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Analyzing the removal of lead from synthesis wastewater by electrocoagulation technique using experimental design

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ABSTRACT

The electrocoagulation treatment of wastewater is the best applicable method to remove lead from the aqueous solutions using aluminium electrodes. The aim of the present study is to investigate the effect of the operational parameter son the efficiency of lead removal from synthesis wastewater using an experimental design. Applied current (0.5–2.5) Amps., pH (2–12), stirring speed (0–300) rpm, electrolytic time(5–60) min, and the initial concentration of lead (10–300) ppm were tested to establish the mathematical correlations of the removal efficiency and the energy consumption using a central composite design rotatable and uniform. The results showed clearly the variation of the output responses values according to the values of the operational variables. The optimum values of the operational variables were evaluated for each value of the designed removal efficiency as well as the values of energy consumption measured consequently.

Keywords: Wastewater; Lead; Electrocoagulation; Experimental design; Energy consumption; Electrodes consumption

1. Introduction

A significant amount of industrial wastewater is discharged daily in the modern world [1] into the environmental system [2] as a result of the continuous development and advancement in technology. The pollutants in the industrial wastewater are classified to be bio-degradable and non-degradable [3]. The former type is referred to as domestic wastewater which is released in residential areas. It is recognized as heavily contaminated with various organic and inorganic pollutants [4]. The latter type of industrial wastewater contains several types of toxic contaminants such as pesticides, cyanides, and heavy metals.

Each metal, which has a specific gravity greater than five is classified as a heavy metal [5]. There are numerous types of heavy metals, but lead, chromium, and mercury are known as the most toxic and dangerous than other kinds of heavy metals. Lead can cause damage to the central nervous system, the kidney, liver and reproductive system when its value exceeds 0.05 ppm according to the rules of World Health Organization (WHO) [2].

The increment of water usage leads to the release of large amounts of wastewater that added more of impurities into the aquatic system which must then be treated by the treatment processes. Several industries in Iraq, such as the chemical and petrochemical industries have consumed, in 2014 only, more than 44300 m^3 of fresh water per day and have released more than 17500 m^3 of wastewater per day [6] that contain various kinds of organic and inorganic pollutants. Table 1 lists details of fresh water consumed and wastewater discharged from Iraqi industries according to the Central Statistical Organization (CSO)report for the year 2014.

Water has become a vital resource; the increase in population and the rapid industrial development have led to an increase for water's domestic and industrial usage [7]. Therefore, these wastewater should be treated and pollutants should be removed from both economic and environmental points of view [1] using an innovative and reasonable technique.

Several techniques are used to remove heavy metals from wastewater such as chemical precipitation [5], ion

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exchange [8], adsorption [9], membrane filtration [10], and electrocoagulation [11]. Each kind of these treatment processes has advantages and disadvantages from the practical and economic insight. Electrocoagulation is an attractive process which is dependent on the electro chemistry concept using an electrical current to eliminate toxic metals from waste solutions that are discharged from various industries such as metal plating wastewater [11], baker's yeast wastewater [12], paper industries wastewater [13], olive mill wastewater [14], municipal wastewater [15] etc.

Concentric aluminium tubes electrodes were used in the present electrocoagulation cell. The main reactions at electrodes are given in the following Eqs. (1–4):

Anode and cathode :

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

Table 1
Daily amounts of fresh water used and wastewater released from Iraqi industries in 2014 [6]

Type of industry	Fresh water consumed		Wastewater discharged	
	m^3/d	%	m^3/d	%
Chemical and petrochemical	44338.1	43.4	17554.8	38.8
Engineering	20689.2	20.3	11534.5	25.5
Food and medication	3476.0	3.4	1611.5	3.6
Textile	4844.7	4.7	3388.0	7.5
Construction and industrial services	28743.7	28.2	11155.3	24.7
Mixed sector companies	0.0	0.0	0.0	0.0
Total	102100.6	100.0	45244.0	100.0

Cathode:

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

Formation of $Al(OH)_3$:

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

The neutral form of $Al(OH)_3$ is polymerized, as follows, to form flocs which have the high-flocking capacity [16,17] to eliminate the pollutants from wastewater by the adsorption process via the electrocoagulation cell:

$$n\,Al(OH)_3 \rightarrow Al_n(OH)_{3n} \quad (4)$$

Fig. 1 shows the formation of monomer phases by Al^{+3} as a function of the pH in electrocoagulation process.

Several studies were done to investigate the best way and design of the electrocoagulation reactor in order to maintain a higher removal efficiency of toxic metals from the aqueous environments with respect to the conditions of economic and ecological fundamentals. However, there are few previous studies on lead removal, especially when lead is presented alone in waste water samples.

Assadi et al. [20], tried to enhance lead removal using bipolar aluminum electrodes via a batch electrocoagulation reactor under specified operational variables which are the electrolysis time 5–30 min, current density 11, 22, and 33 A/m^2, pH 5–9 and different concentrations of lead 5–15 ppm. Where 94% of removal efficiency was maintained when the current density is 33 A/m^2 of the plane electrode active area, pH is 7, and the contact time is 30 min.

Mohammed et al. [18], on the other hand, achieved 99% of lead removal from the simulated wastewater via a continuous/ batch-mono polar electrocoagulation reactor

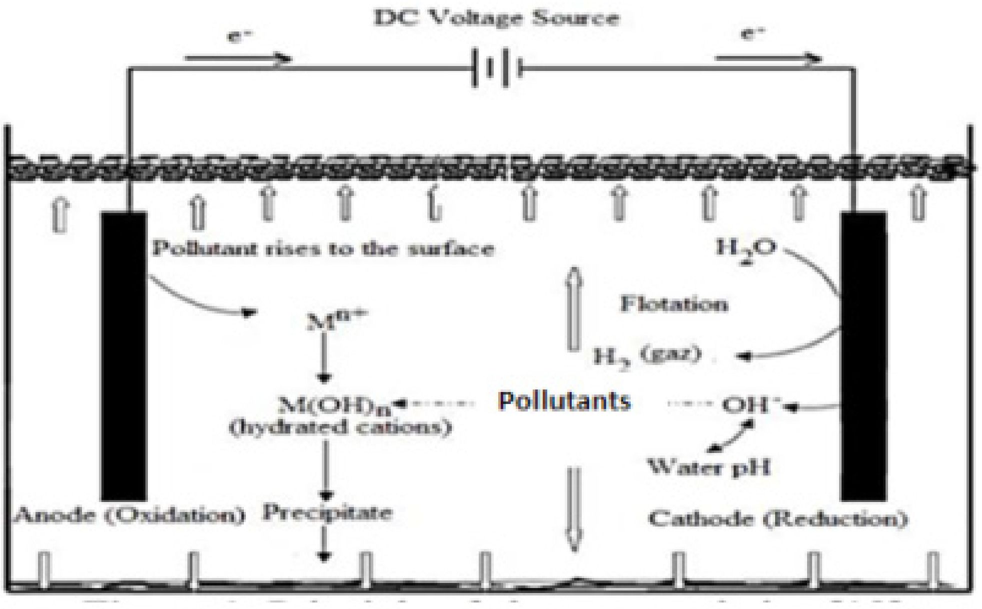

Fig. 1. The formation of monomer phases by Al^{+3} as a function of the pH via electrocoagulation cell.

using aluminum/aluminum and aluminum/stainless steel of electrodes configuration where the former type of electrodes has the highest removal efficiency after 7 min of the experiment while the latter type has the same value of this efficiency after 20 min. Both operation modes are employed under several operating variables such as pH 3–10, contact time 0–120 min, current density 0.915–5.49 mA/cm^2, initial lead concentration 50–250 ppm, plane electrodes surface area 101.95 and 273.12 cm^2, gap between electrodes 1–4 cm, and sodium chloride concentration 100–400 ppm. The highest value of removal efficiency for both types of electrodes metals configuration is maintained when the flow rate is 0.025 L/min.

Bazrafshan et al. [5], reviewed about 100 of published researches (1977–2016) including the ability of electrocoagulation method to remove various kinds of pollutants such as heavy metals using different types of electrodes metals, configuration, arrangement, and mode of operation as mentioned their specifications before. This survey paper proofs that the electrocoagulation technique is the most considerably studied for the treatment of heavy metal wastewater.

The relationship between the required responses and the operational variables were determined for a set of experiments according to the fractional central composite design. The statistical calculations and correlations were accomplished using *Statistica-10* and *Minitab-17*.

2. Experimental work

2.1. Apparatus

Three concentric aluminum tubes electrodes with different diameters and thicknesses are used in a batch electrocoagulation reactor as shown in Fig. 2 with an active area equalling 285 cm^2 approximately.

The outer and inner tubes were classified as an anode electrode, and the mid tube as a cathode electrode. The present study used a plexiglass reactor with a volume of 1000ml, a magnetic stirrer (ALFA company: HS-860); 0–1000 rpm, and a digital timer (SEWAN company).

The ranges of the studied operational parameters in the present experiments are listed in Table 2.

2.2. Materials

Synthesis wastewater samples with an initial concentration of lead were prepared by dissolving the required weight of lead nitrate $Pb(NO_3)_2$ (having 99.99 of purity; *B.D.H*- England) in the distillate water which was measured according to Eq. (5) [18] and weighed using a digital balance (500g × 0.01 g ; PROF company):

$$W = V \times C_i \times (M/m_A) \quad (5)$$

where W is the weight of $Pb(NO_3)_2$ (grams); V: volume of solution (liter); C_i: initial concentration of lead ions in solution (ppm); M: M. wt of the lead nitrate; m_A: atomic weight of lead.

The value of pH was measured using a pH meter (ATC company) and adjusted by hydrochloric acid (0.1 N) and sodium hydroxide (0.1 N). Moreover, 0.5 g/L of sodium chloride was added to prevent the formation of a passivation layer on the anode electrode and to enhance the electrical conductivity of the studied solution.

When the electrodes immersed in the synthesis wastewater, an electric current supplied to the cell using a digital DC-power supply (SYADGONG company-305D; 0–30 V and 0–5 A). Samples were collected from the treated simulated wastewater every15 min and then filtered by cellulose Glass-Micro fibre discs (Grade: MGC; pore diameter is 0.47 micrometer- MUNKTELL).

Consequently, these filtered samples were analyzed by the Atomic Absorption Spectroscopy (AAS- Type-SHIMADZUAA-7000*F*)to evaluate the quantities of lead ions

Table 2
Operational parameters

Parameters	Ranges
Initial lead concentration (ppm)	10–300
pH	2–12
Current or current density (A)	0.5–2.5
Stirring speed (RPM)	0–300
Contact time (min)	5–60

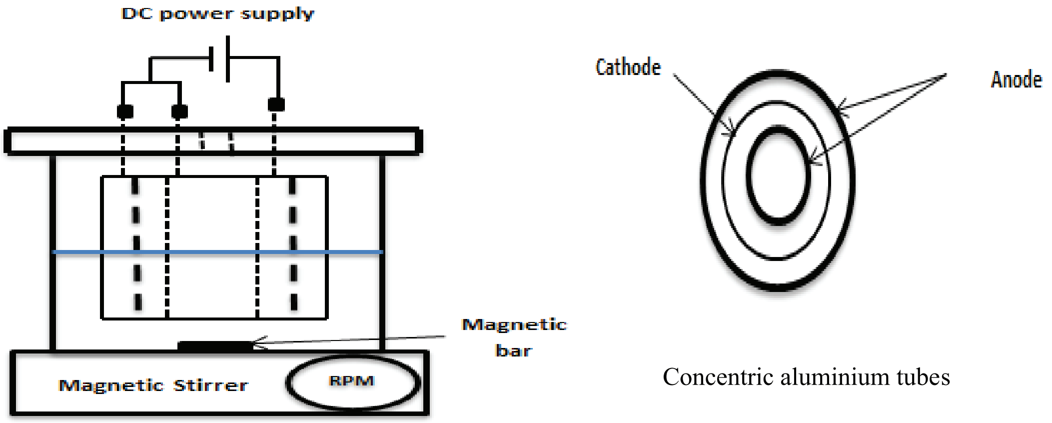

Fig. 2. The schematic of electrocoagulation reactor system and electrodes configuration.

presented in each sample. At the end of each experiment, electrodes were washed one time with 0.1 N HCl and several times with distillate water to ensure it was cleaned well. The same procedure was repeated for the next experiment according to the designed schedule.

The removal lead efficiency was calculated as shown in Eq. (6) where the final lead concentration (mg/l or ppm) is signed as C_f:

$$\text{Removal efficiency } \% = [(C_i - C_f)/C_i] \times 100 \qquad (6)$$

The energy consumption (kWh/m^3) in the electrocoagulation cell was calculated according to the following Eq. (7).

$$E = (U \cdot I \cdot t)/(1000 \cdot V) \qquad (7)$$

where U is the applied voltage (V), I: applied current (A), t: contact time (h), and V is the volume of the simulated wastewater (m^3).

The physiochemical properties of the simulated wastewater were different for each sample of the designed experiments.

An electrical conductivity meter model (ATC-company) ranges of (0–9990 µs/cm) and (1–80°C) and with an accuracy equalling +2% was employed to measure the conductivity parameter of the pretreated solution and after the completion of the treatment process.

2.3. Statistical analysis

The empirical correlations of removal efficiency and energy consumption responses, which are related to the operational variables that listed in Table 2 were studied using a rotatable central composite design uniform- two level factorial-half fraction. The mathematical model could be achieved according to the following quadratic Eq. (8) [19]:

$$Y = B_0 + \sum_{i=1}^{q} B_i X_i + \sum_{i=1}^{q} B_{ii} X_i^2 + \sum_{i} \sum_{j} B_{ij} X_i X_j + \varepsilon \qquad (8)$$

X_1, X_2, and X_q denote the independent variables that are continuous and are controllable with negligible ε error; where B_o, B_i, and B_{ij} are called the regression coefficients which are unknown and to be estimated and ε is a random error (or residual) which is the amount of variation in Y.

Thirty-two experiments were designed as cube points: 16, center points in the cube: 6, axial points: 10, the center points in axial is none, and the rotatability α is 2. Table 3 listed the natural and coded value of operational parameters and Table 4 shows the central composite design data. *Statistica-10* and *Minitab-17* were used for the regression and the graphical analysis of the obtained results.

In order to optimize the studied variables, the following procedure was employed:

1. Fix the value of the initial concentration of lead.
2. Choose the value of removal efficiency in the range of 10–100% with an interval of 10%.
3. Use Minitab-17 program to estimate the optimum value of operating variables except for the initial concentration of lead which are fitted with the specified value of the removal efficiency that mentioned in point 2.
4. Determine the values of energy consumption according to its mathematical correlation which are fitted with the estimated optimum values of operating variables for each value of the initial concentration of lead.

Table 3
Natural and coded operational variables

Natural variable (X_i)	Coded variables				
	–2	–1	0	1	2
X_1 = time (min.)	5	19	33	46	60
X_2 = concentration (ppm)	10	83	155	228	300
X_3 = pH	2	5	7	10	12
X_4 = current (A)	0.5	1	1.5	2	2.5
X_5 = stirring speed (rpm)	0	75	150	225	300

Table 4
Central composite design data

Run	Coded variables				
No.	X_1	X_2	X_3	X_4	X_5
1	–1	–1	–1	–1	1
2	1	–1	–1	–1	–1
3	–1	1	–1	–1	–1
4	1	1	–1	–1	1
5	–1	–1	1	–1	–1
6	1	–1	1	–1	1
7	–1	1	1	–1	1
8	1	1	1	–1	–1
9	–1	–1	–1	1	–1
10	1	–1	–1	1	1
11	–1	1	–1	1	1
12	1	1	–1	1	–1
13	–1	–1	1	1	1
14	1	–1	1	1	–1
15	–1	1	1	1	–1
16	1	1	1	1	1
17	–2	0	0	0	0
18	2	0	0	0	0
19	0	–2	0	0	0
20	0	2	0	0	0
21	0	0	–2	0	0
22	0	0	2	0	0
23	0	0	0	–2	0
24	0	0	0	2	0
25	0	0	0	0	–2
26	0	0	0	0	2
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	0	0	0	0	0

3. Results and discussion

Statistical design of the experiments was performed to investigate the effect of the operational parameters on the specific responses. Fig. 3 shows the main effects of each of the studied independent variables on the efficiency of lead removal, which explains the increase of the removal efficiency along the electrolysis time until it reached somewhere then it was minimized according to the efficiency of the adsorbent formed, it seems to be as an auto catalytic reactor. Consequently,the behavior of lead removal vs. the value of pH was similar to that behavior with time because the value of pH is dependent on the release of OH ion in the cell.

Removal efficiency increases with the increase of the applied current for all values of the initial concentration of the contaminant. Furthermore, lead removal efficiency was minimized along the increase of the value of the stirring speed, which gives an efficient economic view of minimizing the cost of electricity used in this process.

The effect of the studied parameters on the energy consumption value is shown in Fig. 4. This figure represents the direct proportion of the energy consumed via the electrocoagulation process with the contact time and the current supplied to the cell,whereas, the values of pH and stirring speed had no large effect on the energy consumption. Figs. 5 and 6 explain the interactions among the variables where all of these interactions were taken to be into consideration and represented as significant values in the mathematical correlations.

As shown in Fig. 5, the removal efficiency response increases along the time of electrolysis for all the values of the initial concentration of lead except the highest values of concentration which tended to drop for a certain period of time due to the lack of sufficient sites on the surface of the absorbent material that was required to achieve a relatively high removal ratio.

The same behavior was noted vs. pH over the duration of each experiment, where it was clear that this response differs in its behavior according to the value of the acidic function which was related to the release of hydroxyl ion at the cathode and the aluminum ion from the anode as a natural result of the continuous flow of electricity through the electrodes. The formation of adsorbent material in one hand and the change in the value of the pH in the other hand had, in some way, affected the value of the removal efficiency response. This was clearly demonstrated with the

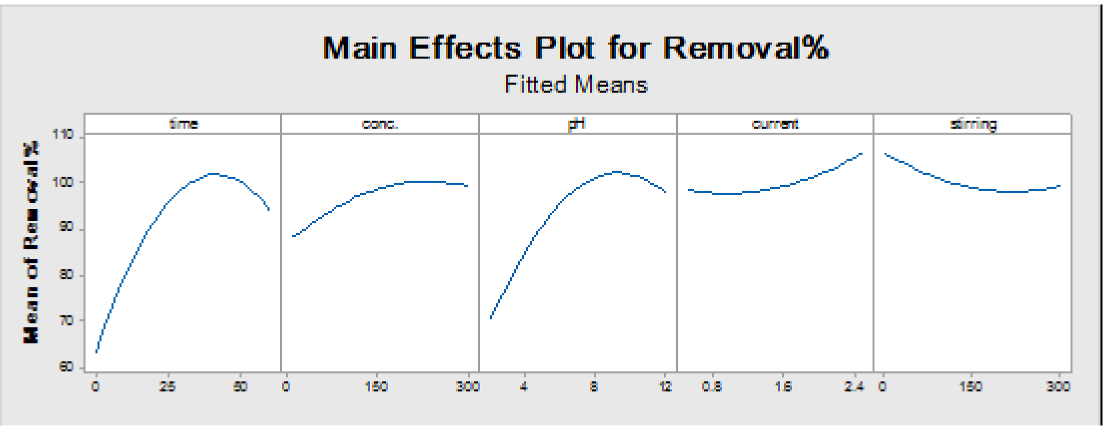

Fig. 3. Main effects plot of variables for removal efficiency.

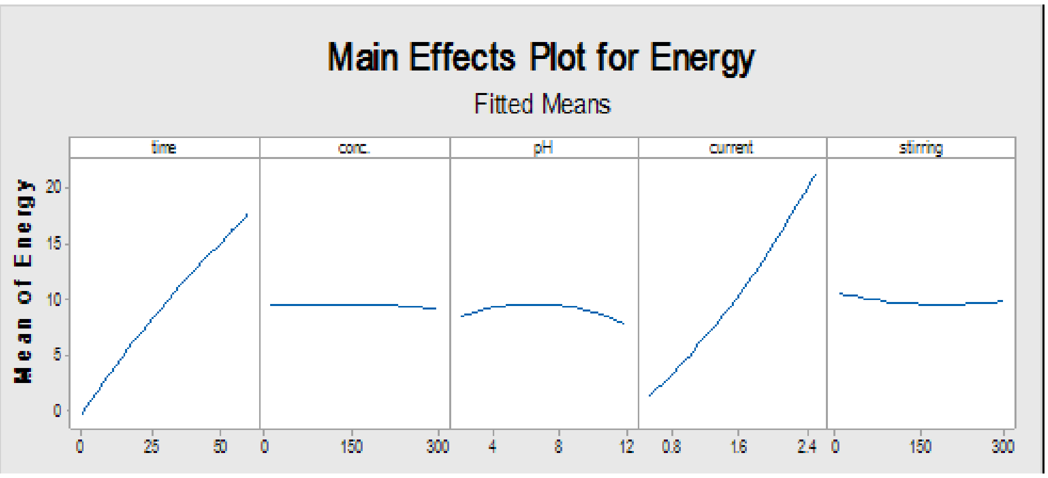

Fig. 4. Main effects plot of variables for energy consumption.

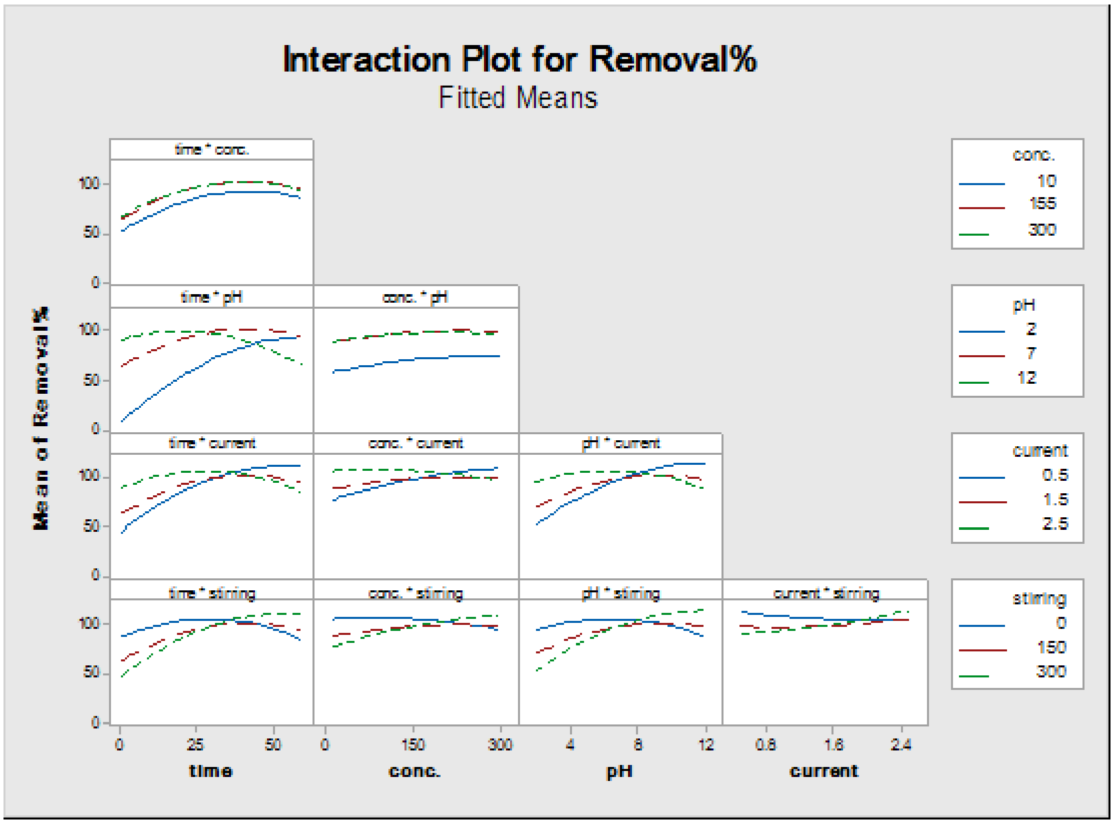

Fig. 5. Interaction plot of variables for removal efficiency.

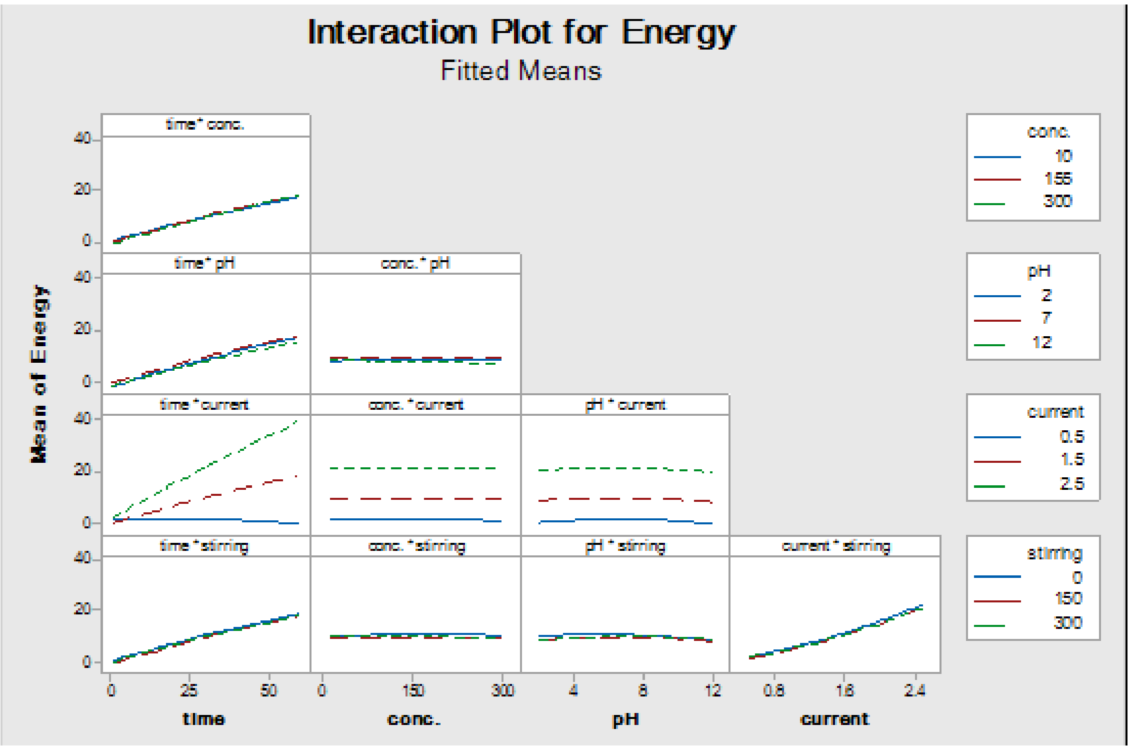

Fig. 6. Interaction plot of variables for energy consumption.

difference in the value of the electrical current supplied to the electrocoagulation cell along the duration of the electrolysis process of each experiment.

The value of the lead removal efficiency of the simulated waste water was inversely proportional to the value of the mixing speed because the higher mixing velocity leads to disperse the bubbles of the generated gases and minimizes their diameter as well as the increase of the contact surface area. This improves the efficiency of the removal through two simultaneous processes, electrocoagulation and electofloatation.

Fig. 6 shows the direct relationship between the energy consumption response and the operational variables throughout the designed electrolysis time. Where the behavior seems very similar to all variables and the simple difference depends on the presence of different components in the solution being processed, which may contribute to some extent in the promotion of electrical conductivity and thus the amount of energy consumed and this seems clear for the concentrated solutions and the most basic. This was different in terms of the change in the amount of mixing speed, since the energy value consumed was very similar in case of different mixing speed values due to the continuous homogeneity of the solution and the distribution of the various components in the solution in an almost consistent manner as well as the contribution of the bubbles of the released gases.

In contrast, the behavior of this response was different depending on the amount of the current supplied to the system as the amount of energy consumed directly proportional to the increase of that current and this seems logical to match the mathematical law related to the calculation of energy consumed in the electrocoagulation reactor according to the time of the experiment.

Due to the current supplied to the electrocoagulation cell, the interactions of the ions released by the oxidation of the artificial anode compresses the diffusion double layer around the charged particles. Ionic species presented in wastewater were neutralized by the counter ions produced via the electrochemical dissolution of the artificial anode which leads, this charge neutralization issue, to enhance the Van der Waals attraction force and minimize the electrostatic inter-particle repulsion then zero net charge result and coagulation process occurs.

Consequently, the flocs formed create a sludge blanket of colloidal particles. These flocs were relatively larger, heavier, and contain less bound water then precipitate out easily better than in traditional chemical precipitation method.

The following table shows the resulted values of the studied responses according to the designed experiments.

The mathematical correlations (second-order polynomial) of both responses which were related to the quadratic and interaction effects of the operational parameters, are shown below:

Removal efficiency response %:

$$
\begin{aligned}
Y_{RER} = {} & -68.9 + 4.201\,X_1 + 0.181\,X_2 + 20.16\,X_3 \\
& + 42.1\,X_4 - 0.530\,X_5 - 0.02681\,X_1^2 - 0.000247\,X_2^2 \\
& - 0.591\,X_3^2 + 3.64\,X_4^2 + 0.000173\,X_5^2 - 0.00049\,X_1\,X_2 \\
& - 0.2103\,X_1\,X_3 - 0.641\,X_1\,X_4 + 0.00408\,X_1\,X_5 \\
& - 0.00240\,X_2\,X_3 - 0.0735\,X_2\,X_4 + 0.000507\,X_2\,X_5 \\
& - 3.57\,X_3\,X_4 + 0.02295\,X_3\,X_5 + 0.0551\,X_4\,X_5
\end{aligned}
\tag{9}
$$

Energy consumption response (kWh/m³):

$$
\begin{aligned}
Y_{ECR} = {} & 0.64 - 0.1168\,X_1 + 0.00629\,X_2. + 0.899\,X_3 - 4.58\,X_4 \\
& - 0.01113\,X_5 - 0.001121\,X_1^2 - 0.000017\,X_2^2 - 0.0627\,X_3^2 \\
& + 1.819\,X_4^2 + 0.000031\,X_5^2 + 0.000142\,X_1\,X_2 \\
& - 0.00284\,X_1\,X_3 + 0.3218\,X_1\,X_4 - 0.000009\,X_1\,X_5 \\
& - 0.000671\,X_2\,X_3 - 0.00029\,X_2\,X_4 - 0.000015\,X_2\,X_5 \\
& - 0.0135\,X_3\,X_4 + 0.000776\,X_3\,X_5 - 0.00241\,X_4\,X_5
\end{aligned}
\tag{10}
$$

Table 5
Responses results

Run No.	Removal efficiency %	Energy consumption kWh/m³	Run No.	Removal efficiency %	Energy consumption kWh/m³
1	39.91	3.19	17	51.99	1.78
2	98.81	6.78	18	99.68	17.70
3	78.14	3.19	19	83.90	10.73
4	99.20	7.09	20	97.92	9.75
5	98.88	2.94	21	62.68	9.43
6	99.18	6.78	22	100.00	8.61
7	99.87	2.81	23	99.50	1.52
8	99.66	6.32	24	100.00	23.29
9	96.77	9.75	25	100.00	12.35
10	99.41	21.89	26	100.00	10.24
11	79.91	9.13	27	99.94	10.08
12	99.91	22.82	28	99.94	10.24
13	99.65	9.75	29	99.94	10.40
14	86.52	21.58	30	99.94	10.73
15	100.00	9.00	31	99.94	10.56
16	100.00	21.58	32	99.94	10.24

Figs. 7–11 show, in two-Y axis graph, the variation of both responses with each one of the operational parameters separately and their correlations when other parameters were taken at their mean values.

$$Y_{ECR\text{-}1} = -0.2410 + 0.3702\ X_1 - 0.0012\ X_1^2 \quad (11)$$

$$Y_{RER\text{-}1} = 51.1253 + 2.2314\ X_1 - 0.0257\ X_1^2 \quad (12)$$

$$Y_{ECR\text{-}2} = 10.2813 + 0.0037\ X_2 - 1.689{*}10^{-5}\ X_2^2 \quad (13)$$

$$Y_{RER\text{-}2} = 83.7876 + 0.0873\ X_2 - 0.0002\ X_2^2 \quad (14)$$

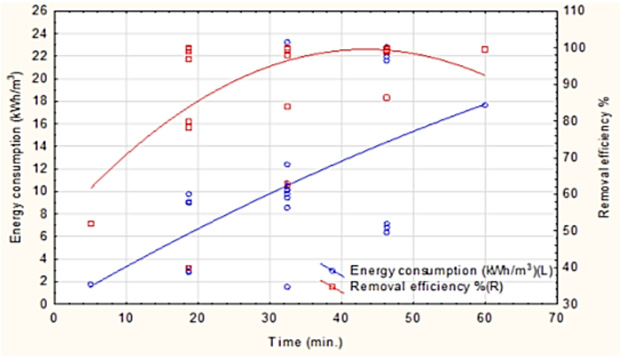

Fig. 7. Removal efficiency and energy consumption vs. time at mean values of other operational parameters.

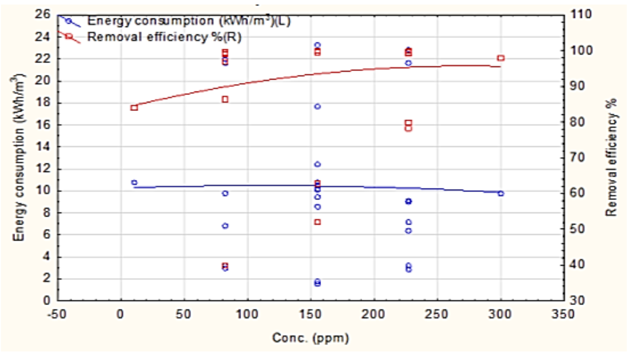

Fig. 8. Removal efficiency and energy consumption vs. initial lead concentration at mean values of other operational parameters.

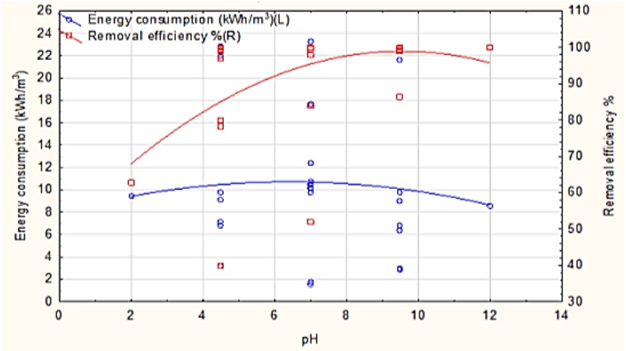

Fig. 9. Removal efficiency and energy consumption vs. pH at mean values of other operational parameters.

$$Y_{ECR\text{-}3} = 7.99490 + 0.84880\ X_3 - 0.0662\ X_3^2 \quad (15)$$

$$Y_{RER\text{-}3} = 49.3811 + 10.3741\ X_3 - 0.5430\ X_3^2 \quad (16)$$

$$Y_{ECR\text{-}4} = -1.8273 + 4.96130\ X_4 + 1.9558\ X_4^2 \quad (17)$$

$$Y_{RER\text{-}4} = 99.1611 - 14.0611\ X_4 + 6.0626\ X_4^2 \quad (18)$$

Fig. 9 clearly shows the effect of the increase in the value of the acidic function of the solution on the values of removal efficiency and energy consumption. As the efficiency of the removal increases with the increase of the value of pH to the maximum when the value of the acidic function within the range 9–10 and this indicates that the basic solutions had a higher removal efficiency than the acidic solutions. The energy consumed in basal solutions also decreases.

While Fig. 10 shows the direct relationship between the supplied current and the value of the energy consumed. This was confirmed according to the mathematical law that binds them. Moreover, the efficiency increases with the increase of the electrical current due to the continuous formation of the adsorbent materials which are contributed to the removal of pollutants from the simulated water.

$$Y_{ECR\text{-}5} = 11.3737\text{-}0.0127\ X_5 + 3.4284{*}10^{-5}\ X_5^2 \quad (19)$$

$$Y_{RER\text{-}5} = 101.4542 - 0.1075\ X_5 + 0.0003\ X_5^2 \quad (20)$$

The following tables and figures explain clearly the results according to the application of the mentioned procedure about the calculating of the optimum values.

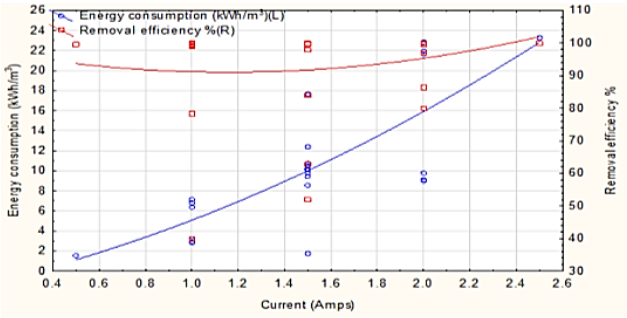

Fig. 10. Removal efficiency and energy consumption vs. applied current at mean values of other operational parameters.

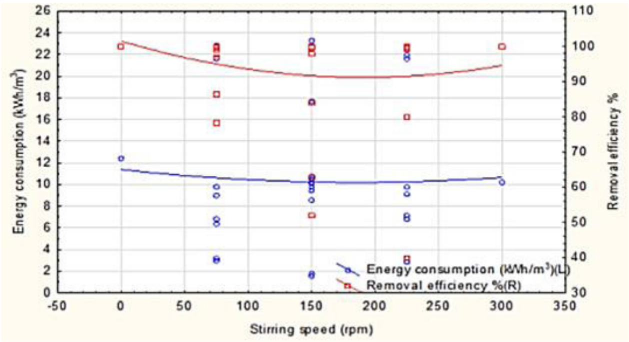

Fig. 11. Removal efficiency and energy consumption vs. stirring speed at mean values of other operational parameters.

Table 6
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 10 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	5.655	2.085	0.536	0	0.594
20	7.342	2.305	0.589	0	0.774
30	9.161	2.542	0.641	0	1.024
40	30.000	5.819	0.500	300	2.073
50	11.937	2.904	0.921	0	1.952
60	30.000	7.000	0.853	300	4.715
70	30.000	7.000	1.315	300	8.502
80	30.000	7.000	1.500	219	9.722
90	60.000	3.958	1.853	300	23.876
100	60.000	2.422	2.440	185	35.937

Table 7
Optimum values of the operating variables and the energy consumption when the initial concentration of lead equals 50 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	34.842	2.100	0.500	300	0.071
20	6.453	2.189	0.578	0	0.847
30	7.558	2.334	2.500	280	5.437
40	5.000	10.10	0.500	300	2.634
50	30.000	5.808	0.500	300	2.110
60	2.000	0.600	300	0.120	0.120
70	2.716	2.500	136	8.085	8.085
80	2.743	2.500	94	8.607	8.607
90	3.500	0.550	75	0.001	0.001
100	2.796	2.500	15	9.893	9.893

Table 8
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 100 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	60.000	12.000	2.443	0	36.187
20	5.514	2.070	0.574	0	0.876
30	7.291	2.298	0.629	0	1.101
40	30.000	4.129	0.500	300	1.495
50	53.960	11.170	2.440	71	33.063
60	10.816	0.500	300	2.093	2.093
70	11.602	0.536	281	1.487	1.487
80	2.400	0.576	200	0.030	0.030
90	11.666	0.530	83	0.209	0.209
100	12.000	0.616	245	0.013	0.013

Table 9
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 150 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	16.652	3.606	0.621	278	1.315
20	60.000	12.000	1.978	0	25.784
30	6.542	2.201	0.641	0	1.055
40	37.642	2.000	0.500	300	0.114
50	9.254	2.554	0.996	0	1.915
60	5.000	9.925	0.500	300	1.894
70	51.086	3.000	0.500	300	0.110
80	56.357	2.000	0.605	300	0.761
90	5.000	11.349	0.583	109	0.003
100	60.000	12.000	0.754	212	1.958

Table 10
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 200 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	60.000	12.000	2.095	0	28.360
20	16.791	3.625	0.611	272	1.084
30	30.622	2.000	0.500	300	0.186
40	8.751	2.488	0.533	0	1.339
50	7.982	2.389	2.500	213	5.462
60	41.990	2.100	0.500	300	0.051
70	60.000	12.000	0.987	80	5.654
80	51.103	10.774	2.392	201	30.315
90	60.000	12.000	0.986	184	5.681
100	60.000	12.000	0.838	206	3.211

Table 11
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 250 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	60.000	12.000	1.928	0	24.643
20	60.000	12.000	1.703	0	19.896
30	60.000	12.000	1.485	0	15.472
40	8.531	2.459	0.528	0	1.217
50	60.000	12.000	1.070	0	7.528
60	8.870	2.503	1.619	0	3.517
70	9.086	2.531	2.038	0	5.665
80	5.000	10.168	0.500	300	0.706
90	60.000	12.000	1.016	182	6.011
100	59.756	12.000	2.443	194	34.911

Table 12
Optimum values of the operational variables and the energy consumption when the initial concentration of lead equals 300 ppm

Y_{RER} %	Time (min.)	pH	Current (A)	St.Sp. (rpm)	Y_{ECR} (kWh/m^3)
10	60.000	12.000	1.767	0	21.072
20	60.000	12.000	1.563	0	16.883
30	60.000	12.000	1.365	0	12.961
40	60.000	12.000	1.172	0	9.276
50	60.000	12.000	1.041	15	6.720
60	30.000	11.052	2.500	0	20.336
70	60.000	12.000	1.045	106	6.279
80	5.000	11.250	2.419	0	3.231
90	5.000	11.257	2.387	162	1.807
100	59.912	2.000	2.476	222	37.555

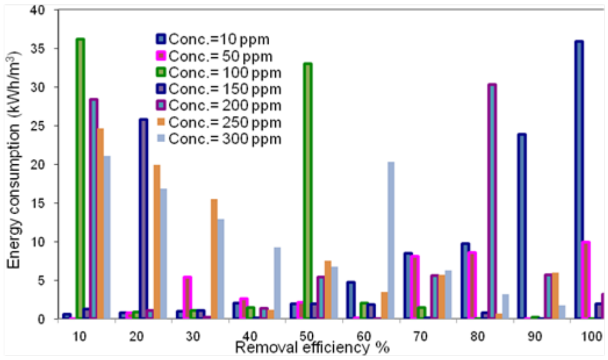

Fig. 12. Energy consumption vs. the intervals of removal efficiency at the estimated optimum values of the operating variables except the initial concentration of lead.

5. Conclusion

The present study proved clearly the efficient experimental design for analyzing the removal of lead from the synthesis wastewater via the electrocoagulation process for all values of the pollutant used. The statistical method used was an imperative issue and more benefit to employ the experimental design to develop the mathematical correlations of lead removal efficiency and energy consumption responses. Graphical responses among the operational parameters interactions were employed, and then double Y-axis graphs were used to study the effect of each parameter on both responses at the condition of mean values of other parameters. Related correlations among these cases were found also. Moreover, optimization results were determined successfully for all of the initial lead concentration selected and the value of removal efficiency required.

Symbols

C_f — Final lead concentration (mg/l or ppm)
C_i — Initial concentration of lead ions in solution (mg/l ppm)
E — Energy consumption (kWh/m^3)
I — Applied current (Amps.)
M — Molecular weight of the lead nitrate(g/mol)
m_A — Atomic weight of lead
t — Contact time (h or min.)
U — The applied voltage (volt)
V — Volume of synthesis solution (liter or m^3)
W — The weight of lead nitrate $Pb(NO_3)_2$ (g)
X_1 — Time (min)
X_2 — Concentration (ppm)
X_3 — pH
X_4 — Applied current (Amps.)
X_5 — Stirring speed (St. Sp.) (rpm)
Y_{ECR} — Energy consumption response
Y_{RER} — Removal efficiency response

References

[1] A.I. Adeogun, R.B. Balakrishnan, Electrocoagulation removal of anthraquinone dye Alizarin Red S from aqueous solution using aluminum electrodes: kinetics, isothermal and thermodynamics studies, J. Electro chem. Sci. Eng., 6 (2016) 199–213.

[2] T.K. Tran, H.J. Leu, K.F. Chiu, C.Y. Lin, Electrochemical treatment for wastewater contained heavy metal the removing of the COD and heavy metal Ions, Int. J. Eng. Res. Sci., 1 (2015) 96–101.

[3] F.M. Hassan, A.N. AL-Baidhani, S.H. Al-Khalidi, Evaluation industrial and domestic wastewater treatment plant of Diala's state company of electrical industries, Iraq, Mesop. Environ. J., 2 (2016) 14–22.

[4] W.T. Al-Mayah, Effect of domestic sewage on water quality of Al-Gharraf River in Al-Haay city, MS.C thesis, University of Baghdad, 2013.

[5] E. Bazrafshan, L. Mohammadi, A.A. Moghaddam, A.H. Mahvi, Heavy metals removal from aqueous environments by electrocoagulation process–a systematic review, J. Environ. Health Sci. Eng., 13 (2015) 1–16.

[6] Central Statistical Organization (CSO)- Planning Ministry,Environmental statistics for Iraq in 2014 report, (2015) 188–189.

[7] H. Polat, D. Erdogan, Heavy metal removal from wastewater by ion flotation, J. Hazard. Mater., 148 (2007) 267–273.

[8] S.K. Gunatilake, Methods of removing heavy metals from industrial wastewater, J. Multi disc. Eng. Sci. Stud., 1 (2015) 12–18.

[9] M.A. Barakat, New trends in removing heavy metals from industrial wastewater, Arabian J. Chem., 4 (2011) 361–377.

[10] B. Tansel, New technologies for water and wastewater treatment: a survey of recent patents, Recent Patents Chem. Eng., 1 (2008) 17–26.

[11] M. Al-Shannag, Z. Al-Qodah, K.B. Melhem, M.R. Qtaishat, M. Alkasrawi, Heavy metal ions removal from metal plating wastewater using electrocoagulation: Kinetic study and process performance, Chem. Eng. J., 260 (2015) 749–756.

[12] M. Al-Shannag1 , Z. Al-Qodah , K. Alananbeh , N. Bouqellah, E. Assirey , K.B. Melhem, COD reduction of baker's yeast wastewater using batch electrocoagulation, Environ. Eng. Manage. J., 13 (2014) 3153–3160.

[13] M. Al-Shannag ,W.k. Lafi, K.B. Melhem, F. Gharagheer, O. Dhaimat, Reduction of COD and TSS from paper industries wastewater using electro-coagulation and chemical coagulation, J. Separ. Sci. Tech., 47 (2012) 700–708.

[14] W.k. Lafi, M. Al-Anber, Z.A. Al-Anber, M. Al-Shannag, A. Khalil, Coagulation and advanced oxidation processes in the treatment of olive mill wastewater (OMW), Desal. Water Treat., 24 (2010) 251–256.

[15] M. Al-Shannag, K.B. Melhem, Z.A. Al-Anber, Z, Al-Qodah, Enhancement of COD-nutrients removals and filterability of secondary clarifier municipal wastewater influent using electrocoagulation technique, J. Separ. Sci. Tech., 48 (2013) 673–680.

[16] B. Lekhlif, L. Oudrhiri, F. Zidane, P. Drogui, J.F. Blais, Study of the electrocoagulation of electroplating industry wastewater charged by nickel (II) and chromium (VI), J. Mater. Environ. Sci., 5 (2014) 111–120.

[17] S.N. Abas, M.H. Ismail, M.L. Izhar, Adsorption process of heavy metals by low-cost adsorbent: a review, World Applied Sci. J., 28 (2013) 1518–1530.

[18] A.A. Mohammed, M.D. Al-Mureeb, Removal of lead from simulated wastewater by electrocoagulation method, J. Eng., 16 (2010) 5811–5821.

[19] F.Y. Al-Jaberi, A.A. Sultan, A.A. Ateeq, The effects of classifying CRM sources on the asphalt cement modification for paving roads, J. Environ. Ecol., 4 (2014) 27–45.

[20] A. Assadi, M.M. Emamjomeh, M. Ghasemi, M.M. Fazli, Efficiency of electrocoagulation process for lead removal from wastewater, J. Qazvin Univ. Med. Sci., 18 (2015) 18–23.

[21] J. Wang, L. Jin, Advanced oxidation processes for wastewater treatment: formation of hydroxyl radical and application, Crit. Rev. Environ. Sci. Tech., 42 (2012) 251–325.

[22] R.W. Peters, Y. Ku, Evaluation of recent treatment techniques for removal of heavy metals from industrial wastewater, AlChESymp. Ser., 81 (1985) 168–203.

[23] S. Bayar, A.E. Yilmaz, R. Boncukcuoğlu, B.A. Fìl, M.M. Kocakerìm, Effects of operational parameters on cadmium removal from aqueous solutions by electrochemical coagulation, Desal. Water Treat., 51 (2013) 2635–2643.

[24] A.A. Mohammed, H.S. Mahmood, Removal of Cu^{2+}, Pb^{2+}, and Ni^{2+} ions from simulated waste water by ion exchange method on zeolite and puroliteC105 resin, J. Eng., 19 (2013) 1328–1340.

[25] W.M. Salih, S.K. Alnasri, A.A. Al-Abdalaali, Removal of boron from simulated iraqi surface water by electrocoagulation method, J. Eng., 18 (2012) 1266–1284.

[26] A.S. Naje, S.A. Abbas, Electrocoagulation technology in wastewater treatment: a review of methods and applications, Civil Environ. Res., 3 (2013) 29–42.

[27] A.N. Ghanim, Optimization of pollutants removal from textile wastewater by electrocoagulation through RSM, J. Babylon Univ. Eng. Sci., 22 (2014) 375–387.

[28] N.C. Joshi, Conventional methods for heavy metal removal, biosorption and the development of low cost adsorbent, Eur. J. Pharm. Med. Res., 4 (2017) 388–393.

[29] F. Fu, Q. Wang, Removal of heavy metal ions from wastewater: A review, J. Environ. Manag., 92 (2011) 407–418.

[30] A. Gupta, J. Joia, A. Sood, R. Sood, C. Sidhu, G. Kaur, , Microbes as potential tool for remediation of heavy metals: a review, J. Microb. Biochem. Tech., 8 (2016) 364–372.

[31] S. Palit, Nano filtration of oil spills : a far-reaching review and a deep comprehension, J. Environ. Res. Develop., 9 (2015) 1–13.

[32] I. Kabdas, T. Arslan, T. Ölmez-Hanc I. Arslan-Alaton, O. Tünay, Complexing agent and heavy metal removals from metal plating effluent by electrocoagulation with stainless steel electrodes, J. Hazard. Mater., 165 (2009) 838–845.

[33] W.S. Al-Rekabi, H. Qiang, W.W. Qiang, , Improvements in wastewater treatment technology, Pakistan J. Nutrition, 6 (2007) 104–110.

[34] É. Fekete, B. Lengyel, T. Cserfalvi, T. Pajkossy, Electrocoagulation: an electrochemical process for water clarification, J. Electro chem. Sci. Eng., 6 (2016) 57–65.

[35] A. Riyanto, A. Hidayatillah, Electrocoagulation of detergent wastewater using aluminium wire netting electrode (awne), Proc. International Conference On Research, Implementation and Education of Mathematics and Sciences 2014, (2014) 151–158.

[36] F.C. Walsh, Electrochemical technology for environmental treatment and clean energy conversion, Pure Appl. Chem., 73 (2001) 1819–1837.

[37] M.A. Olutoye, J.A. Alhamdu, Electrochemical separation of metal silver from industrial wastewater, Adv. Chem. Eng. Sci., 4 (2014) 396–400.

[38] U.T. Un, S.E. Ocal, Removal of heavy metals (Cd, Cu, Ni) by electrocoagulation, Int. J. Environ. Sci. Develop., 6 (2015) 425–429.

[39] C. Zhang, Y. Jiang, Y. Li, Z. Hu, L. Zhou, M. Zhou, Three-dimensional electrochemical process for wastewater treatment: A general review, Chem. Eng. J., 228 (2013) 455–467.

[40] I. Kabdaşl, I. Arslan-Alaton, T. Ölmez-Hanc, O.Tünay, Electrocoagulation applications for industrial wastewater: a critical review, J. Environ. Technol. Rev., 1 (2012) 2–45.

[41] K. Rani, D. Elango, A quantitative comparison between electrocoagulation and chemical dosing, Int. J. Civil Eng. Technol., 5 (2014) 245–251.

[42] H.G. Attia, Decolorization of direct blue dye by electrocoagulation process, J. Eng. Develop., 17 (2013) 171–181.

[43] A. Aoudj, N. Khelifa, M. Drouiche, H. Hecini, Wastewater remediation by electrocoagulation process, Desal. Water Treat., 51(2013) 1596–1602.