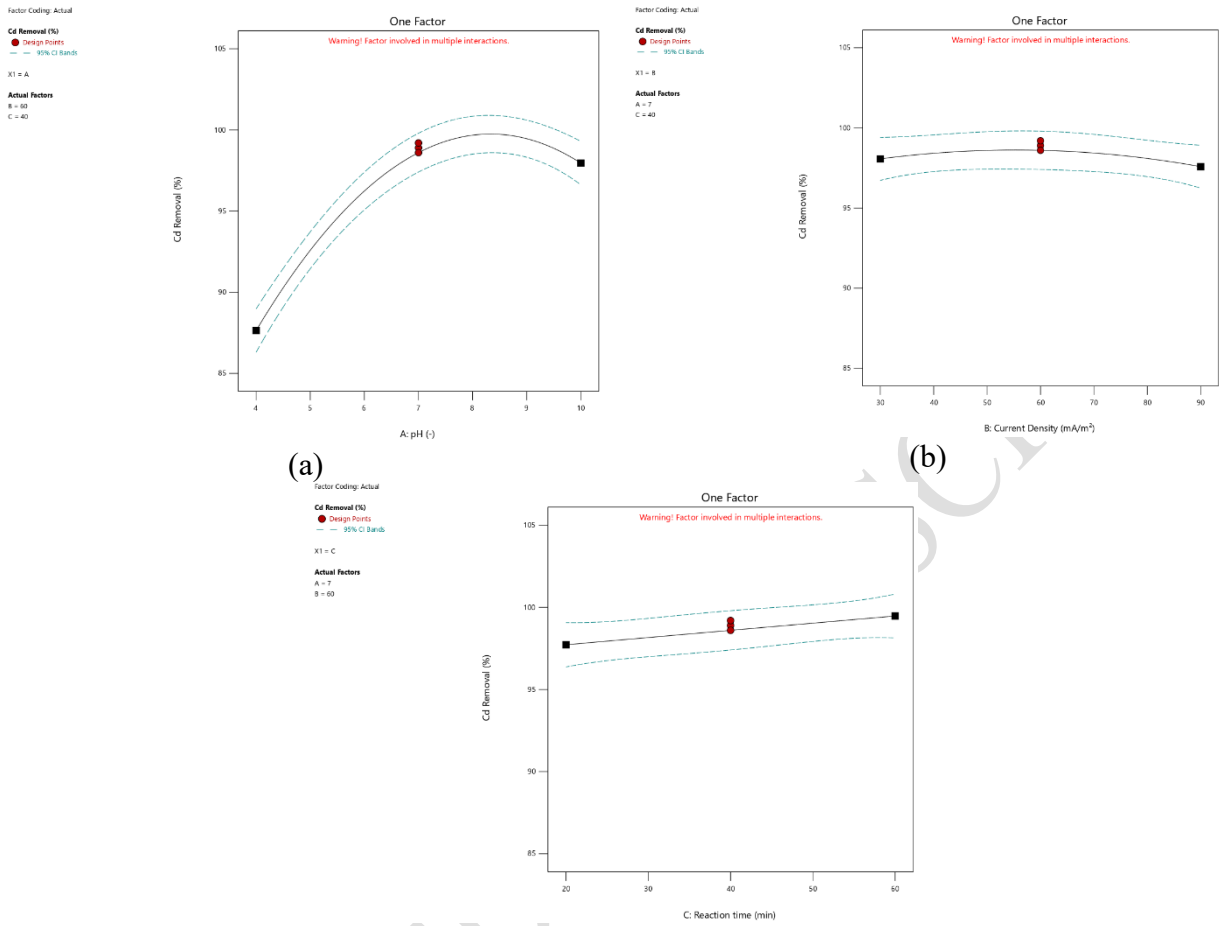


Figure 4. Main effects of pH (a), current density (b) and reaction time (c) on cadmium removal (%)

The main effects of pH, current density and reaction time on the cadmium removal efficiency are shown in Figure 4, while keeping the other variables at their center points. Among these factors, pH is certainly the most important parameter, as the removal efficiency increases significantly from acidic conditions (pH 4) to near-neutral and slightly alkaline conditions (pH 7-8). This observation is in good agreement with previous researches which show the highest metal removal efficiency in electrocoagulation at neutral pH due to the increased formation of metal hydroxide flocs and the enhancement of adsorption capacity (Mollah et al., 2001; Holt et al., 2005). The removal efficiency of cadmium and other heavy metals is reported to increase significantly in the pH range of 6-8 (Emamjomeh & Sivakumar, 2009; Kobya et al., 2010).

On the other hand, the current density in the studied range (30-90 A/m^2) appears to have a relatively weak effect and causes only small changes in the removal efficiency. Although the quantity of coagulant and bubbles increases with the current density, its effect is limited above a certain value, as also observed in previous electrocoagulation studies (Chen, 2004; Holt et al., 2005). Similarly, the effect of the reaction time is positive, but moderate, the removal efficiency improving slowly with the electrolysis time. This behaviour is explained by the slow formation of coagulant species and the longer contact time between the pollutants and the flocs, a phenomenon often reported in the literature (Kobya et al., 2010; Emamjomeh & Sivakumar, 2009).

3.3. Optimization design of experiment

The 3D response surface plots of the interaction effects of key process variables on cadmium removal efficiency are shown in Figure 5. The 3D response surface plots give a clear visualization of the interaction between two variables when the third variable is kept constant. They also allow the identification of optimal regions and performance trends within the experimental domain.

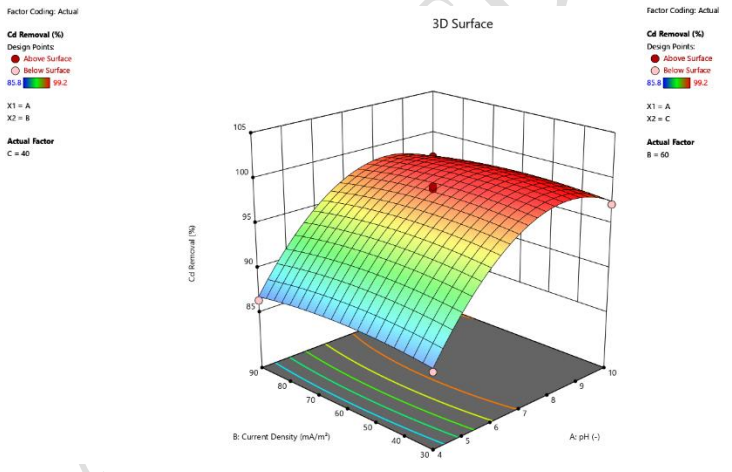
In Figure 5a, the interaction between pH and current density is shown at a fixed reaction time of 40 min. Cadmium removal efficiency increases markedly with increasing pH. For example, at low pH (~4), removal efficiency is still relatively low (~86-88%) even when the current density increases from 30 to 90 A/m². However, for higher pH values (~7-10) the removal efficiency is significantly increased and is around 97-99%. The effect of the current density is relatively less pronounced. The increase of the current density from 30 to 90 A/m^2 leads to a slight increase of removal efficiency (usually in the range of 1-2%). This indicates that the pH is the main factor in this interaction.

Figure 5b depicts the interaction of pH and reaction time at a constant current density of 60 A/m^2. The removal efficiency increases significantly with increasing pH. For instance, the removal efficiency at pH 4 increased from around 87% to 89% when the reaction time varied from 20 to 60 min. At pH 7 the efficiency was improved to around 98-99% under similar conditions. At pH 10 the removal efficiency was consistently above 96% and could be as high as 98.4%. The effect of reaction

time is also apparent. The removal efficiency was improved by around 2–3% when the reaction time was increased from 20 to 60 min, especially at neutral pH, which shows the synergistic effect of pH and reaction time.

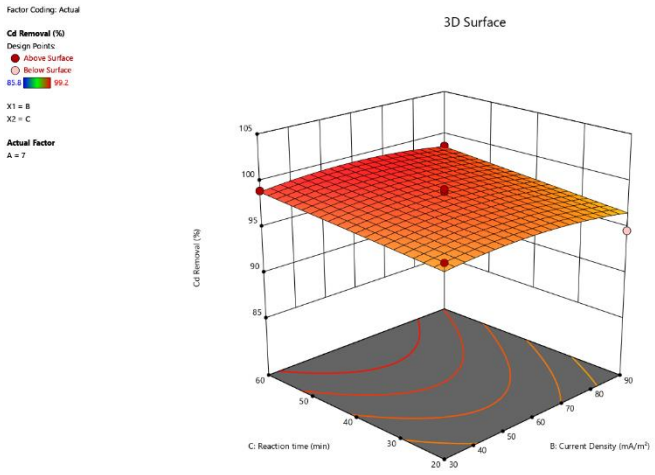
Figure 5c presents the relationship between current density and reaction time at a pH of 6-7. The response surface is relatively flat. The removal efficiency is in a narrow range of about 94-97%. For example, the removal efficiency increases only about 1%-2% when the current density is changed from 30 to 90 A/m^2 at 40 min. Similarly, the removal efficiency is slightly improved when the reaction time is changed from 20 to 60 min. These small changes indicate that the combined effect of current density and reaction time is limited when the pH is maintained near neutral.

The results for the 3D response surface show that the most significant parameter was the pH. An increase of about 13% was detected for the efficiency, from nearly 86% to higher than 99%. Current time appeared to have medium effects (about 2-3% increase), and the other parameter (current density) had a low relevance. These findings are consistent with the ANOVA results and further confirm the dominant role of pH in controlling the electrocoagulation process.



(a) pH and Current density

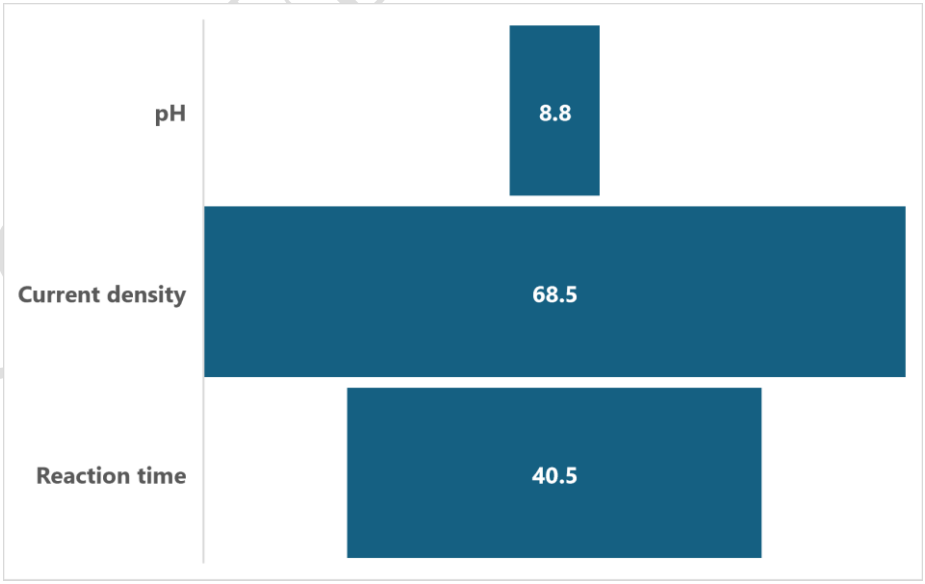
(b) pH and Reaction time



(c) Current density and Reaction time

360 **Figure 5.** Response surface plots showing the interaction effects between (a) pH and Current
361 density, (b) pH and Reaction time, and (c) Current density and Reaction time.

362 A quadratic model was used to optimize the electrocoagulation process and obtain high Cd removal
363 efficiency (95-99.99%) with the minimal chemical input. The optimal conditions obtained were pH
364 8.8, current density 68.5 A/m^2, and reaction time 40.5 min (Figure 6). Results show good match with
365 experimental outcomes. This provides confidence in the reliability and real-time applications of the
366 designed model for efficient Cd removal.



367
368 **Figure 6.** Optimal conditions for cadmium removal by electrocoagulation

369 The comparison of the experimental and the model predicted values shows high degree of agreement
370 in the cadmium removal efficiency under the optimized conditions. The actual removal efficiency

was 97.64% and predicted value was 99.49% with a minimum deviation of only 1.85%. This slight variation indicates that the proposed model has excellent predictive accuracy with robustness and it has successfully captured the relation between process parameters and removal performance. The close agreement between the observed and predicted results confirms the adequacy of the model for process optimization and its applicability in designing efficient cadmium removal systems for practical purposes.

CONCLUSIONS

The experimental results and statistical analysis performed in this research indicated the efficiency and reliability of electrocoagulation (EC) technique for the cadmium removal from wastewater having initial concentration of 100 mg/L. The removal efficiencies obtained were high (85.8% to 99.2%) for the process under various operating conditions and thus, proved the ability of this method to treat the heavy metal contaminated water.

The use of Response Surface Methodology (RSM) coupled with Box-Behnken design was an efficient technique to evaluate and optimize the effects of the most important operational parameters. Of the factors studied, pH was the most significant variable influencing the cadmium removal efficiency, followed by the reaction time, whereas the effect of current density was relatively minor in the range studied. The ANOVA results indicated that the developed quadratic model was statistically significant and robust, with a high F-value and a non-significant lack-of-fit, indicating that the model sufficiently describes the experimental system.

The optimal operating conditions were found to be pH 8.8, current density 68.5 A/m^2 and reaction time 40.5 min. Under these conditions, the model predicted the cadmium removal efficiency of 99.49% which was in good agreement with the experimentally obtained value of 97.64% with a small deviation of only 1.85%. This good agreement shows the high predictive accuracy and reliability of the developed model for the process optimization.

Moreover, the response surface analysis showed that pH is the most important factor influencing the formation of hydroxide flocs and the subsequent cadmium removal, while reaction time facilitates the removal because of increased coagulant generation and contact time. The current density had a relatively weak effect, suggesting that a moderate energy input is sufficient to achieve high removal efficiency and thus benefit the cost effectiveness of the process.

The results of this study provide useful information for the optimization of an electrocoagulation process for cadmium removal and demonstrate the usefulness of RSM as a powerful tool for process design and prediction. The findings contribute to the development of efficient, low-cost and environmentally sustainable treatment technologies for heavy-metal-contaminated wastewater. Future studies are recommended to investigate real wastewater matrices, energy consumption, electrode consumption, and scale-up feasibility to further enhance the practical implementation of this technology.

AUTHOR CONTRIBUTIONS

L.P.T (PhD) and L.T.Y (PhD) conducted all the experiments and simulation and wrote the manuscript. L.P.T (PhD) revised the manuscript.

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