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Research Paper

Integrated hybrid treatment for heavy metal by activated carbon and electro coagulation via new batch design reactor: Clean water production

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ABSTRACT

In this search article, an integrated hybrid treatment system combines adsorption activated carbon (AC) and electrocoagulation (EC) to remove lead metal from produced water. The novel used a batch reactor design that facilitates synergistic connections between the two treatment processes. The process was optimized under optimized conditions using Response Surface Methodology (RSM) with a Box-Behnken (BBD. The optimization process conditions include the electrolysis time, pH, activated carbon dose, and current. Lead removal efficiencies reached 88.4% for activated carbon alone, 95.4% for electrocoagulation alone, and 99.8% for the hybrid method at 45 min electrolysis time, pH 3.0, 1 gm of activated carbon dose, and 1 Amp. The results indicate that the combined scheme significantly enhances the lead metal removal rates from the produced water compared to the individual process methods, providing an active solution for the production of clean water. The hybrid process offers an eco-friendly, cost-effective, and sustainable approach to removing metal pollutants from water resources.

1. Introduction

Heavy metal-induced water source contamination continues to be one of the major economic and environmental issues facing the entire world nowadays. Like inorganic pollutants in water, that not recyclable and tend to accumulate in living things [1]. Although lead was one of the heavy metals that often ends up in wastewater in large quantities as a result of its toxicity, it is also one of the most valuable and frequently used metals in many industrial processes, including plastics, electroplating, metal finishing, and etching [2]. Also, this metal was often toxic, even at low concentrations, and dirty waste may be stored before being released into the atmosphere [3].

The presence of lead ions is a serious matter; meanwhile, they are hazardous to a variety of living things. Wastewater from the crude trade is very diverse and comprises a lot of heavy metals, including lead, copper, zinc, and Chromium [4]. Treatment was still vital before elimination since Oilfield waste contributes to environmental pollution. Because the pollutants of heavy metals are hazardous, non-biodegradable, and loud, old-style separation treatments have numerous drawbacks and are less effective at eliminating them from produced water [5]. However, none of this treatment was acceptable to wastewater with acceptable concentrations. Frequently, further treatment stages are obligatory to attain this objective [6]. The adsorption treatment is a gas or liquid solution that gathers on an adsorbent surface, forming an atomic or molecular film on the adsorbent's surface made up of the atoms or molecules being collected. It is a result of surface energy and a surface phenomenon. The adsorbent's atoms can draw wastewater because they are not encircled by other atoms on the surface [7].

Moreover, it is employed to remove harmful oil and oil-related substances from produced water. Any pollutant substance that has undergone controlled heat treatments to raise its porosity level is referred to as activated carbon [8, 9]. Activated carbon is a potent adsorbent owing to its large pore volume and high surface area to produce adsorbents with low-cost and efficient alternatives. For instance, agricultural materials like sawdust, cellulose, rice husks, coconut shells, and industrial waste products like polymers have grown in popularity in recent years [10]. An electrochemical method of adding coagulants and removing metals, colloidal particles, and other dissolved solids from wastewater is known as electrocoagulation. The redox reaction, which happens when an electric current is permitted through electrodes constructed of iron and/or aluminum, is an efficient treatment method for refining the cleanup of produced water [11]. Metal cations, such as iron or Aluminium, are free when the anode dissolves, whereas the cathode passes hydrogen gas and the hydroxyl ion (OH-), as presented in Fig. 1, [12]. Coagulants, or adsorbents, like $Al(OH)_3$, are formed when some ions come into contact. When electrodes of Aluminum were used in the electro-batch reactor, the subsequent methods occur [13]. In the aluminum anode, aluminum ions are made, which are essential to produce coagulants. Furthermore, during this treatment process, oxygen gas bubbles will be produced, which assist in mild agitation and transport light contaminants to the wastewater's surface [14], as shown in Eqs. 1 and 2, respectively. At the cathode electrode, hydroxyl ions will combine with aluminum metal to generate coagulants, though hydrogen gas bubbles were unconfined to aid in gentle mixing and the flotation of light pollutants toward the produced water's surface [15]. The corresponding chemical reactions are represented by Eqs. 3 and 4, respectively.

This work focused on lead elimination remediation and reusing in the South Iraqi Manufacturing oilfield by a new reactor design combined with adsorption and electrocoagulation. This research presents an innovative batch reactor design that integrates adsorption and electrocoagulation for removing lead from produced water—a novel approach not previously explored. This combined technique seeks to boost the effectiveness of water treatment while offering a sustainable solution for producing clean water in oilfield regions.

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Nomenclature

AC	Activated Carbon	X_1	Electrolysis time (min)
EC	Electrocoagulation	X_2	pH value
$AC-EC$	Hybrid treatment combining Activated Carbon and Electrocoagulation	X_3	Activated carbon dose (g)
PW	Produced Water	X_4	Applied current (A)
RSM	Response Surface Methodology	TSS	Total Suspended Solids (ppm)
BBD	Box-Behnken Design	$Organic\ Con.$	Organic Content (ppm)
$FTIR$	Fourier Transform Infrared Spectroscopy	$Al(OH)_3$	Aluminium hydroxide (coagulant formed during EC)
XRD	X-ray Diffraction	$Fe(OH)_3$	Ferric hydroxide (coagulant formed during EC)
$FE-SEM$	Field Emission Scanning Electron Microscopy	An^+	Metal cation released at anode
EDX	Energy Dispersive X-ray Spectroscopy	OH^-	Hydroxide ion
BET	Brunauer–Emmett–Teller (surface area analysis)	$H_2(g)$	Hydroxide ion
C_o	Initial concentration of lead in water (ppm)	*Greek Symbols*	
C_t	Final concentration of lead after treatment (ppm)	η	Lead removal efficiency (%)

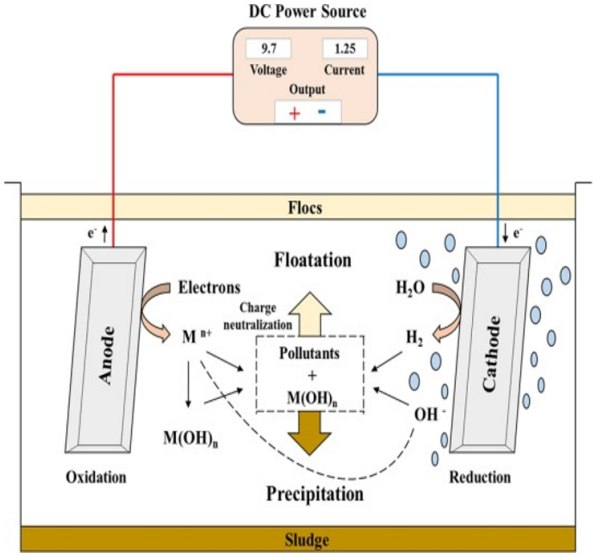


Figure 1. The electrocoagulation Mechanism [16].

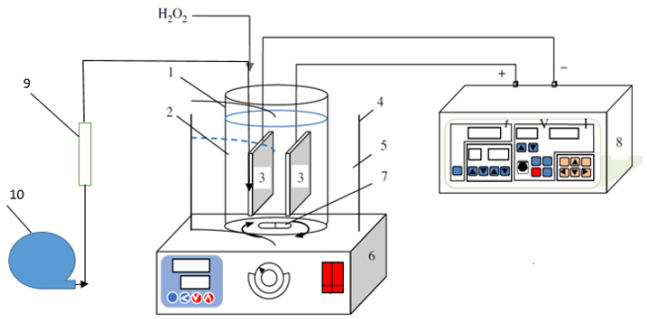


Figure 2. Hybrid treatment (1) Electrocoagulation cell, (2) wastewater, (3) Anode and cathode bars, (4) water bath, (5) pure water, (6) mixing stirrer, (7) magnetic bar, (8) RXN-305D power, (9) Rotameter meter, (10) pump, (11) Activated carbon.

$$Al_s \Rightarrow Al^{3+}_{aq} + 3e^- \tag{1}$$

$$2H_2O \Rightarrow O_2 + 4H^+ + 4e^- \tag{2}$$

$$2H_2O + 2e^- \Rightarrow H_{2g} + 2OH^-_{aq} \tag{3}$$

$$2Al^{3+}_{aq} + 3OH^-_{aq} - \rightarrow Al(OH)_3 \tag{4}$$

2. Experimental

2.1 Materials and analytical measurement

The commercial activated carbon was used in the adsorption method with characteristics measurement. Hydrochloric acid and sodium hydroxide (from Scharlau, Spain) were added to the produced water for pH solution. The electrodes of aluminum and iron were used as anode and cathode, respectively, employed in the electrocoagulation treatment. According to Table 1, the PW is from the wet oil unit. It was conserved using a combination of methods using the new batch apparatus shown in Fig. 2, and sealed in a polypropylene vessel and kept at 5 °C. At the end of each experiment of hybrid treatment, an atomic absorption spectrometer was used to measure the lead ion in PW. Air-acetylene with a flow rate of 55, slot burner 100 mm of 6 mm height, with 283.3 nm peak area mode for metal compounds in wastewater was used to determine the lead concentration [17].

Table 1. The wastewater properties.

Limits	Lead metal (ppm)	pH	Turbidity	TSS (ppm)	Organic Con. (ppm)
Value	3.23	6.77	66.1	16.7	132.5

2.2 The hybrid processes with a new reactor design

The three parts of the power supply, mixing and batch reactor used in the hybrid scheme are presented in Fig. 2. RXN-305D power supply was used in the combined system. The dimensions of the anode and cathode electrons were $(7\times2\times0.1)$ and $(9\times4\times0.11)$ cm^3, respectively. In the AC-EC treatment, the anode and cathode real area were upheld at 25 cm^2, with the space between internal electrodes was conserved at 4 cm. The power supply was studied for the (7 min) to sweep the Aluminum and ferrous ions in the batch electrocoagulation reactor and at that time, different doses of activated carbon were added for all experiments. The lead metal concentration before and after treatment was (C_o) and (C_t), respectively. The Lead removal (LR) can be determined by Eq. 5.

$$\eta = \frac{C_o - C_t}{C_o} \times 100 \tag{5}$$

2.3 Experimental design

The key independent variables of these issues were electrolysis time (X_1), pH (X_2), activated carbon (X_3), and current (X_4), which were persistently reduced to their ranges presented in Table 2. The Minitab software with response surface methodology was used to design the experiments and predict the consequences of the working variables independently and in a relational manner with each other. The BBD is a type of response surface design that allows for efficient estimation of the first- and second-order terms of a response surface model.

Table 2. Working parameters.

Limits	Variable
X_1: time (min)	$10 \rightarrow 45$
X_2: pH	$03 \rightarrow 09$
X_3: Activated carbon dose (gm)	$0.25 \rightarrow 1$
X_4: Current (Amps)	$0.20 \rightarrow 1$

3. Results and discussion

3.1 Examination of the Activated carbon morphology

FT-IR spectroscopy measurements show that the hybrid methods meaningfully affect the structure of activated carbon in Fig. 3. The region from 3000 to 3400 cm^{-1} in the FT-IR spectroscopy test corresponds to hydroxyl ions stretching vibrations, which were typically related to the quantity of hydroxyl groups in AC samples. The comparative strengths in this range drop following treatment of the hybrid, representing a notable reduction for carboxyl groups. The mechanical qualities of treated activated carbon were lost because of this decrease in the partial breakage of hydrogen bond constructions in commercial activated carbon. This observation is consistent with studies by [Jock et al, 2022], who reported similar changes in functional group [18]. The XRD analysis in Fig. 4, the characteristic peaks of the commercial adsorbent sample specify a sodality structure, consistent with standard peaks of activated carbon.

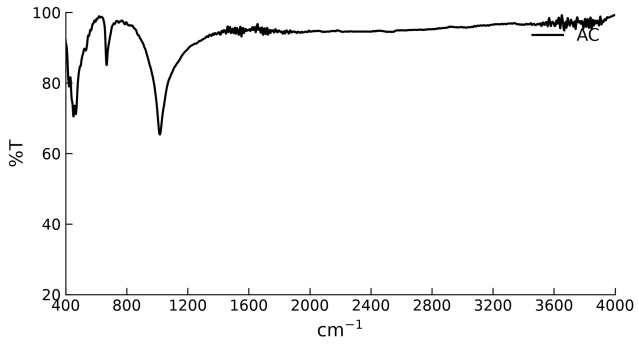


Figure 3. FTIR test of activated carbon, A.

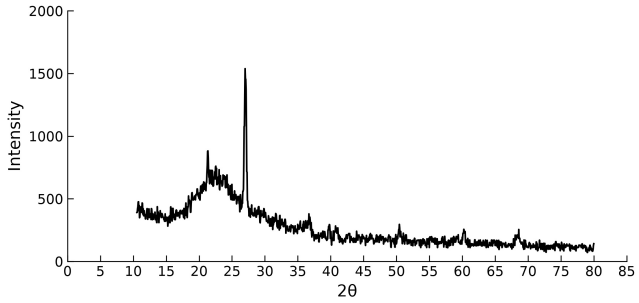


Figure 4. XRD patterns of activated carbon.

The distinctive peaks of the carbon structure were identified through two broad characteristic diffraction peaks that emerge in two varieties (about 20°–30° and 40°–50°) [19]. The particles show an unchanging, polyhedral, almost hexagonal, or spherical particle line construction. The particles were varied in sizes ranging by 500 μm sieve analysis with FE-SEM picture in Fig. 5.

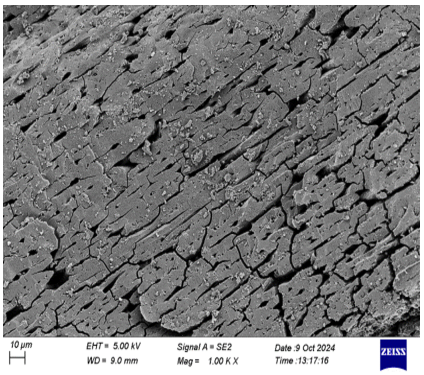


Figure 5. FE-SEM test of activated carbon.

The characteristic different pores of commercial samples of activated carbon were marked in the triangular and the FE- SEM picture demonstrates randomly distributed grains with smaller sizes. From the FE-SEM test, it can be concluded that the formation of microparticles has a homogeneous shape structure and it was grown in very high density with almost uniform spherical shape, [Jun et al, 2021] observed it's beneficial for adsorption processes due to the increased surface area and accessibility of pores [20]. An EDX test was conducted to assess the purity of activated carbon. The analysis revealed the presence of C, Ca, Fe, and O metals in the commercial activated carbon tasters. No impurity peaks were observed, including empirical, descriptive high sample cleanliness, and confirming the presence of the intended metals. Analysis was used to regulate the optical characteristics of the activated carbon as presented in Fig. 6 [21].

With a BET test, the activated carbon example's surface area and pore volume were inspected. It was found that the surface area derived from the present study is 405.31 m^2/g,0.56996 cm^3/g total pore volume, and the average pore diameter is 13.011 nm, signifying that there may have been variations in the example, untried setup, or logical approaches between studies as presented in Fig. 7 [22]. Figure 7 shows the isotherms adsorption-desorption of the activated carbon, which are IV isotherm type according to the IUPAC classification, indicating the presence of mesopores. The hysteresis loop suggests a complex pore structure, which is typical for activated carbons used in adsorption applications.

3.2 Statistical Analysis for Hybrid Methods

Twenty-seven statistically industrialized trials were intended to enhance and examine the integrated result of independent variables aimed at a specific group of process parameters. The independent variables, for instance, pH, activated carbon dose, current, and time for AC, EC, and AC-EC treatments on the lead removal in produced water. Table 3 demonstrates the values of the working variables, lead the elimination of the studied responses. Table 4 illustrates the hybrid treatment of adsorption and electrocoagulation using ANOVA examination. Table 4 displays the findings for each parameter's Fisher value, P-test, adjusted sum of squares, adjusted mean of squares, degree of freedom, and sum of squares. The model's multiple correlation constant, which is 92.5% compatible with the regression's statistical significance, shows that only 7.27 percent of the total variants are not reinforced by work [23]. The high capability reply of elimination along the time of the combined method aimed at all values of the lead ion concentration, without high concentrations that incline toward drop aimed at a certain period because of the absence of passable places on the adsorption surface and electrocoagulation is considerable in the direction of attaining a relatively high removal ratio, is presented in Fig. 8 interaction plot of variables of hybrid methods. Because the lines in these cells are convergent, the integrated properties of time, activated carbon, and current had a significant effect on lead removal in wastewater. According to the results, the AC-EC's metal squalor amplified with cumulative dose, current, and time, increasing from low to high. These core results are obvious in [24]. The main effects of the problems were strong-minded, and the repercussions were analyzed using the "Minitab 17ßoftware. An issue's outcome is still determined by the shift in response brought about by a change in the issue's level. Since it highlights the main points of interest in the experiment, this is often referred to as the principal effect. The chief limitations of each limit on lead removal in wastewater are depicted in Fig. 9. The activated carbon dose, current, and time were the most significant variables affecting lead removal in wastewater [25].

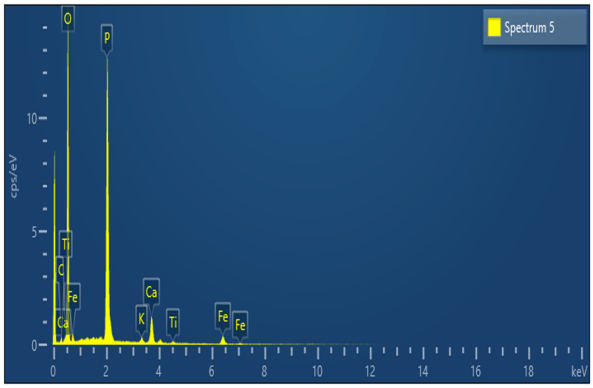
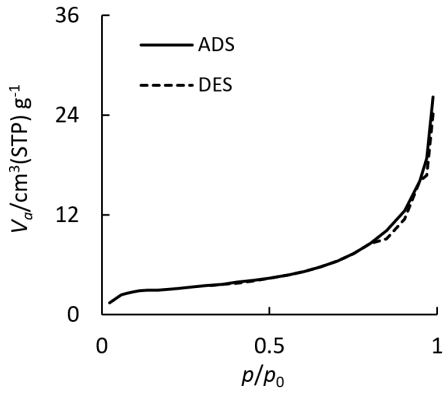
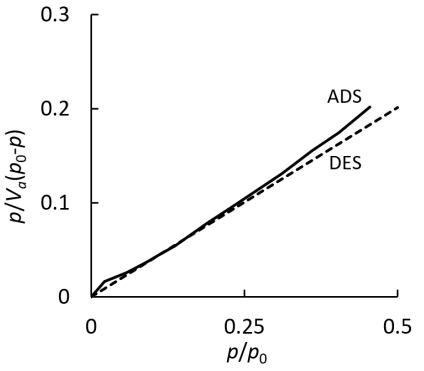


Figure 6. EDX test of activated carbon.



(a) Type IV isotherm



(b) Linear BET plot

Figure 7. Nitrogen adsorption-desorption analysis of activated carbon.

Table 3. Results of the BBD experiments.

X_1	X_2	X_3	X_4	(%) Lead removal by		
				AC	EC	AC-EC
10.0	3	0.625	0.6	31.2	45.3	55.7
45.0	3	0.625	0.6	75.4	80.5	86.9
10.0	9	0.625	0.6	24.4	30.5	41.6
45.0	9	0.625	0.6	45.7	65.8	80.1
27.5	6	0.250	0.2	36.5	40.7	55.8
27.5	6	1.000	0.2	66.7	71.7	81.6
27.5	6	0.250	1.	36.5	77.8	85.8
27.5	6	1.000	1.0	66.7	82.5	90.4
10.0	6	0.625	0.2	42.4	45.3	59.9
45.0	6	0.625	0.2	70.4	72.9	81.6
10.0	6	0.625	1.0	42.4	66.8	76.4
45.0	6	0.625	1.0	77.4	88.8	95.3
27.5	3	0.250	0.6	60.5	71.3	81.6
27.5	9	0.250	0.6	39.4	45.8	59.8
27.5	3	1.000	0.6	82.8	86.9	98.7
27.5	9	1.000	0.6	70.4	77.5	86.4
10.0	6	0.250	0.6	30.1	50.4	60.5
45.0	6	0.250	0.6	55.2	64.6	74.9
10.0	6	1.000	0.6	84.2	88.5	95.4
45.0	6	1.000	0.6	89.4	93.3	98.4
27.5	3	0.625	0.2	87.5	89.4	93.5
27.5	9	0.625	0.2	77.4	80.5	87.5
27.5	3	0.625	1.0	87.5	94.7	99.5
27.5	9	0.625	1.0	77.4	84.8	90.5
27.5	6	0.625	0.6	73.2	84.8	90.6
27.5	6	0.625	0.6	72.8	83.7	89.8
27.5	6	0.625	0.6	73.5	82.9	91.0

X_1: Time (min) **X_2: pH**
X_3: Activated carbon (gm) **X_a: Current Amps**

3.2.1 Electro–electro–activated carbon presentation

One of the objectives of this work was to assess the data on adsorption and electro-coagulation treatment. Fig. 10 shows the lead removal with a changed dose of activated carbon. From the results can be understood that the lead removal is increased with an increase in the dose of activated carbon from 42.1,56.8 and 70.8% at 0.2 *gm* to the all-out elimination of 65.1,78.5 and 90.7% at 1 *gm* of activated carbon dose [26]. The surface area available for adsorption typically rises with the dose of activated carbon. Higher elimination efficiencies could result from more lead ions being deposited onto the adsorbent's surface as the dose increases [27].

3.2.2 Time effect

The effect of time on adsorption and electrocoagulation can vary depending on the system and conditions involved, for instance, the type of adsorbent, the nature of the pollutants, and the specific setup for electrocoagulation and adsorption methods. As presented in Fig. 11, longer oxidation times resulted in improved lead elimination capacities in the wastewater. Given the long time, this may last to be credited to the attendance of an important adsorption activity during the AC-EC treatment. Moreover, lengthy electrocoagulation and adsorption time resulted in step-by-step detoxification of previously inorganic tin, water, and carbon dioxide remained produced [28, 29].

Table 4. Results of the BBD experiments.

Foundation	DOF	Seq. SS	Adj. MS	Fisher	P–test
1-Model	14	4763.84	0340.27	02.65	0.049
Linear	4	3737.29	0934.32	07.27	0.003
X_1	1	1358.94	1358.94	10.57	0.007
X_2	1	0408.33	0408.33	03.18	0.100
X_3	1	1463.02	1463.02	11.38	0.006
X_4	1	0507))	507.00	03.94	00.07
Square	4	0841.60	210.4	01.64	0.229
X_1^2	1	0743.14	743.14	05.78	0.033
X_2^2	1	0128.93	128.93	01	0.336
X_3^2	1	0084.45	84.45	00.66	0.433
X_4^2	1	0000.93	0.93	00.01	0.934
2-Way Interaction	6	0184.94	30.82	0.24	0.955
$X_1 \times X_2$	1	0013.32	13.32	0.1	0.753
$X_1 \times X_3$	1	0032.49	32.49	0.25	0.624
$X_1 \times X_4$	1	0001.96	01.96	0.02	0.904
$X_2 \times X_3$	1	0022.56	22.56	0.18	0.683
$X_2 \times X_4$	1	0002.25	02.25	0.02	0.897
$X_3 \times X_4$	1	0112.36	112.36	0.87	0.368
Error	12	1542.50	128.54	—	—
Lack-of-Fit	10	1541.75	154.18	412.97	0.002
Pure Error	2	0.75	0.37	—	—
Total	26	6306.34	—	—	—

3.2.3 *pH* Effect

The hybrid process is meaningfully influenced by the value of pH, so the finest performance of the method demands a preferred *pH* range. Figure 12 demonstrates that the *pH* increases as the lead removal decreases, and the best pH is 3.0. These clarifications conform to those of Ali et al., 2019 [30], which notes that the *pH* result of the removal of lead ions remains not remarkable. Multiple investigations were conducted with a change in the *pH* range from 3 to 9 to evaluate the result of *pH* on the lead removal by way of per lead ion by hybrid treatment, the lead removal of 69.4,76.4 and 87.2% has remained attained at $pH = 3$. Just overhead this value, the lead competence has stood reduced gradually down to a value of pH=9. An evident reduction of 59.4, 61.2, and 72.4% for adsorption, electrocoagulation, and hybrid treatment. The elimination of lead ion contaminants during the AC-EC process is influenced by *pH*. For instance, the hybrid process's ability to remove lead from generated water was enhanced by a *pH* range of 3 to 9. Because of the presence of $Fe(OH)_3$, which is affected by *pH* and Fe^{3+} concentration, the maximum removal efficiency was specifically noted at *pH* 3.0. This emphasizes how crucial *pH* control is to wastewater treatment [30].

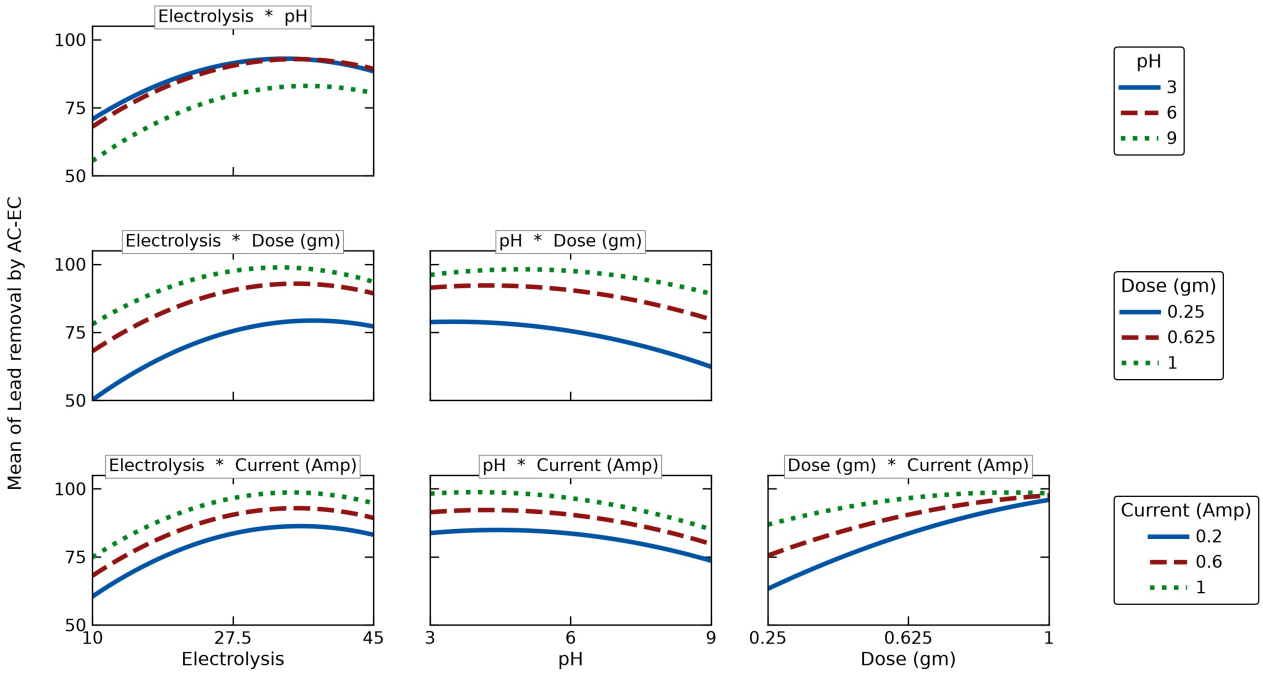


Figure 8. Interaction plot of variables.

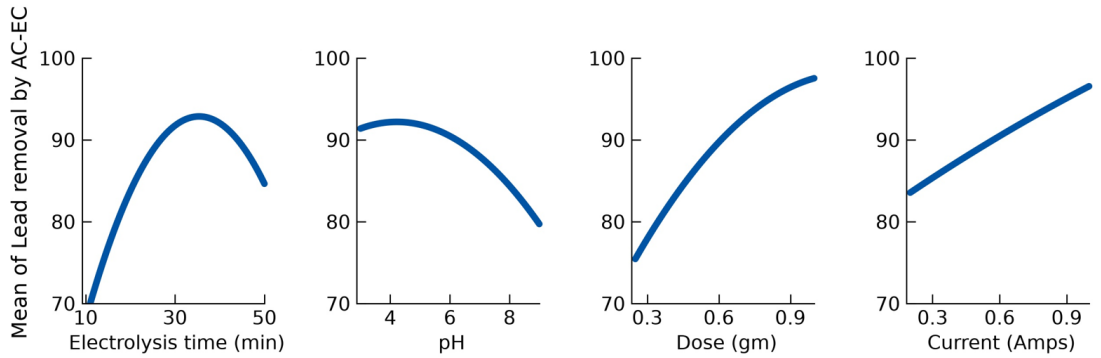


Figure 9. Main plot results for LR.

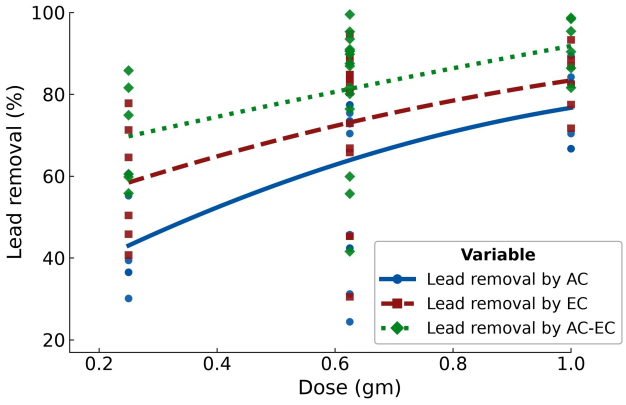


Figure 10. Effect of dose on the lead removal.

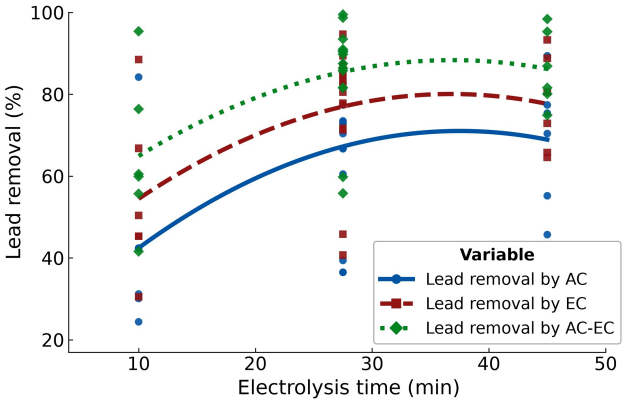


Figure 11. Effect of time on lead removal.

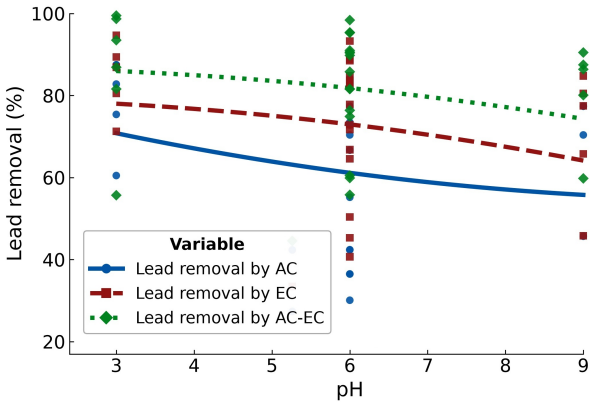


Figure 12**.** Effect of pH on lead elimination.

3.2.4 Current Effect

Figure 13 presents the current sign on the presentation of the hybrid system. The trials were achieved through variable currents from 0.2 to 1 Amps. The metal elimination upsurges with cumulative current, and the all-out lead elimination of 62.1,77.4 and 88.9% were attained at 1 mA, and the lead removal is 60.1,67.4 and 78.7% at 0.2 Amps for adsorption, electrocoagulation, and a hybrid of the two methods at the best condition with 200 rpm and room temperature. By way of the applied current to the electrode upsurges consistently. A higher current would lead to a higher manufacturing rate of adsorption and electro-coagulation that leads to high removal of lead ions in produced water [31].

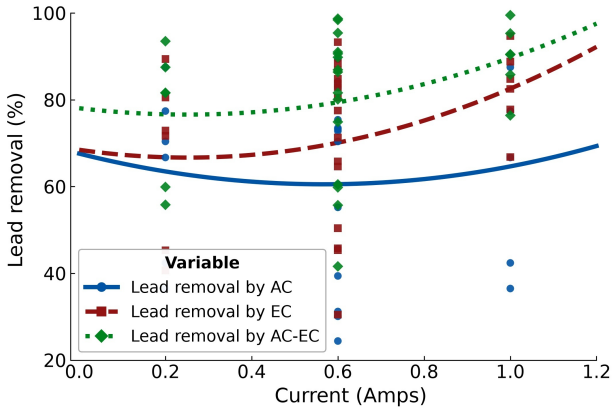


Figure 13**.** Effect of current on lead elimination.

3.3 Enhancing the independent variables

Using Minitab-17, the finest values of independent variables, for instance, time, pH value, activated carbon, and current, were used in the work. The measurement effects of the D-optimization are presented in Fig. 14.

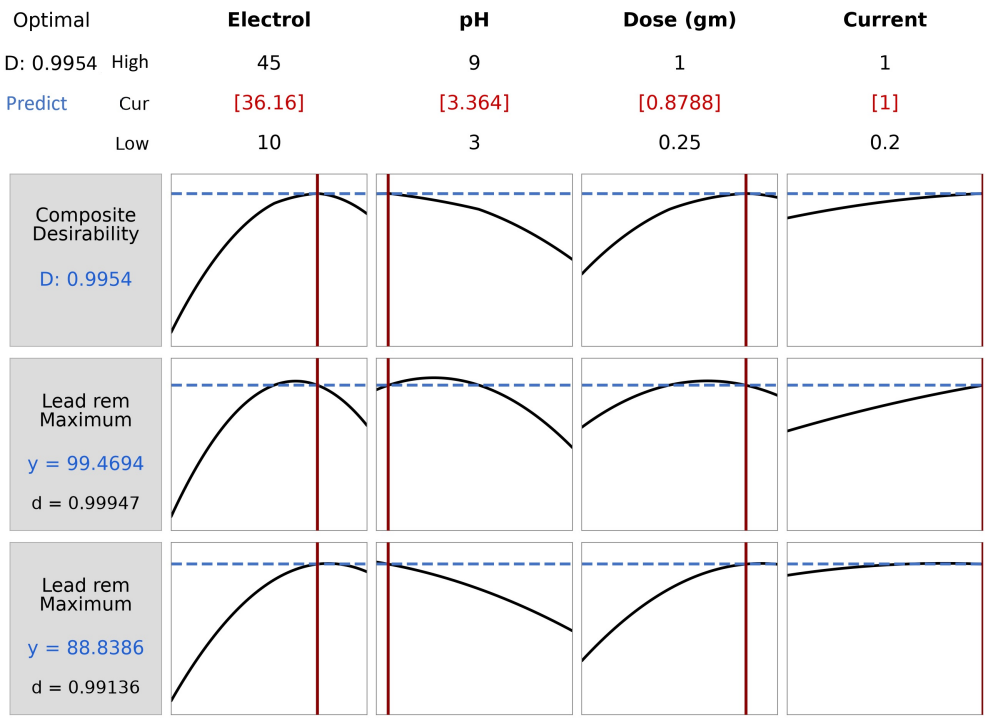


Figure 14**.** Finest independent variables with lead removal.

For the integrated treatment of adsorption and electrocoagulation, the best metal removal competencies were greater than 99%.

3.4 Mathematical Model of Batch Reactor for Lead Removal

The scientific model characteristically defines the dynamic conduct of the combined scheme through a set of equations that relate to process limits. Exact models are used not only to explain the arrangement, but also to work out the effects of various components on the system and to find solutions for most difficulties [32]. The metal elimination in produced water is a multifaceted treatment connecting numerous separate problems to distinguish reactions. The degradation mechanism of lead metal over the adsorption and electro-coagulation consists of several steps, as presented in Fig. 15. The model assumes uniform mixing, steady state conditions, and negligible mass transfer limitations [33,34]. Eqs. 6, 7 and 8 clarify the chemical reaction happening in an electro-coagulation reactor in the case of using (A) metal for both electrodes [35]. A cohort of electro-coagulants owing to the redox reactions occurring on both the anode and cathode.

Metal A at the anode:

$$A_S \rightarrow A_{aq}^{+n} + ne^- \tag{6}$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad (7)$$

In the cathode reaction:

$$2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)} \quad (8)$$

Rebellion of the contaminants, particulate postponement, and contravention of suspensions:

$$A^{+n}_{aq} + ne^- \rightarrow A_S \quad (9)$$

This method requires two obliging procedures: the dissolution of anode metal to its ions, followed by a reaction with hydroxyl ions produced at the cathode. Using an aluminum electrode as an instance, these activities result in the combination of the damaged phases to form flocs Eqs. 10 and Eq. 11, [36].

$$2Al_S \rightarrow 2Al^{+3}_{aq} + 6e^- \quad (10)$$

$$Al^{3+}_{aq} + 3OH^-_{aq} \rightarrow Al(OH)_3 \quad (11)$$

For the electrode of iron, two reaction conditions of ferrous (Fe^{+2}) and Ferric (Fe^{+3}) are produced in Eqs. 12, 13 and 14.

$$Fe_s \rightarrow Fe^{+2}_{aq} + 2e^- \quad (12)$$

$$4Fe^{2+}_{(aq)} + O_{2(g)} + 4H^+_{(aq)} \rightarrow 4Fe^{+3}_{(aq)} + 2H_2O_{(l)} \quad (13)$$

$$Fe^{+3}_{aq} + 3H_2O_l \rightarrow Fe(OH)_3 + 3H^+_{aq} \quad (14)$$

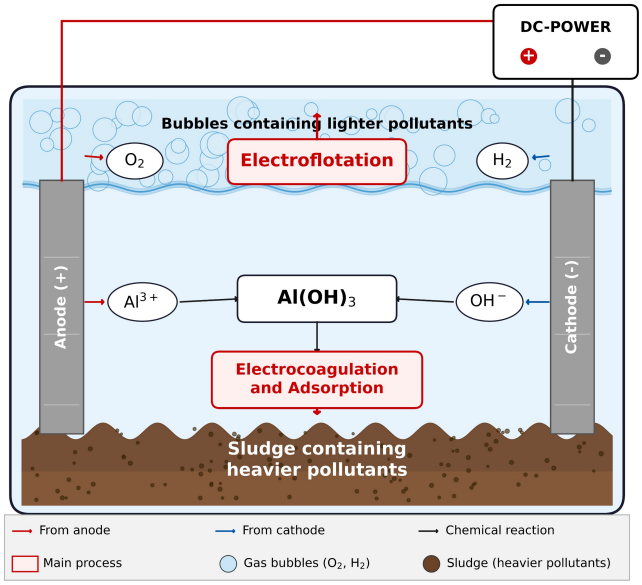


Figure 15. The mechanism suggested for $AC - EC$ treatment.

3.5 Comparison results between this work and previous work

Water used in the crude oil processes for injection contains high metal compounds, achieved by feedstocks that go through catalytic refining processes. The related metal compounds come in a variety of forms, including cyclic or closed-chain compounds. Metal-containing products are typically removed utilizing several technologies and reliable catalytic systems. In the petroleum refining industry, physical separation, chemical processes, and biological degradation are the two procedures used to lower or eliminate the organic level. Table 5 presents the comparison results and parameters (about organic and inorganic elimination compounds by various methods) between this study and previous studies.

Table 5. Comparison results between this work and the last studies related to metal removal compounds by different technologies.

Process method	Operating conditions	Feeds-tock	Reactor type	%Rem-oval	Req.	Ref.
Composite material	200 rpm ; 70 ppm Fe conc ; 55 °C ; 250 *min*	Simulated wastewater	Batch system	96.00	Composite of ferrous and activated carbon	[37]
Electro-Fenton oxidation	200 rpm ; 30 ppm TiO2 6 pH ; 30 min	Refinery wastewater	Electro catalytic	96.27	Catalytic oxidation, and catalyst (TiO2)	[38]
Photovoltaic Cell Electro-Fenton	250 rpm ; 20 ppm H2O2 ; 3 pH ; 25 min	Oily wastewater	Electro-chemical	98.00	Electrooxidation with photovoltaic cell	[39]
Electrocoagulation	300 rpm ; 2.5 Amps current 3 pH ; 60 min	Simulated wastewater	Electrocoagulation	97.30	Electrocoagulation	[40]
Adsorption	1 gm dose ; 1 Amps 3 pH ; 45 min	Produced water	Batch system	88.40	Activated carbon	This work
Electro-coagulation (EO) process	1 gm dose ; 1 Amps 3 pH ; 45 min	Produced water	Electro system reactor	95.40	Aluminium and Iron as anode and cathode	This study
Adsorption and Electrocoagulation	1 gm dose ; 1 Amps 3 pH ; 45 min	Produced water	Novel reactor	99.80	Activated carbon and electro-coagulation	This study

4. Conclusions

This study successfully tested a new, practical way to remove lead from produced water using a unique batch reactor that combines activated carbon adsorption with electrocoagulation. We achieved an impressive 99.8% lead removal rate under the best conditions, which worked much better than using either method alone. These results show that this approach could be a game-changer for cleaning heavy metal-polluted wastewater in oilfields. Next, we plan to scale up the process and see if it works for other heavy metals.

Authors' contribution

Nada D. Ali: Conceptualization, methodology, experimental design, laboratory investigation, data collection, characterization measurements, and writing of the original draft. Hind J. Hadi: Methodology, formal analysis (Box–Behnken design, response surface methodology, ANOVA, optimization), statistical interpretation, characterization data analysis, and manuscript review/editing. Vinous M. Hameed: Supervision, project administration, resources/funding acquisition, validation, writing – review & editing, and corresponding author.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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