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Investigation of electrocoagulation reactor design effect on the value of total dissolved solids via the treatment of simulated wastewater

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ABSTRACT

The aim of the present work is to investigate the effect of the electrodes design in an electrocoagulation reactor as well as specific operational parameters on the value of total dissolved solids (TDS) presented in the simulated wastewater that polluted by lead ions. Triple concentric aluminum tubes electrodes were used in the electrochemical cell. The operating variables were the electrolysis time (5–60 min.), initial lead concentration (10–300 ppm), pH (2–12), electric current (0.5–2.5 Amps.), and mixing speed (0–300 rpm). Response surface methodology method and statistical programs were employed to design experiments and to establish the mathematical correlations. The results show the significant effect of the electrodes design as well as the operational variables on the behavior of TDS response and its maximum limit was found in the range 550–600 ppm.

Keywords: Electrodes design; Simulated wastewater; Lead ions; Total dissolved solids; Electrocoagulation

1. Introduction

A huge amount of industrial wastewaters are discharged daily in the modern society [1] into environment system [2] as a result of the continuous development and advancement in technologies which substantially caused the degradation of the aquatic environment. Several types of wastewater which are directly or indirectly discharged into the aqueous environment, such as landfill leachate, textile, restaurant, car wash, laundry, tannery, and industrial wastewater [3,4].

Solids dissolved in these types of wastewater is one of the important issues in any treatment techniques which are used to minimize this impact in the polluted water. One of these techniques is the electrocoagulation process [5,6] which depends in its performance on many factors such as the electrolysis time, the initial concentration of the pollutant(s), pH of the contaminated solution, the voltage applied, the geometry and arrangement of electrodes, etc. There is a lack of studies that concern the effect of electrodes configuration of the electrocoagulation reactor on the behavior of TDS value under the impact of restricted operational variables [3].

A total dissolved solid term is employed to measure the dissolved substances in aquatic systems and reported as ppm or mg/l [7,8]. In the present study, the simulated solution contains several types of substances presented initially in the pretreated solution such as lead nitrate and sodium chloride, and others are generated during the electrocoagulation operation due to the redox reaction which causes the dissolution of electrodes metals [9,10].

Electrocoagulation process depends in its work on the formation of coagulants as a result of the continuous supply of current by an external source of electricity without any demand to use external chemical additives to minimize the value of TDS and other pollutants. The formation of these auto-coagulants in the electrochemical reactor will affect the behavior of TDS' value since the main object of this kind of treatment process in case of water polluted by toxic metal is the removal of this metal therefore the attention insight to this point of treatment while the value of TDS may be minimized or maximize according to several effects such as the efficiency of this reactor, the value of direct current applied, and the geometry of electrodes which provides the required active area.

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The present work was employed a novel design of electrocoagulation reactor that was innovated by Mohammed and AlJaberi [11] which consists of triple concentric aluminum tubes as electrodes, in order to study the effect of this configuration on the behavior of TDS value under specific operating parameters using Response surface methodology method (RSM) as well as Statistica-10 and Minitab-17 were used to design experiments and established the mathematical correlations.

2. Experimental work

2.1. Apparatus

A plexiglass reactor with a volume of one liter was employed for the electrocoagulation cell that consists of three concentric aluminum tubes electrodes with different diameters and thicknesses, as shown in Fig. 1 with an active area, equals approximately 285 cm^2 where the outer and inner tubes were classified to be the anode electrode and the mid tube as the cathode electrode.

Other tools were utilized in the experiments such as a digital DC- power supply (SYADGONG company-305D); 0–30 volt and 0–5 Ampere, a digital balance (500g × 0.01 g) (PROF company), a magnetic Stirrer (ALFA company: HS-860) ; 0–1000 rpm, pH meter (ATC company), and a digital timer (SEWAN company). Operational studied variables and their ranges are listed in Table 2 shown below:

2.2. Materials

Simulated samples of wastewater were prepared by dissolving the required weight of lead nitrate $Pb(NO_3)_2$(99.99 of purity; B.D.H- England) in distilled water.

The adjusting of solution pH was achieved by using hydrochloric acid (0.1 N) and sodium hydroxide (0.1 N). The adding of 200 ppm of NaCl was taken into consideration in order to prevent the formation of a passivation layer on the electrode and to enhance the conductivity of the studied samples of the synthesis wastewater.

When the electrocoagulation was ready to operate, and the electrodes immersed in the polluted solution, designed electric current was supplied by the DC-power supply. Along the duration of electrolysis of each experiment, samples were collected from the treated solution every 15 min and then filtered by the cellulose Glass-Microfibre discs (Grade: MGC; pore diameter is 0.47 micrometer- MUNKTELL).

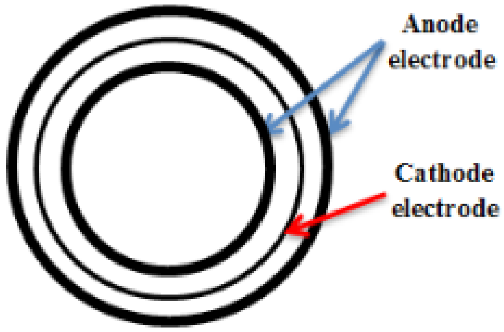

Fig. 1. The schematic of electrodes configuration.

The values of TDS of the simulated wastewater was measured before and after each experiment using TDS meter model (C.C.K.) with a range of 0–2999 ppm and an accuracy equals +2–10%.

After the accomplished of every experiment and to ensure it was cleaned well, electrodes were washed one time with 0.1 N HCl and several times with distilled water.

2.3. Statistical analysis

The empirical correlations of the studied parameters were achieved by employing the rotatable central composite design with uniform - two level factorial-half fraction. The mathematical correlation could be estimated according to the following quadratic equation [12]:

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

where X_1, X_2, to X_q denoted the operating variables that mentioned in Table 1 which are continuous and a controllable with negligible ε error; where B_o, B_i, to B_{ij} are called the regression coefficients that could be estimated using Statistica-10 and Minitab-17 and ε is a random error which is the amount of variation in Y.

Therefore, 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.

3. Results and discussion

Statistical design of experiments was utilized to achieve the actual relation between the operating variables with the TDS response and how far this response was affected by electrodes design under these variables.

Table 2 shows the values of TDS for all samples of simulated wastewater before and after the treatment process via the electrocoagulation reactor.

Fig. 2 illustrates the relationship between the predicted and observed values of TDS response.

The effect of these operational parameters on TDS response is clearly presented in Fig. 3 which shows the notable decrease of TDS value along the duration of each experiment then raises at the final quarter of the experiment time due to the increase of coagulant formed more than that amount required as an adsorbent to remove pollutant from wastewater as a main target of the electrocoagulation process.

Table 1
Operational variables

Parameters	Range
X_1: Electrolysis time (min)	5–60
X_2: Initial lead concentration (ppm)	10–300
X_3: pH	2–12
X_4: Current (Amps.)	0.5–2.5
X_5: Stirring speed (rpm)	0–300

Table 2
Initial and final values of TDS in the simulated wastewater

Run No.	Initial TDS (ppm)	Y_{TDS} (ppm)	Run No.	Initial TDS (ppm)	Y_{TDS} (ppm)	Run No.	Initial TDS (ppm)	Y_{TDS} (ppm)
1	361	556	12	995	587	23	678	589
2	361	562	13	361	626	24	678	568
3	995	590	14	361	586	25	678	575
4	995	598	15	995	651	26	678	587
5	361	634	16	995	636	27	678	573
6	361	601	17	678	678	28	678	579
7	995	661	18	678	574	29	678	553
8	995	638	19	44	517	30	678	553
9	361	510	20	1312	568	31	678	554
10	361	575	21	678	676	32	678	553
11	995	621	22	678	839			

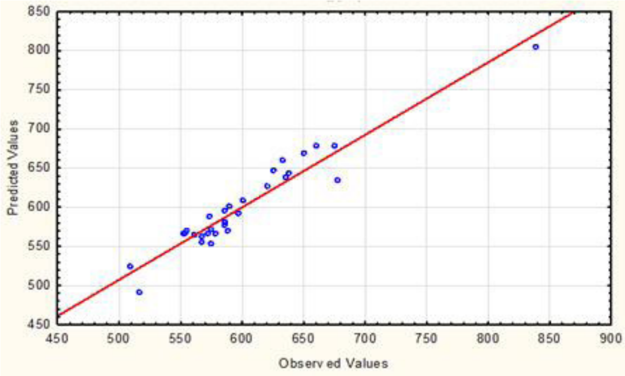

Fig. 2. Predicted values vs. observed values of TDS response.

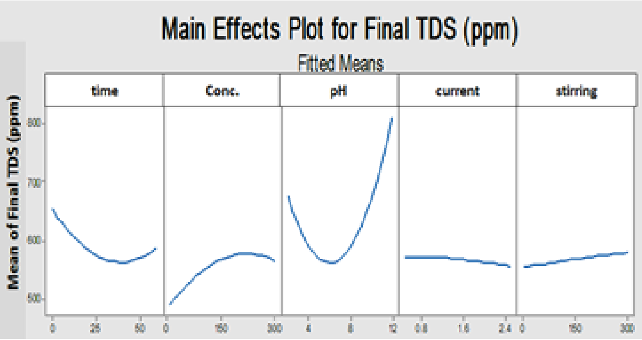

Fig. 3. Main effects plot of variables for TDS response.

Table 3
Empirical correlations of TDS response againsteach one of the operational variableswhen others keeping at their mean values

X: Operating variables	Y: TDS response
X_1: Electrolysis time (min)	$Y = 668.548 - 3.856\ X_1 + 0.0465\ X_1^2$ (3)
X_2: Initial lead concentration (ppm)	$Y = 508.886 + 1.044\ X_2 - 0.0026\ X_2^2$ (4)
X_3: pH	$Y = 821.348 - 85.595\ X_3 + 7.0187\ X_3^2$ (5)
X_4: Current (Amps.)	$Y = 578.350 + 38.900\ X_4 - 15.4667\ X_4^2$ (6)
X_5: Stirring speed (rpm)	$Y = 576.933 + 0.2480\ X_5 - 0.0006\ X_5^2$ (7)

Practically, the value of TDS increases slightly with the raise of the initial lead concentration as shown in Fig. 3 but it tends to minimize slightly at the high value of initial lead concentration due to the efficient removal of lead at this range of concentration. While the behavior of this response with solution pH value was extremely different than other parameters due to the change of pH value of the simulated wastewater along the electrolysis operation due to the continuous release of hydroxyl ions at cathode electrode as a result of the continuous supply of electric current towards these electrodes from the external power supply as well as the continuous dissolution of anode electrode provided a huge amount of aluminum ions that leads to increasing the amount of coagulant formed then the value of TDS especially in more basic solution as noted in Fig. 3. Therefore, the value of TDS was not directly affected by the applied electric current but the results were occurred due to this operating parameter as explained. The continuous raise of mixing speed gave a slight increase of TDS value due to the dispersing of the generated flocs that may prevent the settling or flotation operations then keeping them in suspension status.

The following mathematical correlation relates TDS response to the operating variables with a coefficient of determination (R^2) equals (0.9256):

$$\begin{aligned} Y_{TDS} = {} & 737 - 1.880\ X_1 + 0.951\ X_2 - 67.500\ X_3 - 44.600\ X_4 \\ & + 0.074\ X_5 + 0.0581\ X_1^2 - 0.001881\ X_2^2 + 7.018\ X_3^2 \\ & - 3.500\ X_4^2 - 0.000046\ X_5^2 - 0.00389\ X_1 X_2 - 0.284\ X_1 X_3 \\ & + 0.160\ X_1 X_4 - 0.00255\ X_1 X_5 - 0.0186\ X_2 X_3 \\ & + 0.110\ X_2 X_4 - 0.00018\ X_2 X_5 - 1.100\ X_3 X_4 \\ & - 0.0287\ X_3 X_5 + 0.220\ X_4 X_5 \end{aligned} \tag{2}$$

Table 3 lists the mathematical empirical correlations of TDS response that related this response to the operational parameters individually when other variables keeping at their mean values.

Fig. 4 explains the maximum interactions among the studied variables where all of these interactions were taken to be in consideration and represented as significant values in the mathematical correlations.

Effects of the operational variables on the behavior of TDS along the time of experiment are explained separately as follows.

3.1. Effect of electrolysis time

Figs. 5 to 8 illustrate clearly the nature of the relationship between the final value of TDS and the electrolysis time of the polluted solution under different values of the operational parameters. Where it seems logical that dilute solutions have lower values of TDS than the concentrated solutions. This is also the case when the solutions are acidic or semi-neutral, unlike the basic solutions which have a greater value of TDS due to the abundance of different ions in such solution as the time of reaction increases.

The behavior is almost similar to the decrease and increases in the value of TDS throughout the experiment time by changing the values of the current supplied and the mixing speed according to the designed limits. Where the turbidity is lower in the case of a higher current due to the accumulation of heavy materials as sludge and the

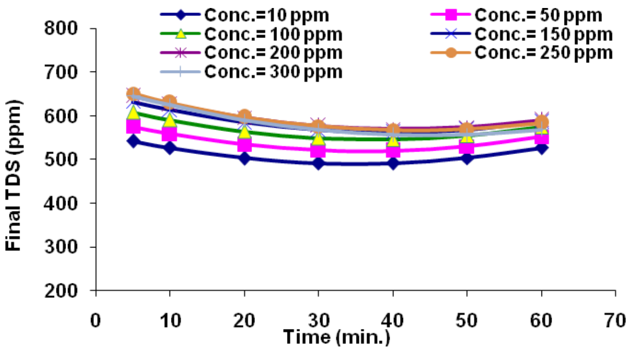

Fig. 5. Final TDS vs. electrolysis time with several constant values of initial lead concentration when other variables keeping at their mean values.

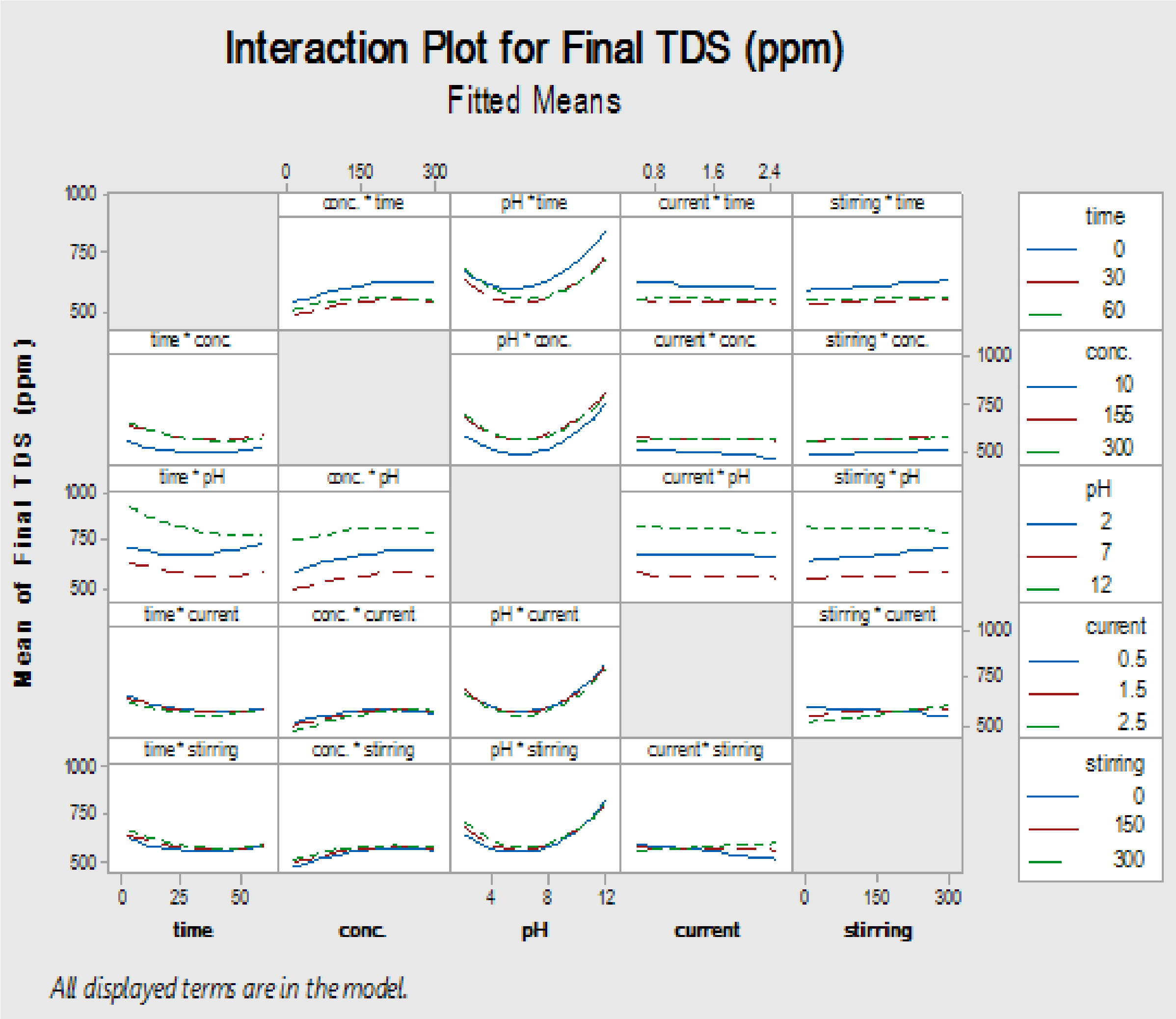

Fig. 4. Interaction plot of variables for final TDS response.

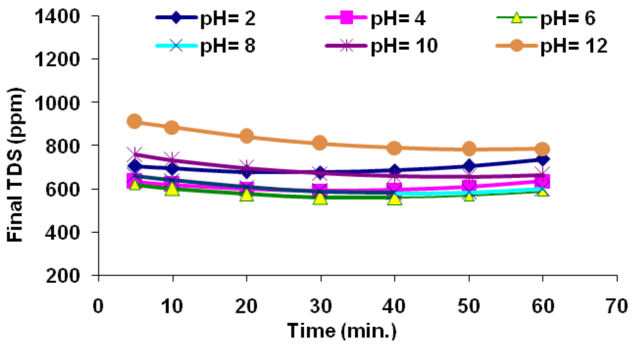

Fig. 6. Final TDS vs. electrolysis time with several constant values of solution pH when other variables keeping at their mean values.

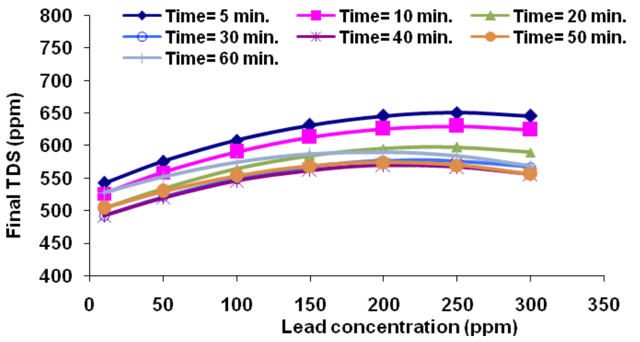

Fig. 9. Final TDS vs. lead concentration with several constant values of electrolysis time when other variables keeping at their mean values.

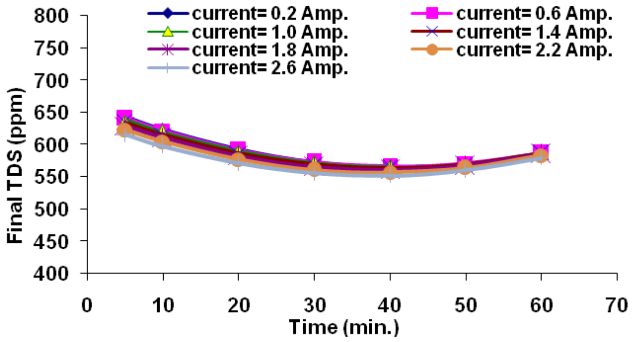

Fig. 7. Final TDS vs. electrolysis time with several constant values of current when other variables keeping at their mean values.

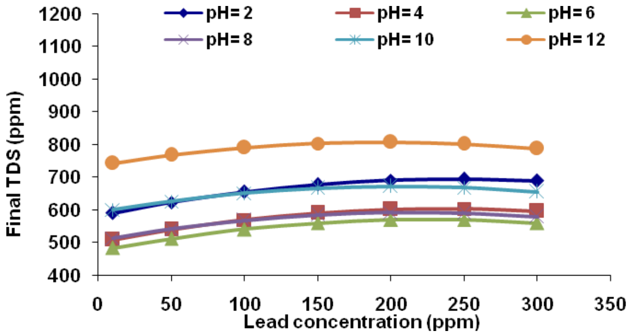

Fig. 10. Final TDS vs. lead concentration with several constant values of solution pH when other variables keeping at their mean values.

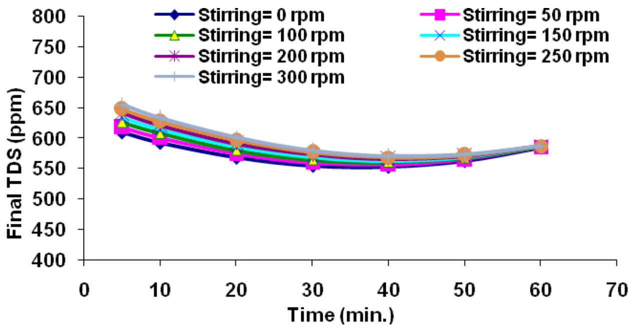

Fig. 8. Final TDS vs. electrolysis time with several constant values of stirring speed when other variables keeping at their mean values.

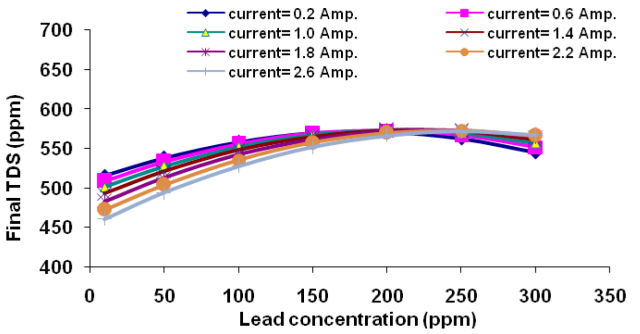

Fig. 11. Final TDS vs. lead concentration with several constant values of current when other variables keeping at their mean values.

floating of light materials due to the effectiveness of electrocoagulation and electroflotation processes, while the high mixing speed throughout the duration of the experiment caused increased turbidity due to dispersion of adsorbed substances and other materials in the entire solution.

3.2. Effect of lead concentration

Figs. 9 to 12 show the direct relationship between the final value of TDS and the concentration of lead in the simulated solution under the effect of other variables. This seems logical due to the abundance of components that increase the degree of turbidity in the polluted solution. Where TDS increases further with the increase of lead concentration when the time of electrolysis is low. As noted, the basic solutions are more turbid than the acidic solution along the increment of lead concentration due to the continuous formation of coagulants.

The electric current value is inversely proportional to the turbidity along the raise of the contaminant in the solution due to adsorption process by coagulants that leads to

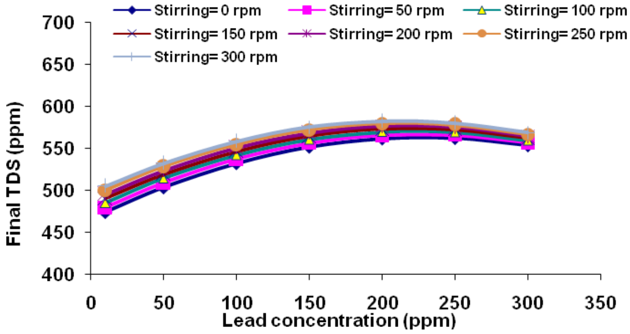

Fig. 12. Final TDS vs. lead concentration with several constant values of stirring speed when other variables keeping at their mean values.

aggregate the pollutant as sludge. The turbidity is directly proportional to the increase of lead concentration in case of different values of mixing speed due to the lake of adsorption process when the stirring speed increases which minimizes the efficient contact between the adsorbent and the adsorbate that keeping them suspended.

3.3. Effect of pH

As shown in Figs. 13–16, the variation of pH value of the simulated wastewater affects the value of TDS response throughout the experiment period based on the initial value of pH and the bonding of the hydroxyl ion with the aluminum ion, which will make the behavior of this response is irregular.

While the behavior is relatively stable against other variables along the increase of pH and the greater value of the turbidity appears at the upper limits designed for them. The uneven behavior of TDS is noted when those variables are presented in their minimum values.

3.4. Effect of current

Figs. 17–20 illustrate the variation in behavior of TDS response along the increase of current applied, where it reaches the lowest value at the mean value of current and then increases. This behavior is observed for all periods of the designed experiments where the process that has the longest period of treatment is less turbid due to the efficient system in reducing turbidity.

Furthermore, the turbidity increases when the lead concentration increases as current raises. The concentrated solutions appear to be the least turbid as the current increases to about 2 Amperes then the status is inverse. The behavior of this response decreases with the increase of the electric current of all solutions in case of different values of pH, and then the turbidity increases as current raises due to the continuous release of different ions as a result of the redox reaction in the electrochemical reactor.

The treatment operation of the polluted solution in case of the absence of mixing factor causes a decrease in the turbidity when the current increases because different components in the solution are not dispersed then TDS tends to change as the mixing speed increases as long as the current raises.

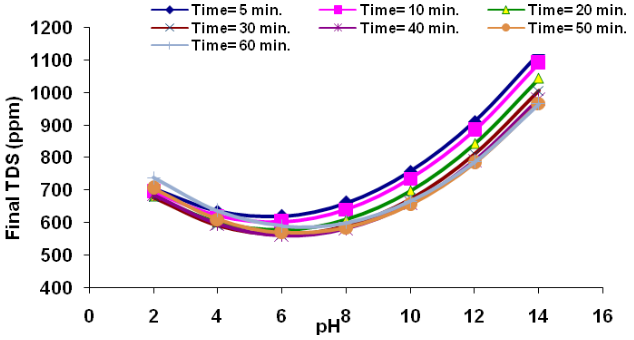

Fig. 13. Final TDS vs. solution pH with several constant values of electrolysis time when other variables keeping at their mean values.

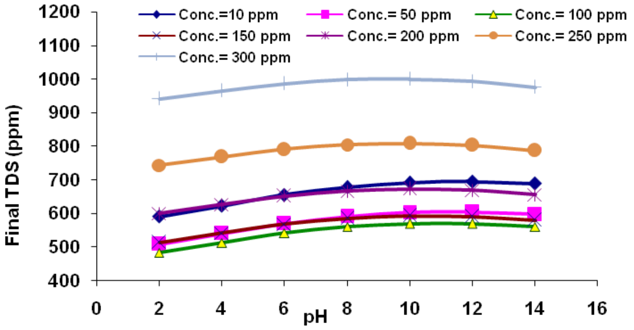

Fig. 14. Final TDS vs. solution pH with several constant values of lead concentration when other variables keeping at their mean values.

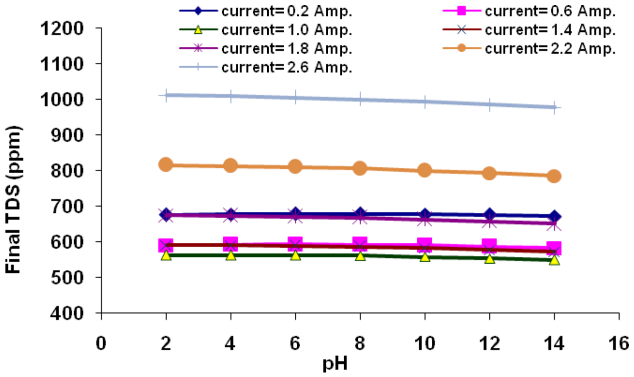

Fig. 15. Final TDS vs. solution pH with several constant values of current when other variables keeping at their mean values.

3.5. Effect of stirring speed

Figs. 21–24 explain how the value of TDS response behaves as the mixing speed in the electrolysis reactor increases against other variables. Where the direct relationship between turbidity and mixing speed for all periods of the experiments due to the lake in contact between the adsorbent and the pollutant that minimize the removal operation which keeps particles in suspension status. The same thing is observed when lead concentration changes in polluted solutions, but dilute solutions remain the least

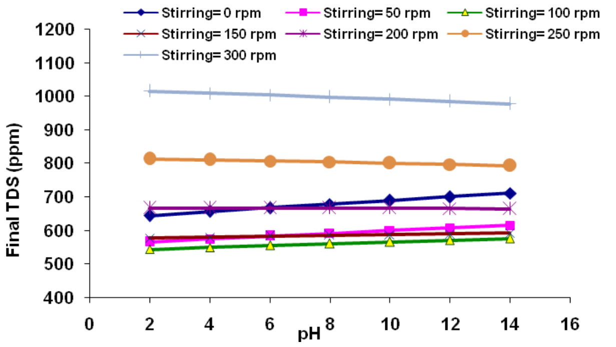

Fig. 16. Final TDS vs. solution pH with several constant values of stirring speed when other variables keeping at their mean values.

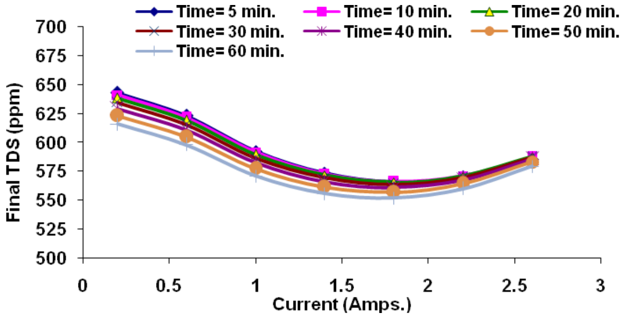

Fig. 17. Final TDS vs. current with several constant values of electrolysis time when other variables keeping at their mean values.

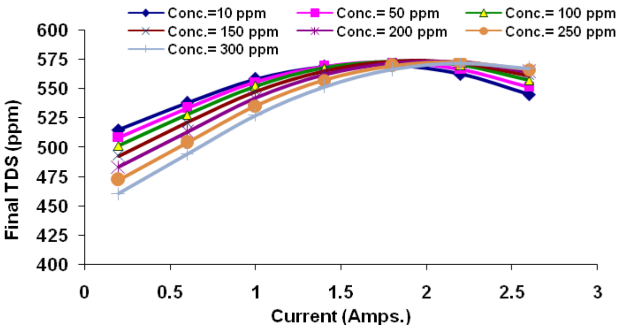

Fig. 18. Final TDS vs. current with several constant values of lead concentration when other variables keeping at their mean values.

turbid despite the increase of mixing speed. The irregular behavior of TDS response is clearly presented when the value of solution pH differs. The basic solutions are the least turbid when the value of mixing speed increases because of its preference to remove the pollutant, but the turbidity increases when the solution is acidic.

The behavior of this response along the raise of mixing speed is uneven when the value of current is changed and the solutions remain more turbid as the current increases as long as the mixing speed raises due to the continuous generation and dispersion of various ions.

The histogram of TDS response is shown in Fig. 25 which clearly indicates that the maximum value of the final TDS presented in the treated solution occurred in the range 550–600 ppm.

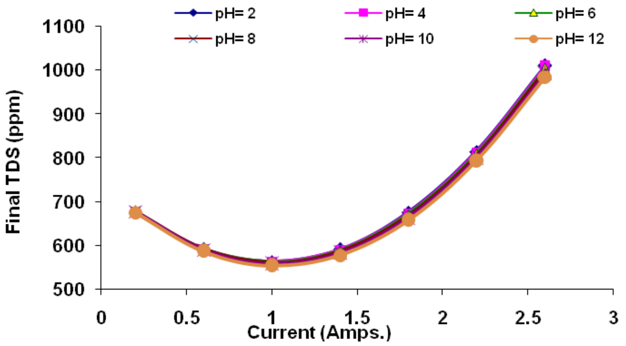

Fig. 19. Final TDS vs. current with several constant values of solution pH when other variables keeping at their mean values.

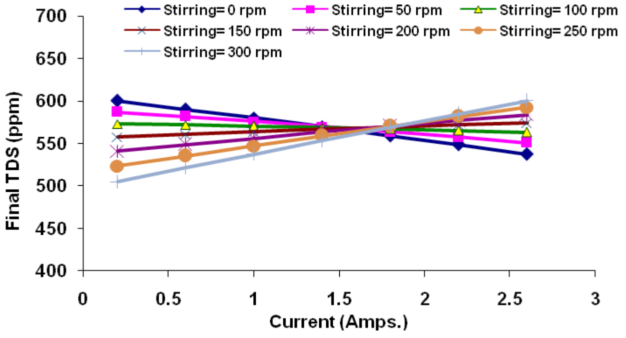

Fig. 20. Final TDS vs. current with several constant values of stirring speed when other variables keeping at their mean values.

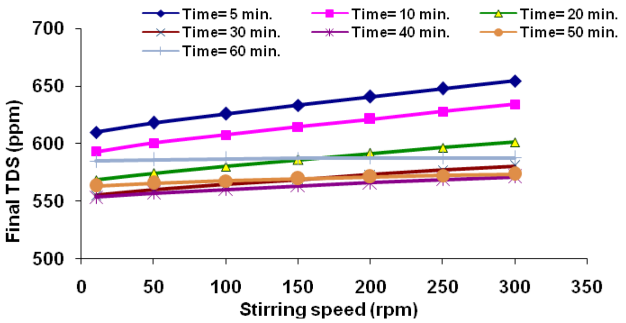

Fig. 21. Final TDS vs. stirring speed with several constant values of electrolysis time when other variables keeping at their mean values.

4. Conclusion

The present study shows clearly the influence of electrodes configuration as well as the operational variables on the bahavior of TDS. Moreover, the regression correlation among TDS response and the operating parameter was estimated with a high value of the coefficient of determination. The results illustrate the effect of each one of the operating variables on TDS response where the empirical

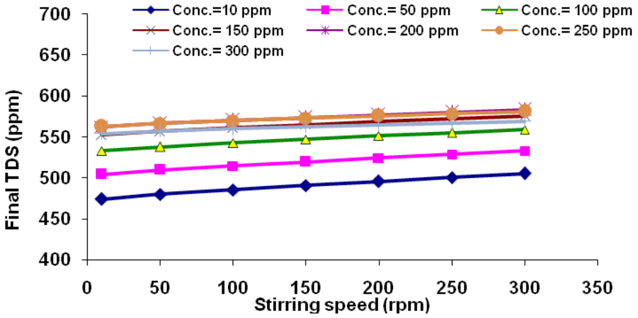

Fig. 22. Final TDS vs. stirring speed with several constant values of lead concentration when other variables keeping at their mean values.

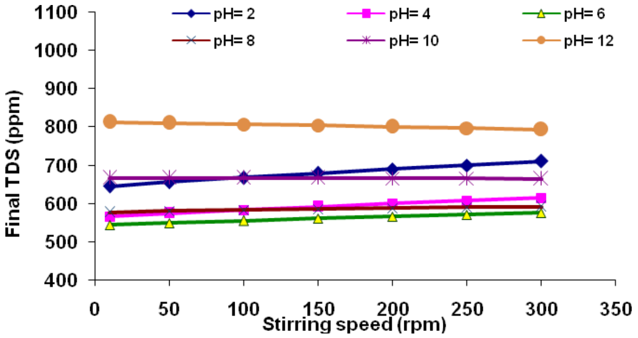

Fig. 23. Final TDS vs. stirring speed with several constant values of solution pH when other variables keeping at their mean values.

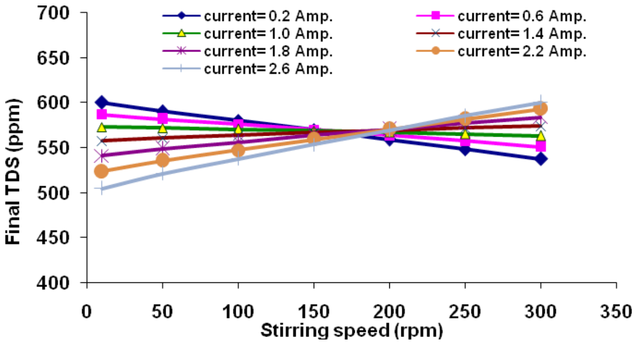

Fig. 24. Final TDS vs. stirring speed with several constant values of current when other variables keeping at their mean values.

correlations that represent this issue were found. In order to find the effect of the variation of variables values on TDS response in a separate manner for each one of the operating variables against several values of another variable and keeping other variables at their mean values. Finally, a brief histogram was found to explain the maximum limit of TDS response that presented in the treated solution.

Symbols

X_1 — Electrolysis time (min.)
X_2 — Lead concentration (ppm)

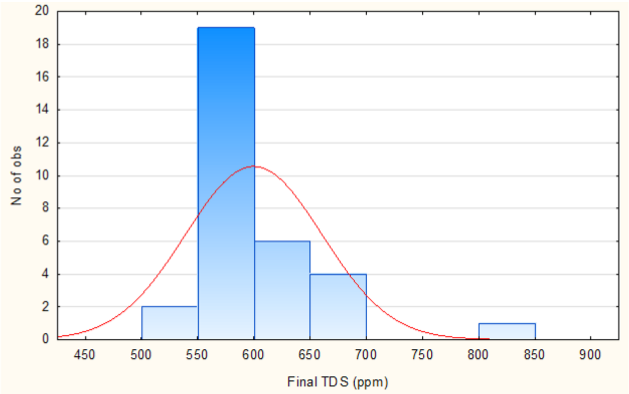

Fig. 25. Histogram of the final TDS response.

X_3 — pH
X_4 — Electric current (Amps.)
X_5 — Stirring speed (rpm)
Y_{TDS} — Total dissolved solids response

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