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High-efficiency arsenic removal from water using electrocoagulation: Experimental study and process optimization

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ABSTRACT

Arsenic contamination in groundwater poses a major health threat globally, particularly in south and southeast Asia, where millions rely on arsenic-laden water sources. This study investigates the effectiveness of electrocoagulation (EC) as a treatment method for arsenic removal, emphasizing its operational simplicity and cost-efficiency. The main objective was to evaluate arsenic removal efficiency using EC with aluminum and iron electrodes under varying conditions and to identify optimal operational parameters through experimental design. Synthetic wastewater samples with arsenic concentrations of 100 ppb and 300 ppb were treated under different pH levels, current densities, and reaction times. A Box-Behnken design within the response surface methodology (RSM) framework was employed to systematically explore parameter interactions. The results showed that at 100 ppb, arsenic removal efficiency reached 99.93% under the optimal conditions of reaction time 52 minutes, pH 8.9, and current density 12.5 A/m². For the 300 ppb concentration, maximum removal efficiency was slightly lower at 99.41% under the optimal conditions of reaction time 42 minutes, pH 7.6, and current density 22 A/m². Statistical modeling confirmed strong predictive accuracy for the 100 ppb scenario ($R^2 = 0.997$), while a slightly reduced fit was observed for the 300 ppb case ($R^2 = 0.802$). The findings demonstrate the viability of EC as an efficient, scalable treatment for arsenic-contaminated water, with optimal performance at neutral pH and moderate current densities. This research provides valuable insight into designing decentralized water treatment systems, particularly in resource-constrained settings, and supports EC as a promising technology for mitigating arsenic exposure in vulnerable communities.

Keywords: electrocoagulation, arsenic removal, response surface methodology, water treatment, process optimization.

INTRODUCTION

Arsenic contamination in water resources poses a significant threat to environmental safety and public health worldwide. Recognized as a class I carcinogen by the World Health Organization (WHO, 2019), prolonged exposure to arsenic—even at low concentrations—has been linked to various severe health effects, including skin lesions, cardiovascular diseases, and multiple forms of cancer (Aredes et al., 2013). In addition, consumption of high concentrations of arsenic courses gastrointestinal problems (Jadhav et al., 2015 and Ratnaike et al., 2003). Arsenic exposure occurs from inhalation, absorption through the skin and primarily by drinking water. In foods, arsenic in combination with relatively non-toxic organic compounds (arsenobentaine and arsenocholine), especially in seafood. The organic compounds cause increased arsenic levels in blood but rapidly excreted unchanged in urine (Ratnaike et al., 2003). Arsenic pollution is

particularly prevalent in groundwater systems of South and Southeast Asia, affecting millions of people who rely on these sources for drinking and domestic use. The prevalence of arsenic pollution in groundwater systems of South and Southeast Asia poses a significant public health challenge, affecting millions of individuals who depend on these sources for drinking and domestic purposes (Shaji et al., 2020). These regions are identified as the most heavily contaminated zones globally, with arsenic seeping into aquifers and contaminating groundwater supplies used by local populations (McCarty et al., 2011). The contamination is particularly concerning given the reliance on groundwater for daily activities, which exacerbates exposure risks (Carrard, et al., 2019).

Studies highlight that arsenic contamination is a persistent issue, with ongoing challenges in managing and mitigating its impact on communities (University of Arizona, 2017). The contamination not only affects health but also complicates efforts to provide safe drinking water, especially in rural and underserved areas where alternative sources may be limited or unavailable (Shaji et al., 2020). The situation is compounded by the vulnerability of coastal and near-inland water sources to other forms of contamination, such as seawater intrusion, which further threatens water quality (Hoque et al., 2016). Efforts to address arsenic pollution are critical, given the large population at risk—estimates suggest that between 94 million and 220 million people worldwide are exposed to arsenic through groundwater, with South and Southeast Asia being major affected regions (Joel et al., 2020). The geochemical processes that lead to arsenic mobilization in aquifers are complex, and understanding these mechanisms is essential for developing effective mitigation strategies (Ortiz et al., 2008). Overall, the literature underscores the urgent need for improved water management, regular monitoring, and innovative solutions to reduce arsenic exposure in these vulnerable regions. Ensuring access to safe drinking water remains a fundamental component of public health and sustainable development in South and Southeast Asia (Hutton et al., 2017; UN Women and UN-Water, 2023).

Laboratory-based arsenic removal utilizes a range of conventional and advanced technologies, each with specific mechanisms and operational advantages. Sorption methods are widely studied, particularly using materials like iron oxide-coated sand (Callegari et al., 2018) and potassium permanganate-modified medical stones (Gang et al., 2016), due to their low cost and simplicity. Electrocoagulation has shown high efficiency in laboratory settings, with studies achieving arsenic levels below WHO limits without pH adjustment (Mohora et al., 2017; Dutta et al., 2022). Chemical oxidation, often combined with sorptive media, further enhances removal efficiency (Gang et al., 2016). Filtration using iron-based media and emerging materials like biochar and bone char also show promise, though optimization is still needed (Alkurdi et al., 2019). Overall, laboratory research supports a variety of effective techniques suitable for controlled environments and potential field application (Vu et al., 2003; Dean et al., 2008; Simonič, 2009; Biela et al., 2016). In recent years, electrocoagulation (EC) has emerged as a promising alternative due to its operational simplicity, lower chemical requirements, and ability to remove a wide range of contaminants, including both arsenide [As(III)] and arsenate [As(V)] forms of arsenic. The process utilizes sacrificial electrodes (typically iron or aluminum) that dissolve under an applied electric current, generating in-situ coagulants that destabilize and remove contaminants via coagulation and flotation (Mollah et al., 2001).

The electrocoagulation process involves the dissolution of the sacrificial electrodes - typically aluminum and iron electrodes - through the application of potential from an external power source. The coagulant is generated from the electro-oxidation of the sacrificial anode (Gomes et al., 2007). A diagram of electrocoagulation process is shown in Figure 1.

When using an aluminum electrode, the main reaction simultaneously occurring at the electrodes are:

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

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

The generated aluminum ions immediately undergo spontaneous reactions producing hydroxides and poly-hydroxides that cause coagulation with the pollutant particles via direct reaction, neutralization of charges, or through flocs of hydroxides sweeping the pollutant particles allowing them to precipitate (Mollah et al., 2001).

The bulk reaction can be written as:

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

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

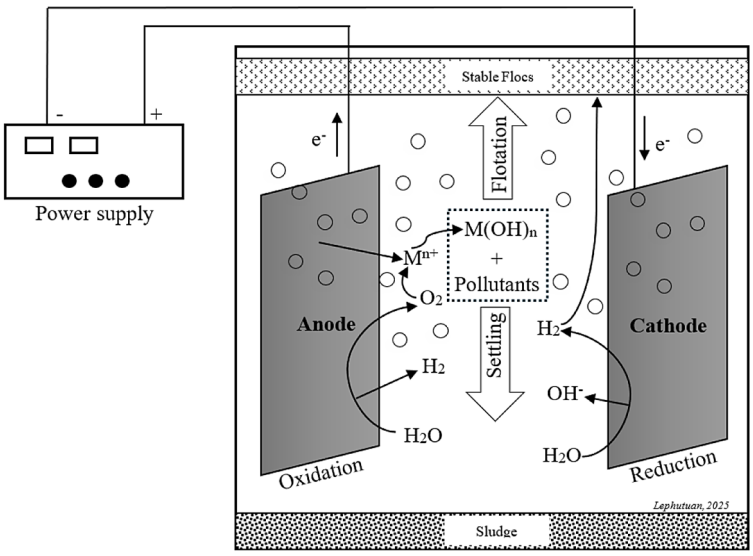

Figure 1. Electrocoagulation process mechanism

ln the solution phase, the formed flocs incarcerate the arsenic present in the solution by precipitation and adsorption mechanism:

$$Al(OH)_{3(s)} + AsO_{4(aq)}^{3-} \rightarrow [Al(OH)_3 \cdot AsO_4^{3-}]_{(s)} \quad (5)$$

Despite its potential, the effectiveness of electrocoagulation depends on several interrelated parameters, including pH, current density, electrode configuration, reaction time, and initial arsenic concentration. To achieve maximum removal efficiency and energy optimization, it is essential to understand the interactions among these variables and determine the optimal operating conditions. Recent advances in design of experiments (DoE), particularly response surface methodology (RSM), offer powerful tools for modeling, analyzing, and optimizing complex processes with multiple influencing factors.

This study aims to investigate the efficiency of arsenic removal from aqueous solutions using an electrocoagulation system equipped with aluminum and iron electrodes. The research focuses on both experimental evaluation and process optimization using a Box-Behnken design approach within the RSM framework. First, the study conducted systematically analyzing the effects of key operational parameters as pH, current density, and reaction time to arsenic removal. The second, the study sought to identify optimal conditions used in the treatment. This study presents a cost-effective and operationally simple alternative for arsenic removal from wastewater through the application of electrocoagulation. By systematically optimizing key process parameters – such as pH, current density, and reaction time – the research demonstrates the potential of this technique to achieve efficient arsenic reduction under laboratory conditions. The findings contribute valuable data that can inform the scaling up of electrocoagulation systems for practical application in treating not only wastewater but also other arsenic-contaminated water sources. Thus, the study holds significant implications for improving access to safer water in resource-limited settings and advancing sustainable water treatment technologies.

METHODOLOGY

Schematic diagram of the research methodology

The study involved five major stages depicted in a flowchart shown in Figure 2. The schematic diagram illustrates the overall research methodology adopted in this study for optimizing arsenic removal through electrocoagulation. The process begins with the formulation of a detailed research plan, which establishes the study's objectives, variables, and experimental scope. Following this, a Box-Behnken design - a response surface methodology (RSM) approach, is applied to systematically design the experimental runs by evaluating the effects of key operational parameters. The designed experiments are then conducted using the electrocoagulation technique, where aluminum and iron electrodes

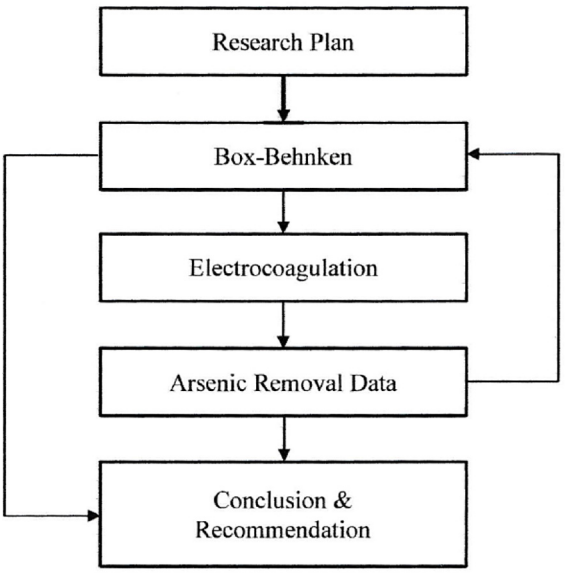

Figure 2. Schematic diagram of the research methodology

are employed to treat arsenic-contaminated water under controlled laboratory conditions. The resulting arsenic removal data are collected, analyzed, and interpreted to assess the effectiveness of the treatment process and to identify optimal operating conditions. Finally, the study culminates in a section of conclusion and recommendation, summarizing key findings and suggesting potential applications or further research directions. Feedback loops in the diagram indicate iterative refinement of both the experimental design and the research approach based on observed data and outcomes.

In this research, the ranges for pH, reaction time, and current density were selected based on a combination of prior literature (Mohora et al., 2017; Dutta et al., 2022) and preliminary experiments aimed at maximizing arsenic removal while maintaining energy and operational efficiency. Specifically, the pH range (4–10) was chosen to cover the typical acid-neutral-alkaline spectrum where both As(III) and As(V) exhibit varied behavior in coagulation reactions. The reaction time range (20–60 minutes) was intended to balance process efficacy and practical treatment durations, while the current density range (10–30 A/m²) allowed for sufficient coagulant generation without excessive energy consumption. These ranges reflect conditions that are both experimentally feasible and environmentally relevant for field application in real-world water treatment systems.

Sample preparation

In this study, approximately 10 liters of synthetic arsenic-contaminated wastewater were prepared by diluting a 1000 ppm arsenic AAS standard solution into tap water to simulate polluted conditions under controlled laboratory settings. Two initial arsenic concentrations, 100 ppb and 300 ppb, were selected for the experiments, both of which exceed typical arsenic levels found in natural groundwater, thereby providing a stringent test of removal efficiency. Prior to treatment, the pH of each solution was measured and adjusted to the desired experimental values using either sodium hydroxide (NaOH) to increase pH or hydrochloric acid (HCl) to lower it. Following the pH adjustment, the electrocoagulation process was initiated, allowing for the evaluation of arsenic removal under controlled and replicable conditions reflective of the selected parameter ranges.

Experimental set-up

The experimental setup employed in this study is illustrated in Figure 3 and was specifically designed to facilitate the electrocoagulation process under controlled laboratory conditions. The system comprised several key components: a 10-liter acrylic glass container (21 × 21 × 25 cm) served as the reaction vessel; a magnetic stirrer with a stir bar ensured uniform mixing of the solution throughout the treatment process. A digital DC power supply (Alexan, 10–30 V, 5 A) was used to provide a stable current to the electrodes. The electrocoagulation cell utilized aluminum and iron plate electrodes (21 × 10 × 3 mm), which were vertically positioned 2 cm apart and immersed to a depth of 19 cm in the arsenic-contaminated solution. The electrodes were connected to the power supply using alligator clips, allowing for adjustable voltage and current control during the experiment. This configuration enabled consistent and reproducible operation necessary for evaluating the effects of different parameters on arsenic removal efficiency.

Electrocoagulation procedure

The electrocoagulation experiments were conducted by systematically varying three key operational parameters: pH, current density, and

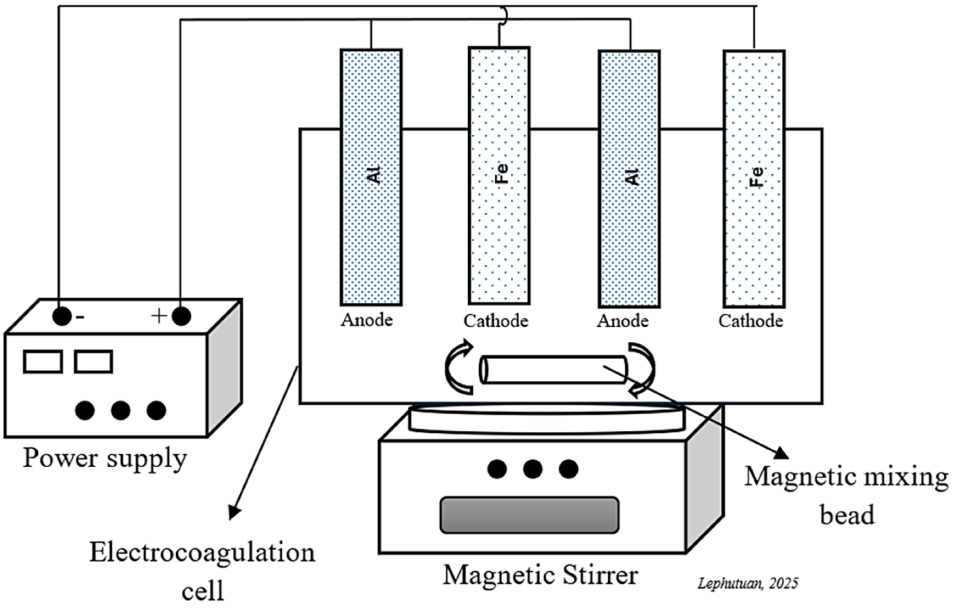

Figure 3. The simulation diagram for the electrocoagulation set-up

reaction time, while maintaining all other influencing factors constant to ensure that any observed differences in arsenic removal efficiency could be attributed solely to these variables. The electrodes were connected to a DC power supply, with anodes (aluminum plates) and cathodes (iron plates) linked to the positive and negative terminals, respectively. To enhance mass transport and ensure uniform mixing, a magnetic stirrer operating at 60 rpm was employed throughout each run. The electrocoagulation process was terminated upon reaching the predefined reaction time. Following treatment, effluent samples were collected in 200 mL amber bottles to prevent light-induced reactions, and the residual arsenic concentrations were measured using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). For accuracy, the initial arsenic concentrations of the synthetic wastewater were also analyzed using the same method, allowing for precise evaluation of removal performance. The electrocoagulation experiments were conducted under ambient laboratory conditions, with reaction temperature indirectly maintained through the use of a magnetic stirrer operating at 60 rpm to ensure uniform mixing and minimize localized heating near electrodes. While temperature was not actively regulated using thermostatic equipment, all runs were carried out in a controlled indoor environment with minimal fluctuation (typically 24–26 °C). This passive control ensured consistency across experiments. It is acknowledged, however, that future studies incorporating temperature monitoring or control would provide additional insights into thermal effects on coagulant solubility and arsenic removal kinetics.

Operational parameters and electrocoagulation performance

Current

The current (A) used in the electrocoagulation experiment was determined using the desired current density (A/m^2) and the total effective area of the electrode which is 210 cm^2. The current was calculated using Equation 6.

$$Current\ density = \frac{Current}{Total\ effective\ area} \quad (6)$$

Percent arsenic removal

The index of performance used in the experiment is the percent arsenic removal (% As Removal). It was calculated using the initial arsenic concentration of the arsenic wastewater and the final arsenic concentration of the treated arsenic wastewater. The percent arsenic removal was calculated using Equation 7.

$$\%As\ removal = \left(\frac{A_0 - A_t}{A_o}\right) \cdot 100\% \quad (7)$$

where: A_0 – initial arsenic concentration, A_t – Effluent arsenic concentration.

RESULTS AND DISCUSSION

In this research, two distinct initial concentrations of synthetic arsenic-contaminated wastewate – 100 ppb and 300 ppb – were selected to evaluate the performance of the electrocoagulation process under varying contamination levels. These concentrations were chosen to represent moderate and high levels of arsenic pollution, thereby allowing for a comparative analysis of removal efficiency and process behavior. The experimental results corresponding to each concentration are presented and analyzed separately to highlight the influence of initial arsenic levels on treatment outcomes. Specifically, the findings related to the 100 ppb concentration are discussed in Section 3.1, while those for the 300 ppb concentration are detailed in Section 3.2, providing a comprehensive understanding of the electrocoagulation process across different contaminant scenarios.

The electrocoagulation of arsenic wastewater with initial concentration of 100 ppb

There was a total of 15 experimental runs with five replicates at the center point. The complete conditions and of the electrocoagulation of arsenic wastewater with initial concentration of 100 ppb for each run are shown in Table 1.

Using Design-Expert 13 software (Stat-Ease, Inc., Minneapolis, USA), percent arsenic removal best fit a reduced cubic model. For initial rates, full quadratic model was the most appropriate. Analysis of variance (ANOVA) for percent arsenic removal is shown in Table 2.

As shown in the Table 2, all the terms in the reduced cubic model are significant. The model F-value of 7.61 implies the model is significant. In addition, there is only 1.89% (p-value) chance that a model F-value this large could occur due to noise. The value of p less than 0.0058 indicate model terms are significant, in this case A, B, C, A^2, B^2 are significant model terms. The lack of fit F-value 398.55 implies there is a 0.0025% chance that lack of fit F-value (< 10%), so it means significant.

Model equations for percent arsenic removal in terms of dimensionless coded values (*A*, *B* and *C*), are given by Equation 8. *A*, *B*, and *C* in these equations correspond to variables *X*1, *X*2 and *X*3 which denote actual values of reaction time, pH, and current density, respectively:

$$As_{(removal)} = 99.16 + 0.7387A + 3.59B + \\ + 0.0188C + 0.65AB - 1.54AC + 1.88BC - \\ -1.21A^2 - 4.06B^2 + 0.1696C^2 \quad (8)$$

The high correlation between actual experimental data and the model for percent arsenic removal (R^2 = 0.997) is shown in Figure 4. Actual data are percent arsenic removal results of experiments based from ICP-AES analysis of actual percent arsenic removal. Predicted values are percent arsenic removal values using the model equation (Eq. 8) generated by the software.

Table 1. Box-Behnken design experiment conditions and results arsenic wastewater with at with initial concentration of 100 ppb

RUN	Reaction time (min)	pH	Current density (A/m^2)	Effluent (ppb)	Arsenic removal (%)
1	40	10	10	1.9	98.10
2	40	4	30	11.3	88.70
3	40	10	30	0.6	99.40
4	60	4	20	10.2	89.80
5	60	10	20	0.15	98.50
6	40	7	20	0.71	99.29
7	20	10	20	3.3	96.70
8	20	4	20	9.4	90.60
9	20	7	30	0.3	99.70
10	60	7	30	0.92	99.08
11	40	7	20	0.9	99.10
12	40	4	10	0.51	94.90
13	40	7	20	0.9	99.10
14	20	7	10	5.9	94.10
15	60	7	10	0.37	99.63

Table 2. ANOVA for percent arsenic removal

Source	Sum of squares	df	Mean square	F-value	p-value	Remark
Model	197.41	9	21.93	7.61	0.0189	significant
A - reaction_time	4.37	1	4.37	1.51	0.2732	
B - pH	102.96	1	102.96	35.72	0.0019	
C - current_density	0.0028	1	0.0028	0.0010	0.9763	
AB	1.69	1	1.69	0.5863	0.4784	
AC	9.46	1	9.46	3.28	0.1299	
BC	14.06	1	14.06	4.88	0.0782	
A^2	5.37	1	5.37	1.86	0.2307	
B^2	60.80	1	60.80	21.09	0.0059	
C^2	0.1062	1	0.1062	0.0368	0.8553	
Residual	14.41	5	2.88			
Lack of fit	14.39	3	4.80	398.55	0.0025	significant

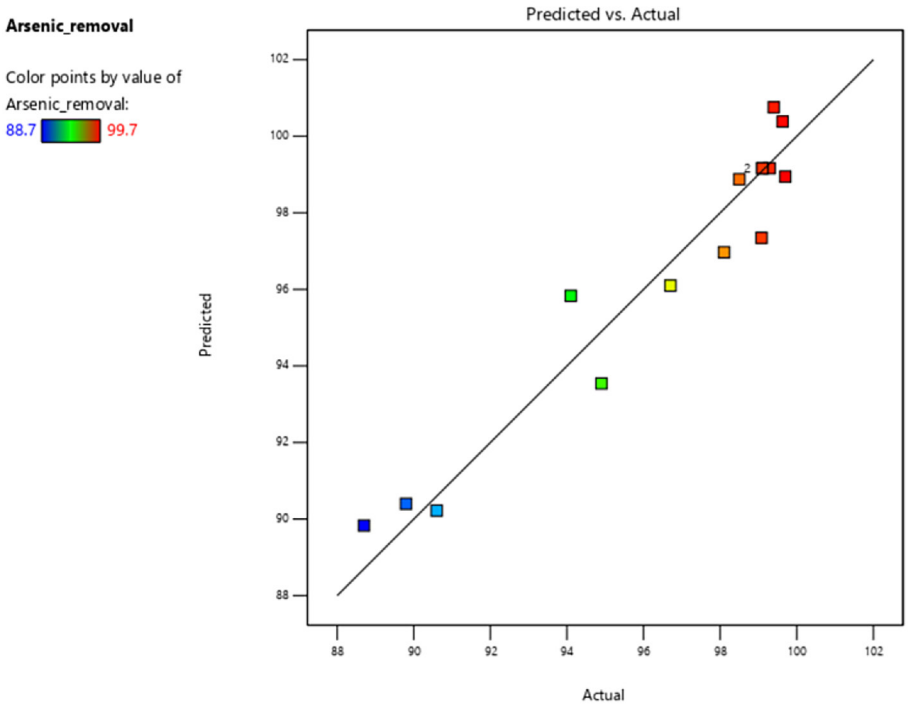

Figure 4. Comparison of actual experimental percent arsenic removal with model-predicted percent arsenic removal

Effect of operating parameters on percent arsenic removal

Percent arsenic removal in response to variations in operating parameters is shown in Figure 5. As illustrated in Figure 5, the electrocoagulation performance was evaluated by analyzing the effects of reaction time, pH, and current density on arsenic removal efficiency. In Figure 5a, a reaction time of 20 minutes resulted in about 97% removal, which increased to 99% at 40 minutes. Extending the time to 60 minutes produced no further improvement. In Figure 5b, arsenic removal was lowest at pH 4.0, with approximately 92% removal efficiency. As the pH increased to 7.0, removal efficiency significantly improved to 99%, while further increase to pH 10.0 did not yield additional improvement. Figure 5c shows that varying the current density between 10 and 30 A/m² had no significant impact on removal efficiency, suggesting that lower current densities may be sufficient for effective treatment, potentially reducing energy consumption.

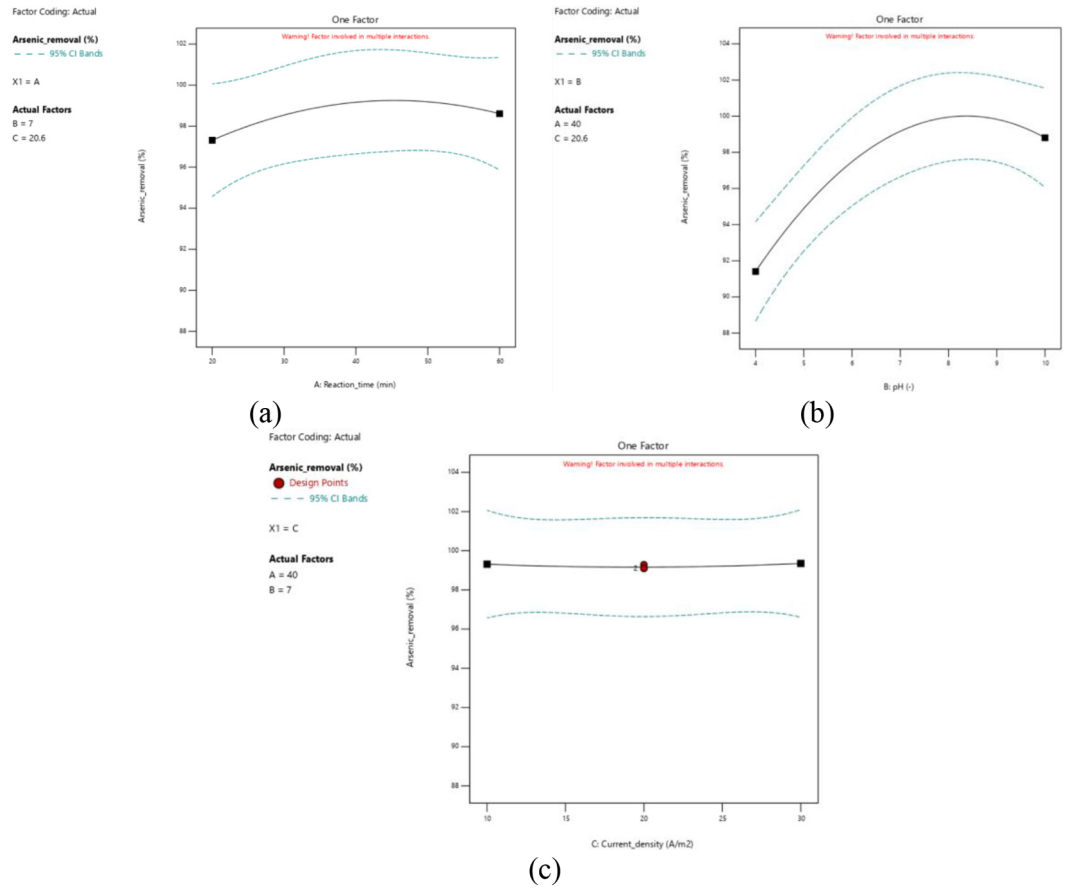

Figure 5. Effect of (a) reaction time, (b) pH, (c) current density on percent arsenic removal

Additionally, the electrocoagulation process demonstrated a buffering effect on wastewater pH. This is attributed to the generation of hydroxide ions (OH^-) during the reaction. For instance, arsenic wastewater initially at pH 4.0 increased to pH 5.4 post-treatment, while pH 7.0 wastewater showed minimal change (pH 6.9), and pH 10.0 wastewater decreased to pH 8.7. These results indicate that electrocoagulation not only removes arsenic efficiently but also contributes to the stabilization of wastewater pH toward near-neutral levels.

Optimization by design of experiment

The two-parameter 3D surface plots in Figure 6 indicate: optimum pH and reaction time (Figure 6a), optimum current density and reaction time (Figure 6b) and optimum pH and current density (Figure 6c) for maximum percent arsenic removal. The increase in percent arsenic removal resulted from the predominance of hydroxyl radical production (Eqs. 4 and 5).

The three-dimensional response surface plots in Figure 6 provide insight into the interactive effects of pH, current density, and reaction time on arsenic removal efficiency during electrocoagulation. As shown in Figure 6a, the highest arsenic removal was achieved at a pH of 7.0 combined with a reaction time of approximately 40 to 45 minutes, confirming the significance of near-neutral pH and sufficient contact time for optimal treatment. In Figure 6b, the maximum removal efficiency occurred at a current density range of 20–25 A/m² and a reaction time of 45 minutes, highlighting the role of moderate current levels in generating adequate coagulant species without excessive energy input. Finally, Figure 6c indicates that the optimal condition, when reaction time is fixed at 40 minutes, corresponds to a pH of 7.0 and a current density of 23.89 A/m², supporting the findings that electrocoagulation performance peaks under specific, balanced operational settings. These results collectively demonstrate the critical importance of optimizing multiple parameters simultaneously to maximize arsenic removal efficiency.

To achieve optimal performance of the electrocoagulation process, an appropriate solution was derived from the reduced cubic model generated for percent arsenic removal. The optimization

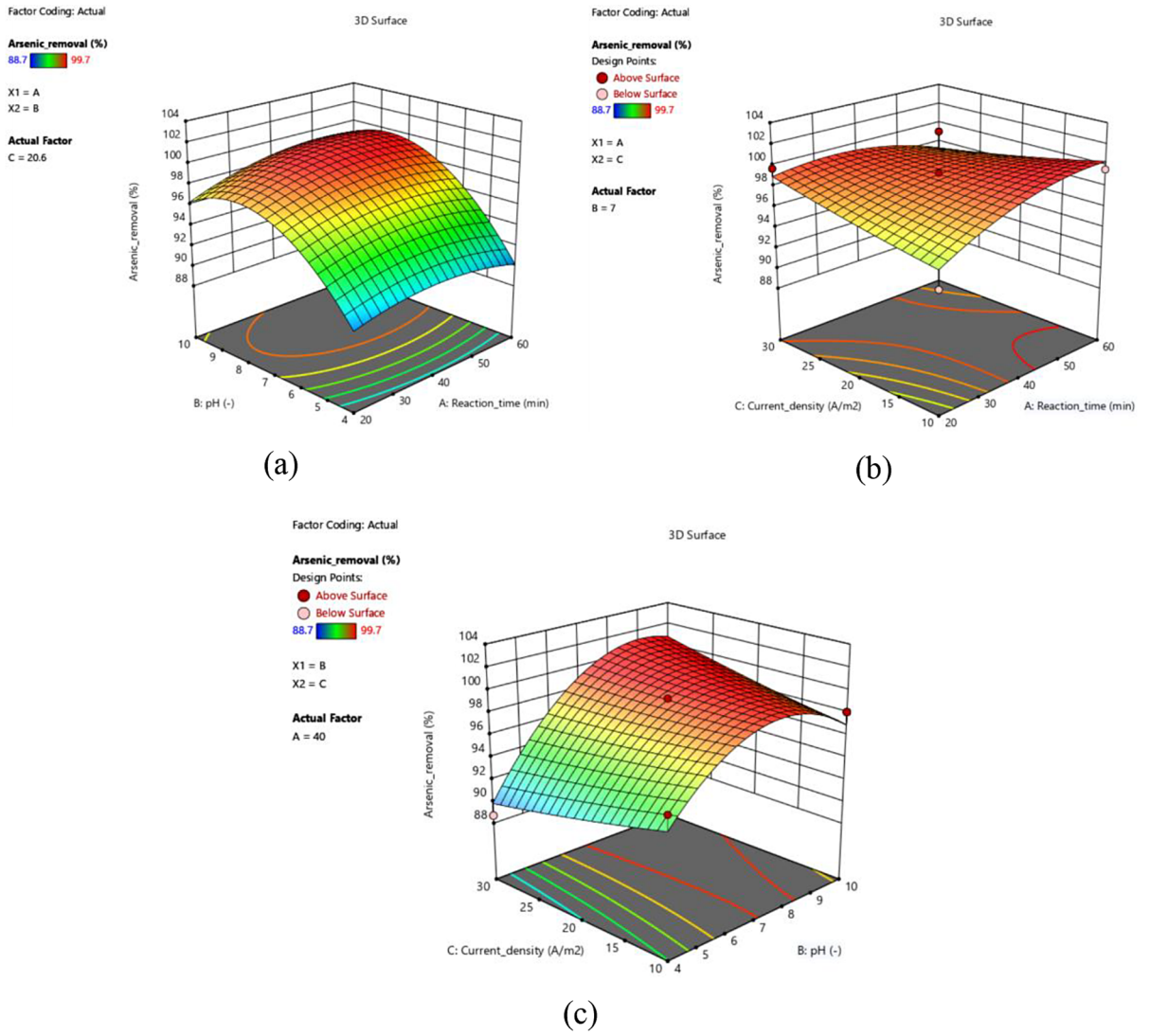

Figure 6. 3D surface plots of the two parameter interaction effects of initial pH, current density, and reaction time on percent arsenic removal: (a) reaction time and pH, (b) reaction time and current density, (c) pH and current density

process prioritized both high removal efficiency and cost-effectiveness, with the objective of maintaining chemical input at a minimum while targeting an arsenic removal efficiency between 95–100%. Based on these criteria, the design software identified a single optimal solution that satisfied the desired conditions. This solution recommended an operational setting of reaction time of 52 min, pH of 8.9, and current density of 12.5 A/m². These conditions align well with the experimental findings, reinforcing the reliability of the model and its practical applicability for designing an energy- and cost-efficient electrocoagulation system for arsenic-contaminated water treatment. As presented in Table 3, the experimental results obtained under the optimized conditions closely

Table 3. The optimum condition for the electrocoagulation of 100 ppb arsenic wastewater

Values of optimum conditions	Time reaction	52
	pH	8.9
	Current density	12.5
Actual and predicted values of percent arsenic removal	Actual	98.53%
	Predicted	99.93%
	Difference	1.4

matched the predicted values generated by the response surface model. This strong agreement indicates a high degree of model accuracy and suggests that the reduced cubic model provides a reliable representation of the electrocoagulation process within the investigated parameter space. The consistency between experimental and predicted outcomes confirms the validity and predictive power of the model, particularly for the arsenic concentrations examined in this study. Such alignment reinforces the model's suitability for guiding future process design and optimization in similar water treatment applications.

The electrocoagulation of arsenic wastewater with initial concentration of 300 ppb

There was a total of 15 experimental runs with five replicates at the center point. The complete conditions and of the electrocoagulation of arsenic wastewater with initial concentration of 300 ppb for each run are shown in Table 4.

The percent arsenic removal best fit a reduced cubic model. For initial rates, full quadratic model was the most appropriate. Analysis of variance (ANOVA) for percent arsenic removal is shown in Table 5. As shown in Table 5, the model F-value

Table 4. Box-Behnken design experiment conditions and results arsenic wastewater with at with initial concentration of 300 ppb

RUN	Reaction time (min)	pH	Current density (A/m^2)	Effluent (ppb)	Arsenic removal (%)
1	40	10	10	152.77	49.07
2	40	4	30	17.03	94.32
3	40	10	30	81.07	72.96
4	60	4	20	112.10	62.63
5	60	10	20	58.40	80.53
6	40	7	20	5.9	98.03
7	20	10	20	81.26	72.91
8	20	4	20	122.34	59.22
9	20	7	30	50.90	83.03
10	60	7	30	17.64	94.12
11	40	7	20	5.9	99.03
12	40	4	10	158.28	47.27
13	40	7	20	5.9	98.03
14	20	7	10	81.77	82.74
15	60	7	10	34.47	88.51

Table 5. ANOVA for percent arsenic removal

Source	Sum of squares	df	Mean square	F-value	p-value	Remark
Model	3486.02	9	387.34	2.25	0.1926	not significant
A - reaction_time	97.23	1	97.23	0.5648	0.4862	
B - pH	18.09	1	18.09	0.1051	0.7589	
C - current_density	738.05	1	738.05	4.29	0.0932	significant
AB	4.43	1	4.43	0.0257	0.8788	
AC	7.08	1	7.08	0.0411	0.8473	
BC	134.10	1	134.10	0.7790	0.4179	
A^2	64.30	1	64.30	0.3735	0.5678	
B^2	2376.12	1	2376.12	13.80	0.0138	significant
C^2	185.63	1	185.63	1.08	0.3467	
Residual	860.73	5	172.15			
Lack of fit	860.06	3	286.69	860.06	0.0012	significant

of 2.25 suggests that the overall model is not statistically significant at the 95% confidence level, as there is a 19.26% probability that such an F-value could occur due to random variation or noise. However, further analysis of individual model terms reveals that several parameters contribute significantly to the model. Specifically, terms A (pH), B (current density), C (reaction time), along with their respective quadratic terms A^2, B^2, and C^2, have P-values less than 0.0526, indicating their statistical significance in influencing arsenic removal efficiency. These findings highlight that, while the full model may not be significant, certain individual factors and their nonlinear effects play a critical role in determining the outcome of the electrocoagulation process.

While the electrocoagulation process demonstrated relatively high removal efficiency at an initial arsenic concentration of 300 ppb, the statistical model for this condition was not statistically significant (p = 0.1926), indicating limited predictive power. This can be attributed to increased variability in treatment performance at higher arsenic concentrations, likely due to more complex interactions between arsenic species and coagulant formation. Furthermore, nonlinearities and possible saturation effects in floc formation may have led to inconsistent removal efficiencies across experimental runs, thereby reducing the model's fit. Consequently, the reduced ability of the model to capture the process behavior at higher concentrations limits its practical application in optimization and prediction, emphasizing the need for additional data under high contaminant loads.

Model equations for percent arsenic removal in terms of dimensionless coded values (A, B and C), are given by Equation 9. A, B, and C in these equations correspond to variables $X1$, $X2$ and $X3$ which denote actual values of pH, current density, and reaction time, respectively:

$$As_{(removal)} = 98.36 + 3.49A + 1.50B + \\ + 9.61C + 1.05AB + 1.33AC - 5.79BC - \\ -4.17A^2 - 25.37B^2 - 7.09C^2 \quad (9)$$

The high correlation between actual experimental data and the model for percent arsenic removal (R^2 = 0.9903) is shown in Figure 6. Actual data are percent arsenic removal results of experiments based from ICP-AES analysis of actual percent arsenic removal. Predicted values are percent arsenic removal values using the model equation (Eq. 9) generated by the software.

Effect of operating parameters on percent arsenic removal

Percent arsenic removal in response to variations in operating parameters is shown in Figure 7. As illustrated in Figure 8, the influence of pH,

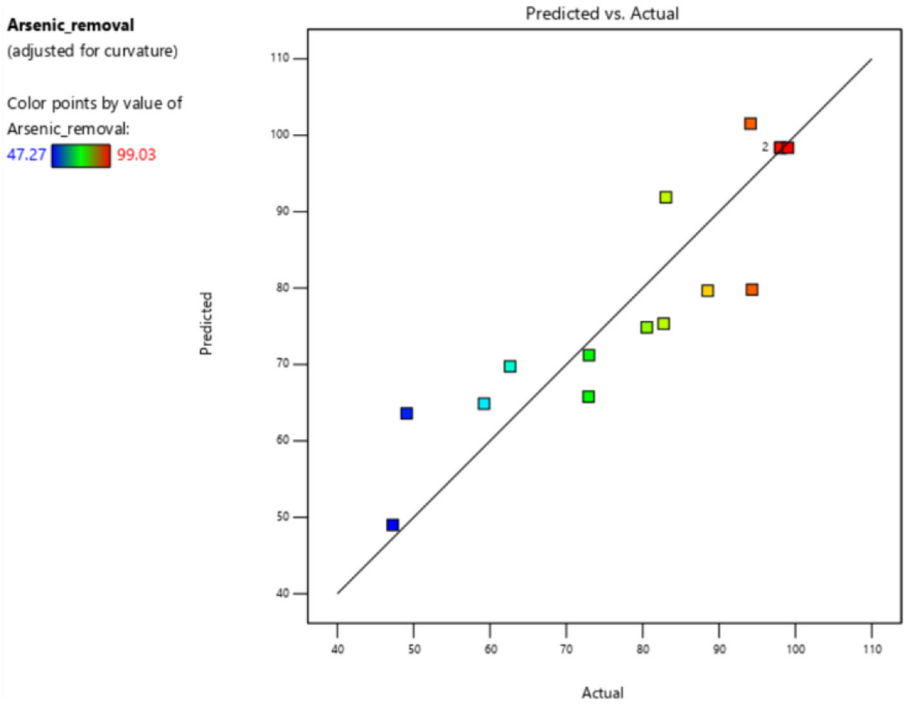

Figure 7. Comparison of actual experimental percent arsenic removal with model-predicted percent arsenic removal

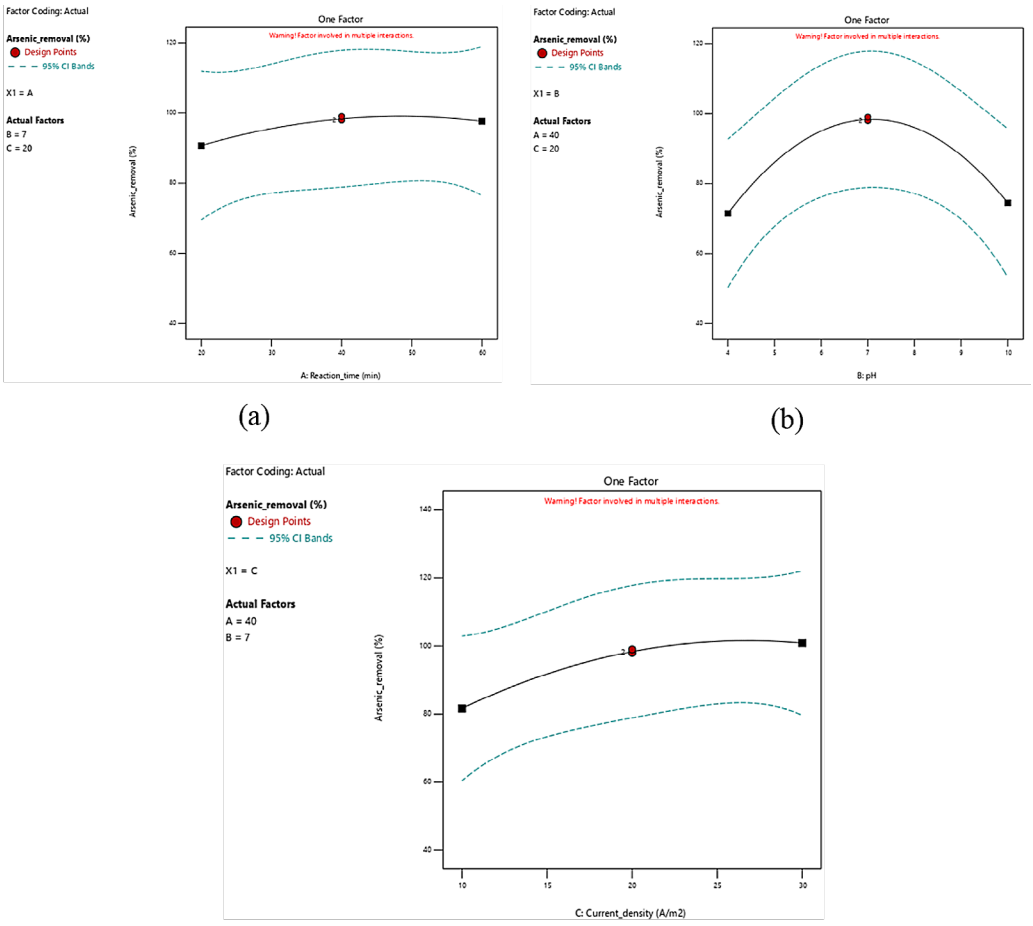

Figure 8. Effect of (a) reaction time, (b) pH, (c) current density on percent arsenic removal

current density, and reaction time on arsenic removal efficiency was further examined. Figure 8a reveals that reaction time had a relatively minor effect, with only slight variations in arsenic removal observed between 20 and 60 minutes, suggesting that most removal occurs within the early stages of the process. In Figure 8b, both pH 4.0 and pH 10.0 yielded the lowest removal efficiencies, approximately 75%, while a neutral pH of 7.0 resulted in the highest removal efficiency, ranging from 96% to 98%, reaffirming the critical role of pH in optimizing electrocoagulation performance. Figure 7c shows that a current density of 10 A/m² achieved only 80% removal, whereas increasing the current density to 20 A/m² significantly improved removal efficiency to about 95%. A further increase to 30 A/m² produced only a marginal gain, indicating diminishing returns beyond a certain threshold. These results underscore the importance of optimizing pH and current density over extended reaction time in achieving efficient arsenic removal.

Optimization by design of experiment

The two-parameter 3D surface plots in Figure 9 indicate: optimum pH and reaction time (Figure 9a), optimum current density and reaction time (Figure 9b) and optimum pH and current density (Figure 9c) for maximum percent arsenic removal. The increase in percent arsenic removal resulted from the predominance of hydroxyl radical production (Eqs. 4 and 5).

As shown in Figure 9, the response surface analysis highlights the optimal combinations of process parameters that result in the highest arsenic removal efficiency during electrocoagulation. In Figure 9a, the maximum arsenic removal was observed at a pH of 7.0 combined with a reaction time of approximately 40–45 minutes, indicating that near-neutral pH and moderate treatment duration are ideal for maximizing efficiency. Figure 9b demonstrates that the highest removal efficiency also occurred at a current density of approximately 20–25 A/m² when the reaction time was extended

to 45 minutes, emphasizing the importance of sufficient electrical input for coagulant generation. Additionally, as illustrated in Figure 9c, when the reaction time was fixed at 40 minutes, the most effective parameter combination was a pH of 7.0 and current density of 20 A/m², further confirming the consistent role of these conditions in achieving optimal treatment outcomes.

An appropriate solution for the reduced cubic model generated for percent arsenic removal is necessary for optimization. For a cost-effective operation, the amount of chemicals added was kept at a minimum while percent arsenic removal was set to a target of 95–100% for best removal efficiency. The software generated only one solution with these criteria: reaction time = 42 min, pH = 7.6, and current density = 22 A/m^2. As shown in Table 6, the experimental results obtained under the optimal operating conditions exhibited only negligible differences from the predicted values generated by the model. This close correspondence indicates a strong model fit and confirms the predictive accuracy of the response surface methodology within the range of arsenic concentrations examined. The minimal deviation between observed and predicted outcomes supports the model's robustness and validates its suitability for optimizing the electrocoagulation process.

In general, with an initial arsenic concentration of 100 ppb, the EC process achieved exceptionally high removal efficiency, with most runs exceeding 95% removal and optimized conditions yielding a removal of 99.93%. The model developed for this dataset was statistically significant, with an F-value of 7.61, and a high R^2 of 0.9993 (99.93%), indicating excellent predictive capability and model reliability. In contrast, with an initial arsenic concentration of 300 ppb, although

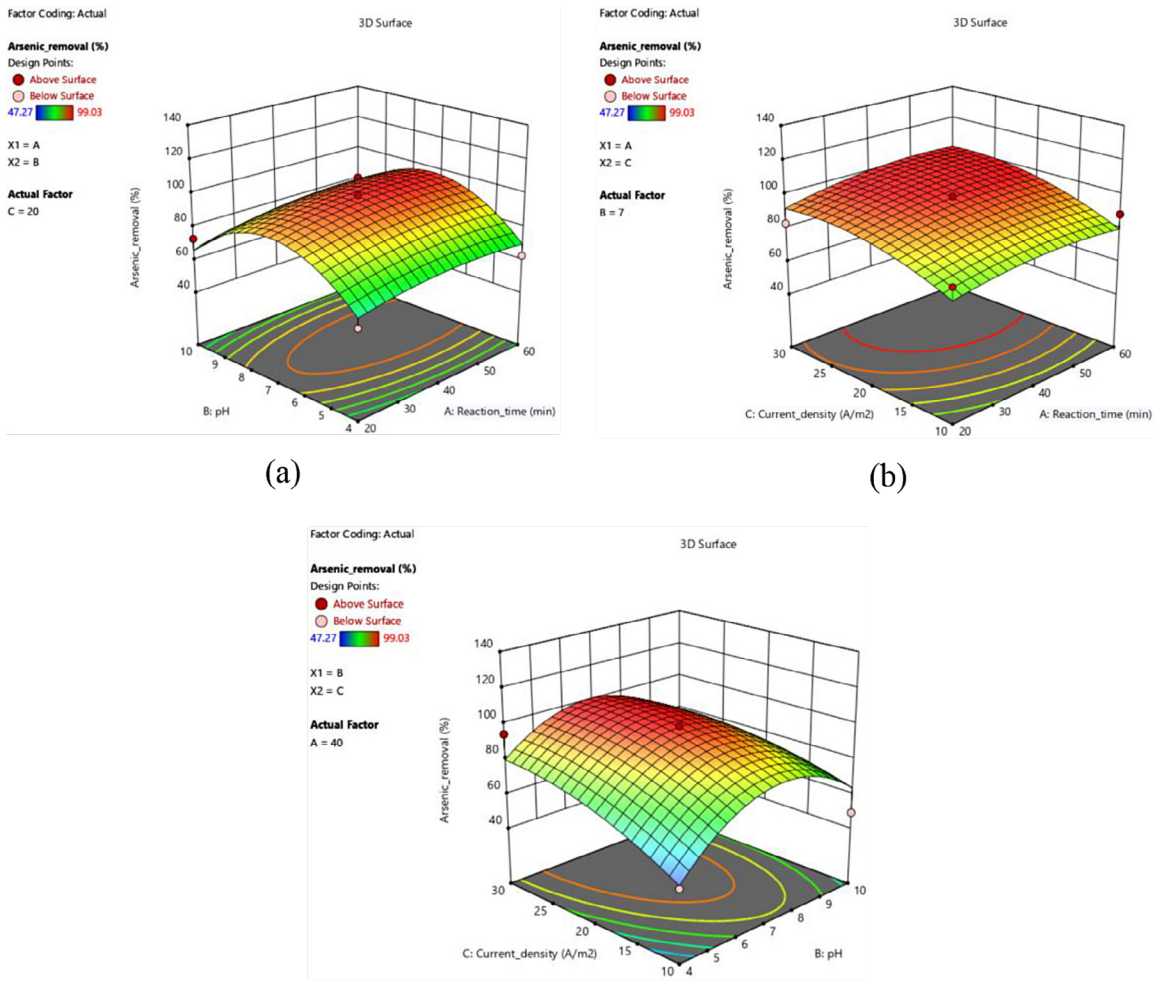

Figure 9. 3D surface plots of the two parameter interaction effects of initial pH, current density, and reaction time on percent arsenic removal: (a) reaction time and pH, (b) reaction time and current density, (c) pH and current density

Table 6. The optimum condition for the electrocoagulation of 300 ppb arsenic wastewater

Values of optimum conditions	Time reaction	42
	pH	7.6
	Current density	22
Actual and predicted values of percent arsenic removal	Actual	97.83%
	Predicted	99.41%
	Difference	1.58

removal efficiencies remained relatively high under optimal conditions (removal of 99.41%), the overall performance was more variable, and the model was not statistically significant (F-value = 2.25, p = 0.1926). While individual parameters like pH, current density, and their quadratic terms were still influential, the lower model significance and R^2 of 0.802 (80.2%) suggest increased process complexity at higher contaminant loads. Notably, both studies found that reaction time (40 min to 50 min), slightly alkaline pH (7.5 to 9.0), and moderate current densities (~12–20 A/m²) were optimal, but the higher arsenic load required slightly more precise tuning to achieve near-complete removal. These findings imply that while electrocoagulation is effective across a range of arsenic concentrations, lower concentrations allow for more stable and predictable treatment outcomes.

CONCLUSIONS

This study investigated the effectiveness of the electrocoagulation process for arsenic removal using synthetic arsenic-contaminated wastewater at concentrations of 100 ppb and 300 ppb. The experimental design employed the Box–Behnken method to systematically vary key operational parameters as reaction time, pH, and current density to identify optimal conditions for maximum arsenic removal. The results demonstrated that electrocoagulation is highly effective under the optimized conditions. For the 100 ppb arsenic solution, the process achieved a maximum removal efficiency of 99.93% at optimal conditions of reaction time = 52 minutes, pH = 8.9, and current density = 12.5 A/m², while for the 300 ppb solution, the process achieved a maximum removal efficiency of 99.41% at optimal conditions of reaction time = 42 minutes, pH = 7.6, and current density = 22 A/m². These results affirm the potential of electrocoagulation as a reliable and scalable method for arsenic removal from contaminated water.

Despite demonstrating high arsenic removal efficiency, this study has several limitations that warrant further investigation. Firstly, although visible precipitate formation was observed during electrocoagulation, the amount and physicochemical characteristics of the sludge were not analyzed. Understanding the composition, stability, and potential environmental impact of the resulting sludge is essential for assessing the long-term sustainability of the process. Secondly, while a combination of aluminum and iron electrodes was employed, the study did not include a comparative analysis to determine the individual contribution of each electrode material to the arsenic removal mechanism. Such insights are crucial for optimizing electrode selection based on contaminant type and treatment goals. Furthermore, the study focused on short-term batch experiments, without addressing the long-term performance and durability of the electrodes. Electrode degradation over repeated use, as well as potential secondary contamination from dissolved metal ions, remain unexplored and could significantly affect the process's operational viability. Future research should prioritize the characterization and management of the electrocoagulation sludge, isolate and compare the roles of different electrode materials, and assess long-term system performance, including electrode stability and lifecycle analysis, to enhance the practical implementation of electrocoagulation in real-world settings.

REFERENCES

1. Alkurdi, S., Herath, I., Bundschuh, J., Al-juboori, R., Vithanage, M., Mohan, D. (2019). Biochar versus bone char for a sustainable inorganic arsenic mitigation in water: What needs to be done in future research?. *Environment international. 127*. https://doi.org/10.1016/j.envint.2019.03.012
2. Aredes, S., Pawlik, M. (2013). The Removal of arsenic from water using natural iron oxide minerals.

Journal of Cleaner Production. 29–30. 208–213. https://doi.org/10.1016/j.jclepro.2012.01.029

3. Biela, R., Kučera, T. (2016). Efficacy of sorption materials for nickel, iron and manganese removal from water. *Procedia Engineering. 162*. 56–63. https://doi.org/10.1016/j.proeng.2016.11.012
4. Callegari, A., Ferronato, N., Rada, E., Capodaglio, A., Torretta, V. (2018). Assessment of arsenic removal efficiency by an iron oxide-coated sand filter process. *Environmental Science and Pollution Research. 25*. https://doi.org/10.1007/s11356-018-2674-y
5. Carrard, N., Foster, T., Willetts, J. (2019). Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water, 11*(8), 1605. https://doi.org/10.3390/w11081605
6. Dean, S., Wang, S., Zhao, X. (2008). A review on advanced treatment methods for arsenic contaminated soils and water. *Journal of Astm International. 5*. https://doi.org/10.1520/JAI101591
7. Dutta, N., Gupta, A. (2022). Development of arsenic removal unit with electrocoagulation and activated alumina sorption: Field trial at rural West Bengal, India. *Journal of Water Process Engineering. 49*. https://doi.org/10.1016/j.jwpe.2022.103013
8. Shaji, E., Santosh, M., Sarath, K.V., Pranav Prakash, Deepchand, V., Divya, B.V. (2021). Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula[J]. *Geoscience Frontiers, 12*(3): 101079. https://doi.org/10.1016/j.gsf.2020.08.015
9. Gang, Z., et al. (2016). Load model and modified model medical stone on the removal of arsenic in drinking water. Proceedings of the *2016 4th International Conference on Mechanical Materials and Manufacturing Engineering, Atlantis Press.* https://doi.org/10.2991/mmme-16.2016.191
10. Gomes, J., Daida, P., Kesmez, M., Weir, M., Moreno C.H., Parga Torres, J., Irwin, G., McWhinney, H., Grady, T., Peterson, E., Cocke, D. (2007). Arsenic removal by electrocoagulation using combined Al–Fe electrode system and characterization of products. *Journal of hazardous materials. 139*. 220–31. https://doi.org/10.1016/j.jhazmat.2005.11.108
11. Hoque, M.A., Scheelbeek, P.F.D., Vineis, P. et al. Drinking water vulnerability to climate change and alternatives for adaptation in coastal South and South East Asia. *Climatic Change 136*, 247–263 (2016). https://doi.org/10.1007/s10584-016-1617-1
12. Hutton, G., Chase, C. Water Supply, Sanitation, and Hygiene. In: Mock CN, Nugent R, Kobusingye O., et al., editors. *Injury Prevention and Environmental Health*. 3rd edition. Washington (DC): The International Bank for Reconstruction and Development / The World Bank; 2017 Oct 27. Chapter 9. Available from: https://www.ncbi.nlm.nih.gov/books/NBK525207/ https://doi.org/10.1596/978-1-4648-0522-6_ch9
13. Jadhav, S., Bringas, E., Yadav, G., Rathod, V., Ortiz, I., Marathe, K. (2015). Arsenic and fluoride contaminated groundwaters: A review of current technologies for contaminants removal. *Journal of environmental management. 162*. 306–325. https://doi.org/10.1016/j.jenvman.2015.07.020
14. Podgorski, J., Berg, M. (2020). Global threat of arsenic in groundwater. *Science 368*, 845–850. https://doi.org/10.1126/science.aba1510
15. McCarty K.M., Hanh H.T., Kim K.W. (2011). Arsenic geochemistry and human health in South East Asia. *Rev Environ Health. 26*(1): 71–8. https://doi.org/10.1515/reveh.2011.010. PMID: 21714384; PMCID: PMC3128386.
16. Mohora, E., Rončević, S., Agbaba, J., Zrnić T.K., Tubić, A., Dalmacija, B. (2017). Arsenic removal from groundwater by horizontal-flow continuous electrocoagulation (EC) as a standalone process. *Journal of Environmental Chemical Engineering. 6*. https://doi.org/10.1016/j.jece.2017.12.042
17. Mollah, M., Schennach, R., Parga T.J., Cocke, D. (2001). Electrocoagulation (EC) – Science and applications. *Journal of hazardous materials. 84*. 29–41. https://doi.org/10.1016/S0304-3894(01)00176-5
18. Ortiz Escobar, M., Hue, N., Cutler, W. (2008). *Recent developments on arsenic: contamination and remediation.*
19. Ratnaike, R. (2003). Acute and chronic arsenic toxicity. *Postgraduate medical journal. 79.* 391–6. https://doi.org/10.1136/pmj.79.933.391
20. Simonič, M. (2009). Removal of inorganic As5+ from a small drinking water system. *Journal of the Serbian Chemical Society*. 74. https://doi.org/10.2298/JSC0901085S
21. UN Women and UN-Water. 2023. *Spotlight on SDG 6: From commodity to common good: A feminist agenda to tackle the world's water crisis.* https://www.unwomen.org/sites/default/files/2023-07/from-commodity-to-common-good-a-feminist-agenda-to-tackle-the-worlds-water-crisis-en.pdf
22. University of Arizona, *Water Resources Research Center, Arizona Water Resource, 2017-Winter.* Arizona Memory Project, accessed 26/06/2025, https://azmemory.azlibrary.gov/nodes/view/261306
23. Vu, K., Kaminski, M., Nunez, L. (2003). Review of arsenic removal technologies for contaminated groundwaters. https://doi.org/10.2172/815660
24. WHO (2019). *List of Classifications, Agents classified by the IARC Monographs, Volumes 1–124*. IARC Monographs on the Evaluation of Risk to Humans. IARC. July 7, 2019. Retrieved July 14, 2019. https://monographs.iarc.who.int/list-of-classifications.