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Evaluating Electrocoagulation Process for Water Treatment Efficiency Using Response Surface Methodology

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ABSTRACT

The electrocoagulation process became one of the most important technologies used for water treatment processes in the last few years. It's the preferred method to remove suspended solids and heavy metals from water for treating drinking water and wastewater from textile, dairy, and electroplating factories. This research aims to study the effect of using the electrocoagulation process with aluminum electrodes on the removal efficiency of suspended solids and turbidity presented in raw water and optimizing by the response surface methodology (RSM). The most important variables studied in this research included electrode spacing, the applied voltage, and the operating time of the electrocoagulation process. The samples were taken from the Al Qadisiyah water treatment plant. The treatment set up was in a batch mode; two parallel plates of aluminum were used as electrodes. Experimental results showed that the maximum removal efficiency of 96% for turbidity and 97% for TSS were obtained at operating time 60 minutes, voltage 30 V, and electrode spacing 1.7cm. Two models for predicting removal efficiency obtained, the first model was for turbidity with a correction factor of 94.7%, and the second one was for the TSS with a correction factor of 94.85%.

Keywords: Electrocoagulation, Al - Qadisiyah water treatment plant, Total suspended solids, turbidity.

تقييم كفاءة عملية التخثير الكهربائي في معالجة المياه باستخدام طريقة سطح النمذجة

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الخلاصة

أصبحت عملية التخثير الكهربائي واحدة من أهم التقنيات المستخدمة لعمليات معالجة المياه في السنوات القليلة الماضية. إنها الطريقة المفضلة لإزالة المواد الصلبة العالقة والمعادن الثقيلة من المياه لمعالجة مياه الشرب ومياه الصرف الصحي من مصانع النسيج، والألبسة، والطلاء الكهربائي. الهدف من هذا البحث هو دراسة تأثير استخدام عملية التخثير الكهربائي مع أقطاب

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الالمنيوم على كفاءة إزالة المواد الصلبة العالقة والكدر في المياه الخام باستخدام طريقة منهجية سطح الاستجابة. اهم المتغيرات التي تمت دراستها في هذا البحث هو المسافة بين الاقطاب ، والجهد المطبق ، ووقت التشغيل لعملية التخثير الكهربائي. تم اخذ العينات من محطة معالجة مياه القادسية لهذه الدراسة. تمت عملية المعالجة بطريقة ال (batch mode) ، باستخدام لوحان متوازيان من الألومنيوم يستخدمان كأقطاب كهربائية. أظهرت النتائج المختبرية أن أقصى كفاءة إزالة تبلغ 96% للكدر و 97% لـ للمواد الصلبة العالقة و التي تم الحصول عليها في وقت التشغيل 60 دقيقة ، والجهد 30 فولت ، المسافة بين الاقطاب 1.7 سم. تم الحصول على نموذجين للتنبؤ بكفاءة الإزالة ، وكان النموذج الأول للكدر بعامل تصحيح 94.7% والثاني لـ للمواد الصلبة العالقة بعامل تصحيح 94.85%.

الكلمات الرئيسية: عمية التخثير الكهربائي ، محطة معالجة ماء القادسية، المواد العالقة الصلبة، الكدر، كفاءة الازالة.

1. INTRODUCTION

Water quality is a growing global concern. Polluted water and inadequate sanitation kill two children every minute worldwide (Ewaid, et al., 2017). High concentrations of suspended solids decrease water quality. This adversely affects aesthetics and recreation in surface water bodies (Appleby and Appleby, 1989).

In the last few years, water levels in Iraq's rivers have rapidly decreased to less than a third of their normal capacity. Poor drinking water and sanitation have increased the risk of waterborne diseases, especially among vulnerable groups such as children and women (Iraq, UN, 2013). Therefore a modern, simple, economic and effective technologies should be applied for water treatment. Electrocoagulation treatment is the preferred method to remove suspended solids and heavy metals from water for treating drinking water and wastewater from textile, diary, and electroplating factories (Chen, 2004).

In an EC unit, electrical current applied through a set of metal electrodes, most often made from aluminum or stainless steel, submerged in the raw water to be treated. Metal ions dissolved from the anode by the current, while hydrogen gas produced at the cathode. After dissolving in the raw water, the metal ions react with the water, creating metal hydroxides, which again react with dissolved pollutants and colloids in the water, in the same way, traditional chemical precipitation works. For aluminum electrodes, the following reaction takes place in the anode (Mollah, et al., 2001)



At the other half of the cell, the water is hydrolyzed to form hydrogen gas by the following reaction:



The product of anodic reaction (M^{+}) combines with the cathodes product (OH^{-}) to form insoluble products, as shown in the reaction below:



As well as for the products are: $Al(OH)^{+2}$, $Al(OH)_2^{+2}$, $Al(OH)_4^{-}$, $Al_6(OH)_{15}^{+3}$, $Al_7(OH)_{17}^{+4}$, $(OH)_{20}^{+4}$, $Al_{13}O_4(OH)_{24}^{+4}$, and $Al_{13}O_4(OH)_{24}^{+4}$ These intermediate compounds then transform into $Al(OH)_3$ (Mollah, et al., 2004)



The most common and best form of aluminum electrode is called **Keggin cation $Al_{13}O_4(OH)_{24}^{+7}$** , which is considered as the main source of precipitate and soluble complexes is known as Al_{13} ion (Sarpola, 2007). The most important parameters that can affect the electrochemical process is the applied voltage, the distance between electrodes. Therefore the effect of them on the total suspended solids and turbidity removal efficiency were studied in this research. As the applied voltage increased, the removal efficiency and the current passing through the solution increased (Wang, et al., 2009). The distance between electrodes is related to the resistance that occurs through the solution, as this distance decreases, the rate of anode dissolution increases, and the rate of Al^{+3} production increase because of the increase in the current (Ahmed and Muhanned, 2010). It is not simple to evaluate the optimum condition in the electrocoagulation process, so response surface methodology (RS M) used in this research for that purpose. RSM is a merging of mathematical and statistical techniques employed to amplify and optimize different processes (Bennajah, 2007). This research aims to study the effect of using the electrocoagulation process with aluminum electrodes on the removal efficiency of suspended solids and turbidity presented in raw water and optimizing by the response surface methodology (RS M).

2. MATERIAL AND METHOD

2.1 Electrocoagulation Process Description

The experiments carried out in a batch electrocoagulation system. A schematic diagram is shown in Fig.1. It consists of two parallel plates of aluminum electrodes with the dimensions of (10 x 4 x 2 mm) to obtain an active area of 121.4 cm². The composition of the aluminum electrodes is as shown in Table1.

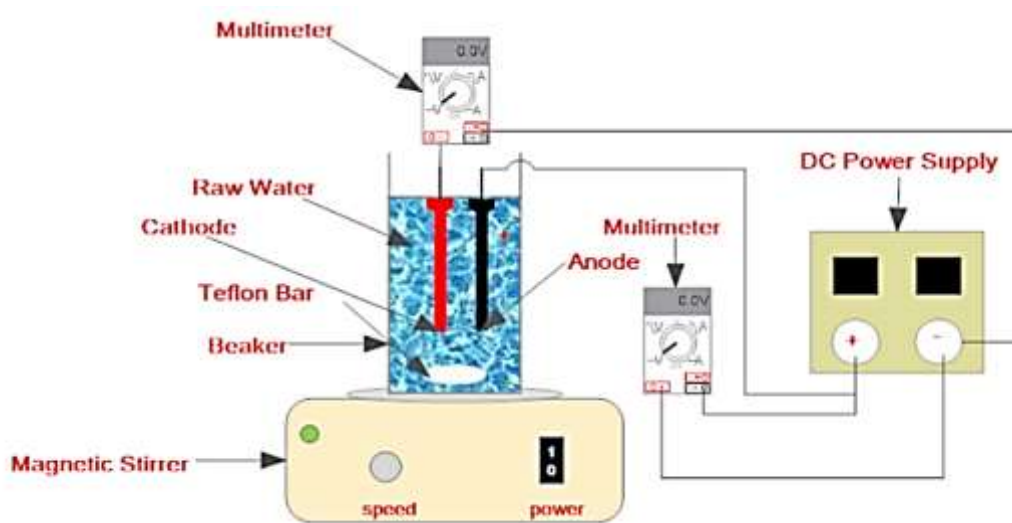


Figure.1 Schematic diagram of the experimental setup.

Table 1. The composition of electrodes.

Electrode type	Code	Composition, % Wt	
Al	1099	Al=99.99	Cu, Si, Fe < 0.01

The real photo of the electrocoagulation system at the laboratory shown in Fig.2.

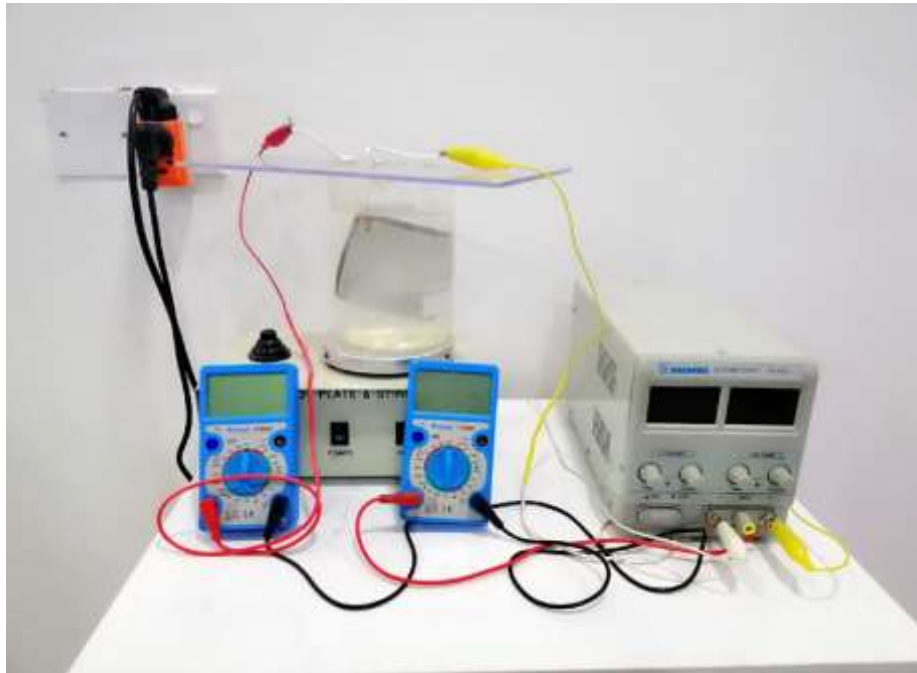


Figure.2 Electrocoagulation system at the laboratory.

Other tools are as follows:

- 1- Digital DC power supply; Type DAZHENG (PS-302D) with a range 0-30V and 2A.
- 2- Multi-meter (A-meter and volt-meter) was used to measure the current and voltage for the system.
- 3- Magnetic stirrer, Stirring speed: 60-1500 rpm, (LMS-HTS-1003, Japan).
- 4- Aluminum electrodes.
- 5- Graduated cylinders.
- 6- Stopwatch.
- 7- The compact Lovibond® infrared turbidity meter TurbiCheck was used for turbidity measuring
- 8- A Lovibond / Photometer MultiDirect instrument used for TSS determination.

The batch electrocoagulation reactor is made of Plexiglas with a volume of 1 liter with a dimension of 11 cm in diameter, 12 cm height of an effective volume of 1140.4cm³.

2.2 Data Collection and Analysis

The real water sample used in this research was collected from AL-Qadiseyah WTP has the characteristics, as shown in Table 2.

Table 2. Characteristics of the water sample.

Parameter	Unit	Value
Turbidity	NTU	51.3
Total suspended solids (TSS)	mg/L	37
Electrical Conductivity	µs/cm	1280
PH	-	7.58



2.3 Experimental setup and procedure

The experiments were carried out in the electrocoagulation cell using a magnetic stirrer to obtain a proper mixing with speed 150 rpm (Bayar, et al., 2011). (1L) of the sample was introduced into the cell for each experiment. The cell was comprised of two parallel plates of aluminum electrodes as anode and cathode with a variable distance of (1-3) cm between them.

According to (Mameri, et al., 2001) and (Alameen and Majeed, 2020), the surface area to volume ratio of the electrodes should be in the range of (6.9- 42.5) m^2 / m^3 , so the electrodes in this research designed with a surface area to volume ratio (A/V) of $10.65\text{m}^2/\text{m}^3$ which it is in this cited range.

Electrodes were connected to the terminals of a DC power supply. The electrical circuit was switched on as soon as the electrodes were covered by the electrolyte. The reactor operates at a constant voltage and varied current to sustain the required voltage. The process started, and the voltage was kept constant using one of (5-30) volt with an hour in each run.

During each run, samples of 10 ml were taken each 10 min during the process. It was let to settle and was taken to be analyzed.

At the end of each run, the system was washed several times with water and once with HCl to remove any solids tending to cling at the inside walls of the cell and to avoid passivity of the electrodes.

3. RESULTS AND DISCUSSION

3.1 The effect of the operation parameter on the suspended solids and turbidity removal efficiency

This set of experimental runs showed the influence of voltage on the suspended solids and turbidity removal efficiency using aluminum electrodes at a different spacing distance (1, 2, and 3 cm). The voltage values tested were (from 5 volts to 30 volts). The majority of papers use a spacing of 1 to 3 cm. Smaller spacing causes a pressure drop in open system operation, and larger spacing causes a decrease in the internal resistance of the cell, causing higher current for the same performance. Higher voltage range consumes high energy, and lower voltage has no significant effect. As for the time, longer treatment duration leads to larger reactor volume for the same flow rate (Mameri, et al., 2001).

It is shown in **Fig. 3**, for 1 cm spacing, the highest TSS elimination was obtained after 60 minutes of treatment at a voltage 30V.

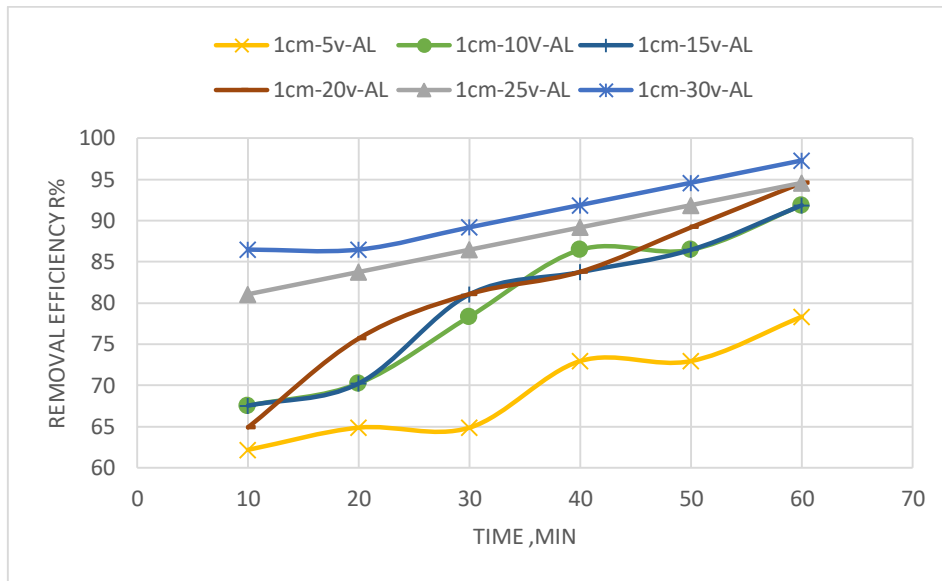


Figure 3. TSS removal efficiency at 1cm spacing between electrodes.

The turbidity removal reached 90% for voltage higher than 25V after 50 min, as shown in Fig.4.

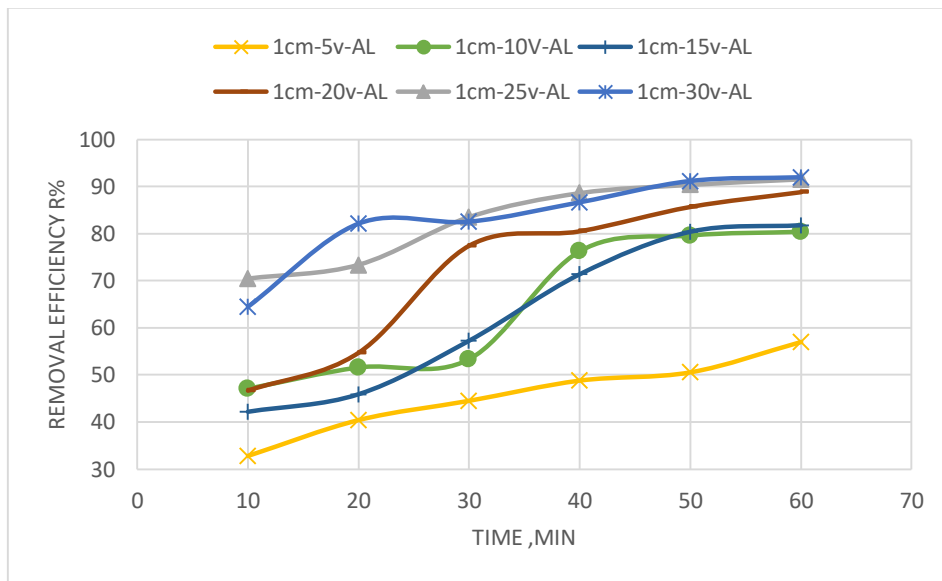


Figure 4. Turbidity removal efficiency at 1cm spacing between electrodes.

When electrode spacing increased to 2 cm, the time and voltage required to reach the maximum removal were slightly increased, as shown in Fig. 5, and Fig. 6. 95% TSS elimination was obtained after 60 minutes of treatment at 30V. At the same time, the turbidity removal reached 90% for voltage higher than 25V after 50 min.

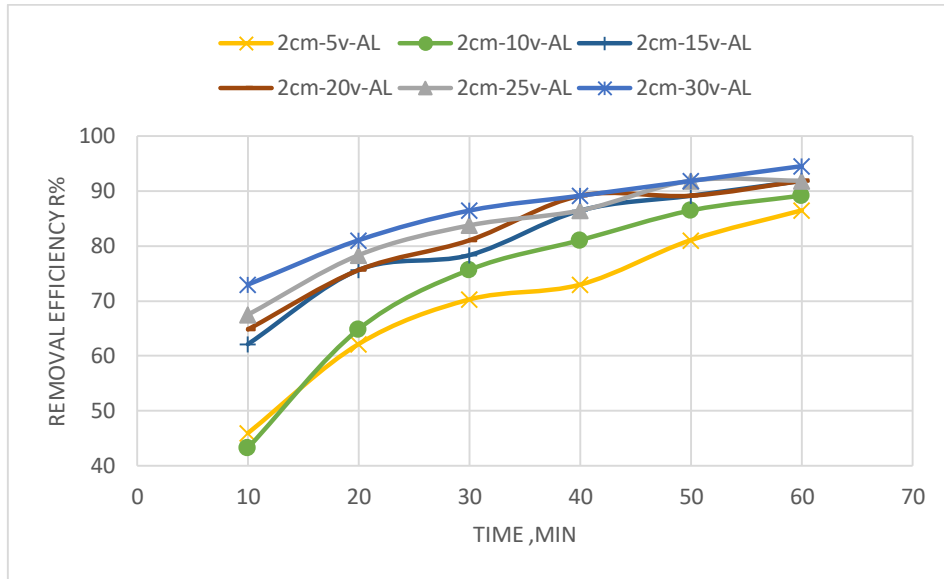


Figure 5. TSS removal efficiency at 2cm spacing between electrodes.

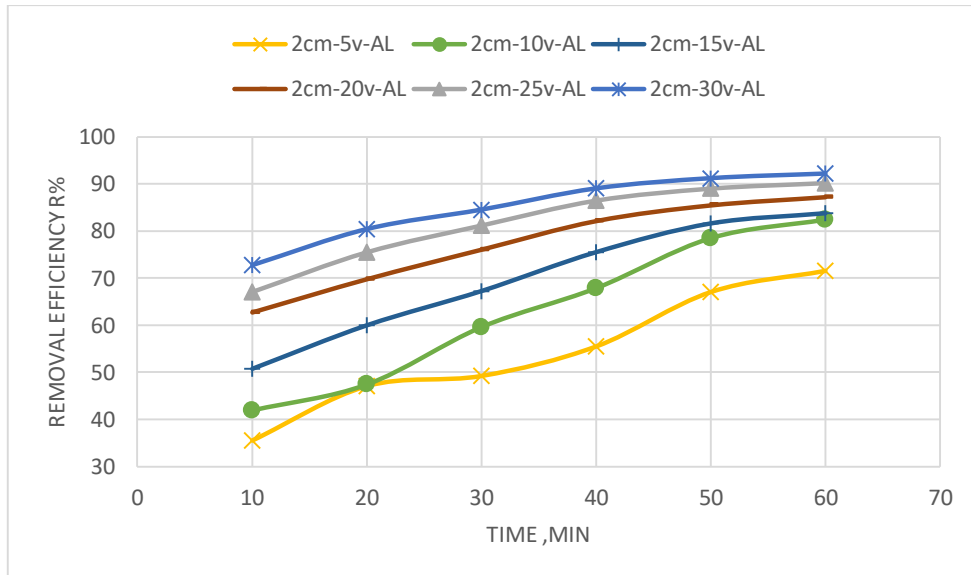


Figure 6. Turbidity removal efficiency at 2cm spacing between electrodes.

The final spacing studied was 3 cm, as shown in Fig.7, complete TSS elimination was obtained after 60 minutes of treatment at 30 V.

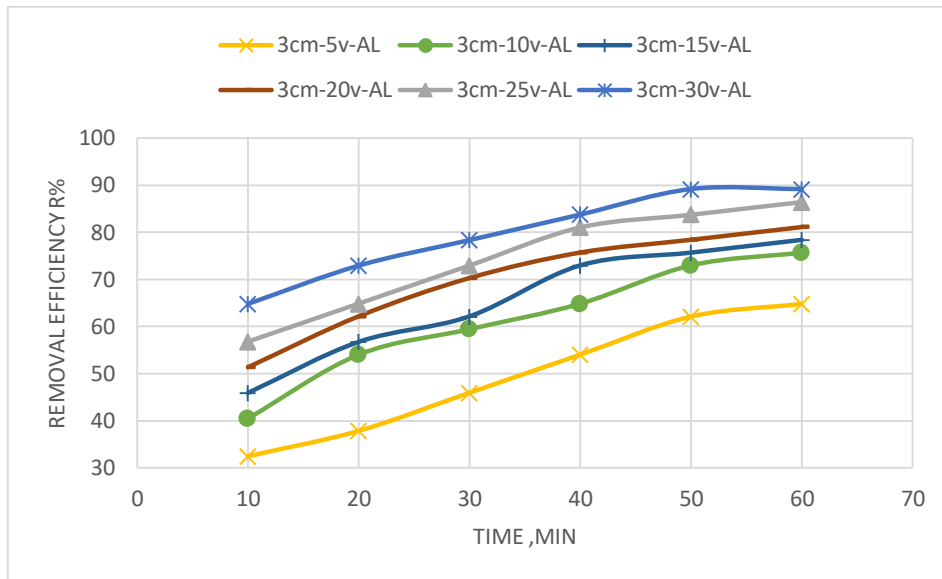


Figure 7. TSS removal efficiency at 3cm spacing between electrodes.

The turbidity removal reached 90% for voltage higher than 25V, as shown in Fig.8.

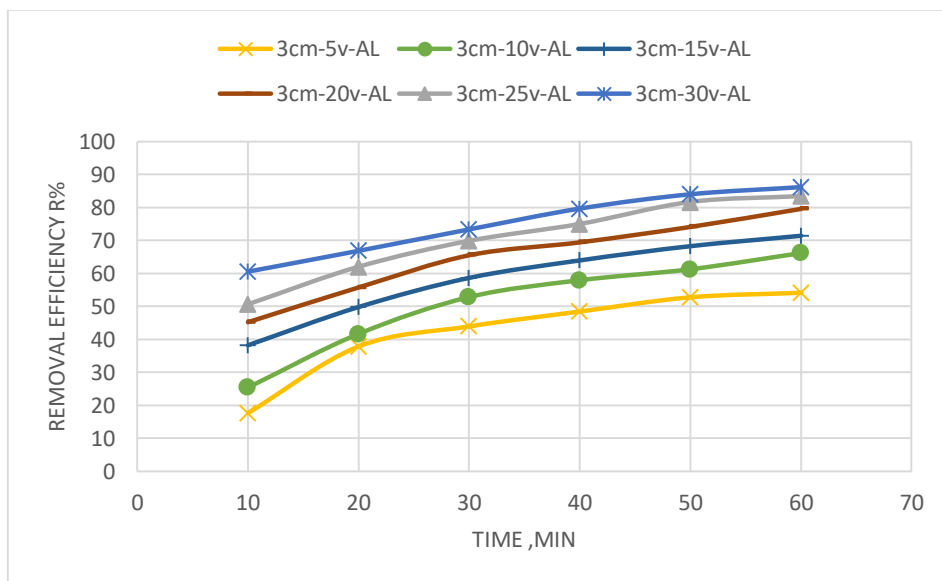


Figure 8. Turbidity removal efficiency at 3cm spacing between electrodes.

After studying the electrode spacing for aluminum, it was found that the 1cm electrode spacing at any voltage gave higher removal were the majority of the removal of TSS was 90%-95, and turbidity was about 90 %. This behavior was also observed by (Modirshala, et al., 2007)

3.2 Optimization of Electrocoagulation Process by Response Surface Methodology

Experimental design for Response Surface Methodology (RSM) is a useful statistical tool for the optimization of different processes and widely used for experimental design. In this method, the leading objective is to optimize the response surface influenced by different parameters. RSM also identified the relationship between the controllable input parameters and the response variable.



The general behavior of electrocoagulation simulated by a mathematical equation: this equation represents the regression model. Response surface methods are used to examine the relationship between two response variables (Turbidity and TSS), and a set of quantitative experimental, the factors considered in this study are: (voltage, electrode spacing, and time).

The models obtained by RSM using Minitab 17 software in this research are as follows:

3.2.1 Turbidity Model

The turbidity removal modeled using the RSM in Minitab 17 software, the regression equation of the turbidity represented in Eq.6

$$R\%_1 = -16.28 + 26.38 \text{ spacing, cm} + 2.679 \text{ voltage, v} + 1.367 \text{ time} - 7.321 \text{ spacing, cm} * \text{spacing, cm} - 0.02571 \text{ voltage, v} * \text{voltage, v} - 0.00805 \text{ time} * \text{time} - 0.0658 \text{ spacing, cm} * \text{voltage, v} - 0.0032 \text{ spacing, cm} * \text{time} - 0.00916 \text{ voltage, v} * \text{time} \tag{6}$$

The correlation coefficient “R2” is equal to 94.7%, which can give a good correlation between parameters and responses.

The relation between the removal and the effecting variables (voltage and spacing) is also represented in the 2D contour graph. The graph is calculated by the Minitab 17 software was the darker the green color, the higher the removal, as shown in **Fig.9**.

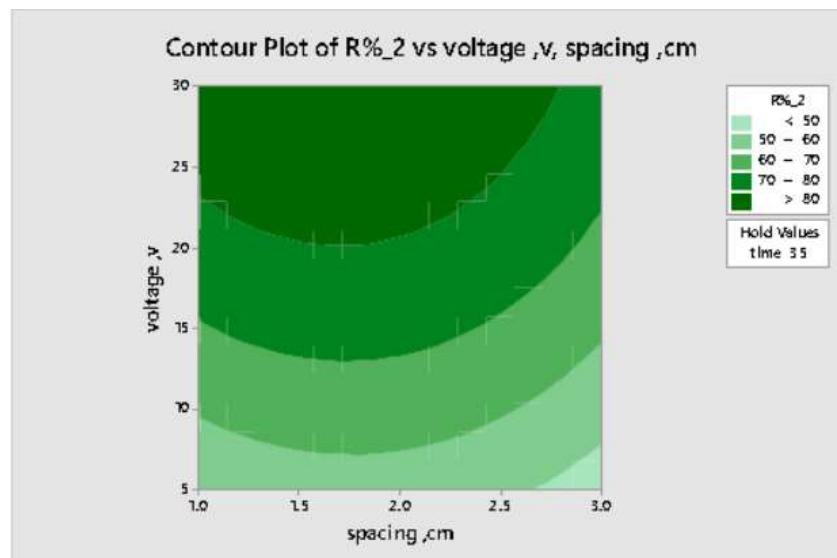


Figure 9. The 2D contour graph for the relation between the turbidity removal efficiency and the effecting variables.

The optimization performance of the design and response variables is shown in **Fig.10**, where the best optimization is approached by an overall removal of 97.5% at optimum operating conditions, time at 60 min, 30 voltage, and 1.64 cm spacing.

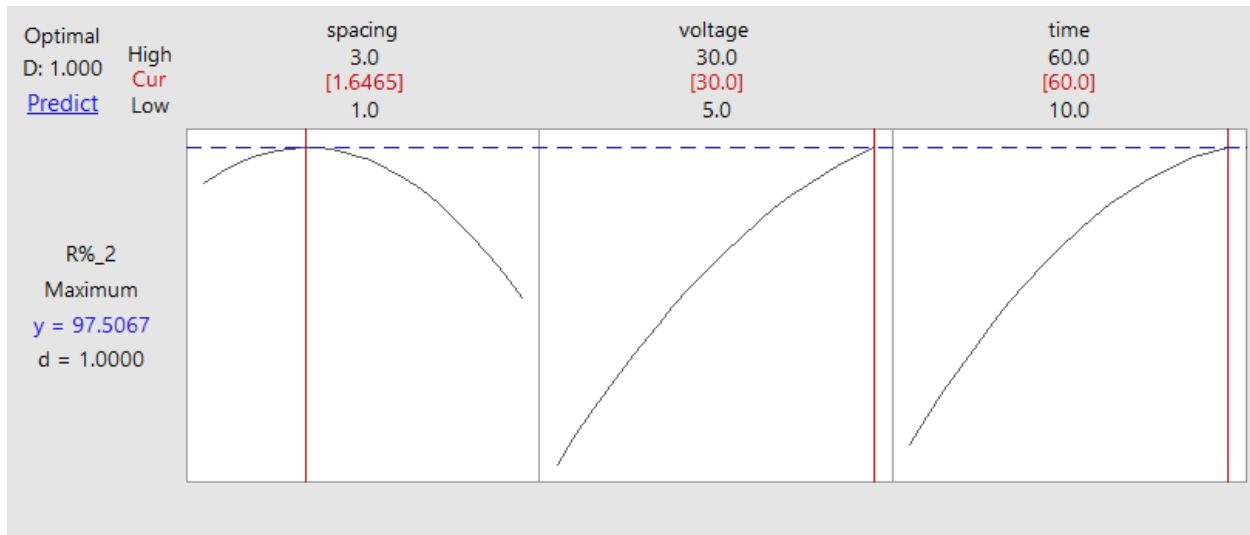


Figure 10. Optimum Operating Conditions for Turbidity Removal.

3.2.2 Total Suspended Solids Model

The total suspended solids removal efficiency model represent in Eq.7.

$$R\%_2 = 38.36 + 5.59 \text{ spacing, cm} + 1.422 \text{ voltage, v} + 0.959 \text{ time} - 5.030 \text{ spacing, cm} * \text{spacing, cm} - 0.01684 \text{ voltage, v} * \text{voltage, v} - 0.00670 \text{ time} * \text{time} + 0.1776 \text{ spacing, cm} * \text{voltage, v} + 0.1120 \text{ spacing, cm} * \text{time} - 0.01005 \text{ voltage, v} * \text{time} \quad (7)$$

The correlation coefficient “R²” is equal to 94.85%, which can give a good correlation between parameters and responses.

The relation between the removal and the effecting variables (voltage and spacing) is also represented in the 2D contour graph. The graph is calculated by the Minitab 17 software was the darker the green color, the higher the removal, as shown in Fig.11.

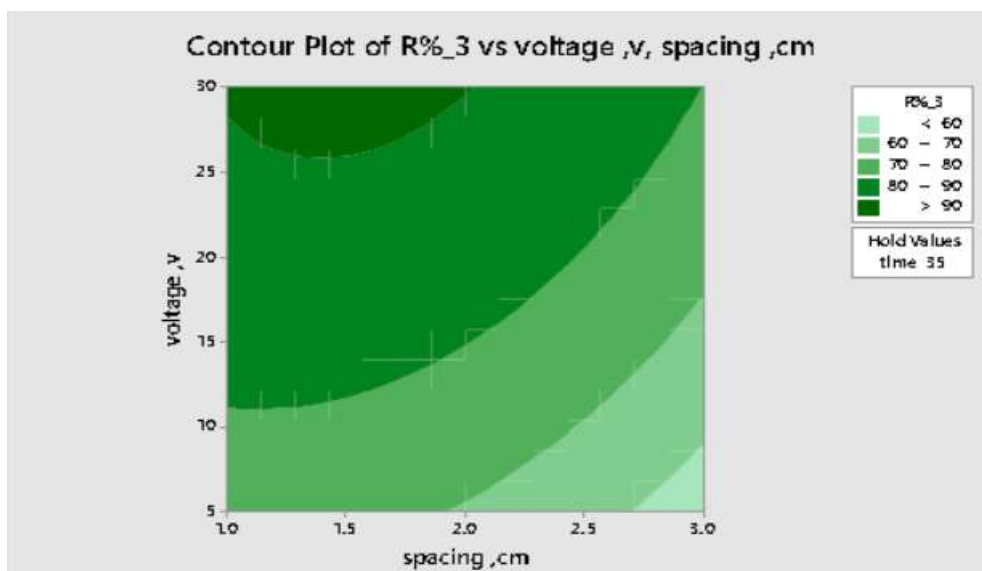


Figure 11. 2D Contour Graph of the Total Suspended Solids Removal Efficiency and the Effecting Variables.



The optimization performance of the design and response variables is shown in Fig.12, where the best optimization is approached by an overall removal of 100% at optimum operating conditions, time at 60 min, 30 voltage, and 1.75 cm spacing.

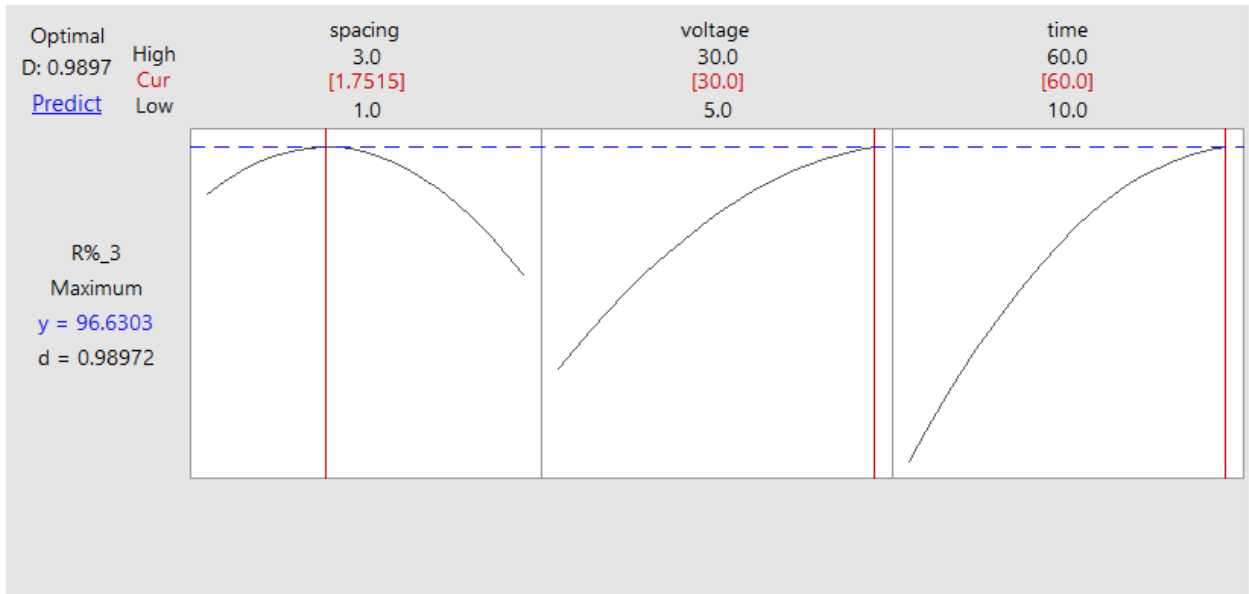


Figure 12. The optimal result of total suspended solids removal.

3.2.3 The Optimum Condition for Both Total Suspended Solids and Turbidity

It is important to get the optimal condition to obtain the highest removal for both the TSS and turbidity, as shown in Fig.13. At 96% TSS removal and 97% turbidity removal, the conditions were 1.7cm spacing, 30 volts, and 60 min

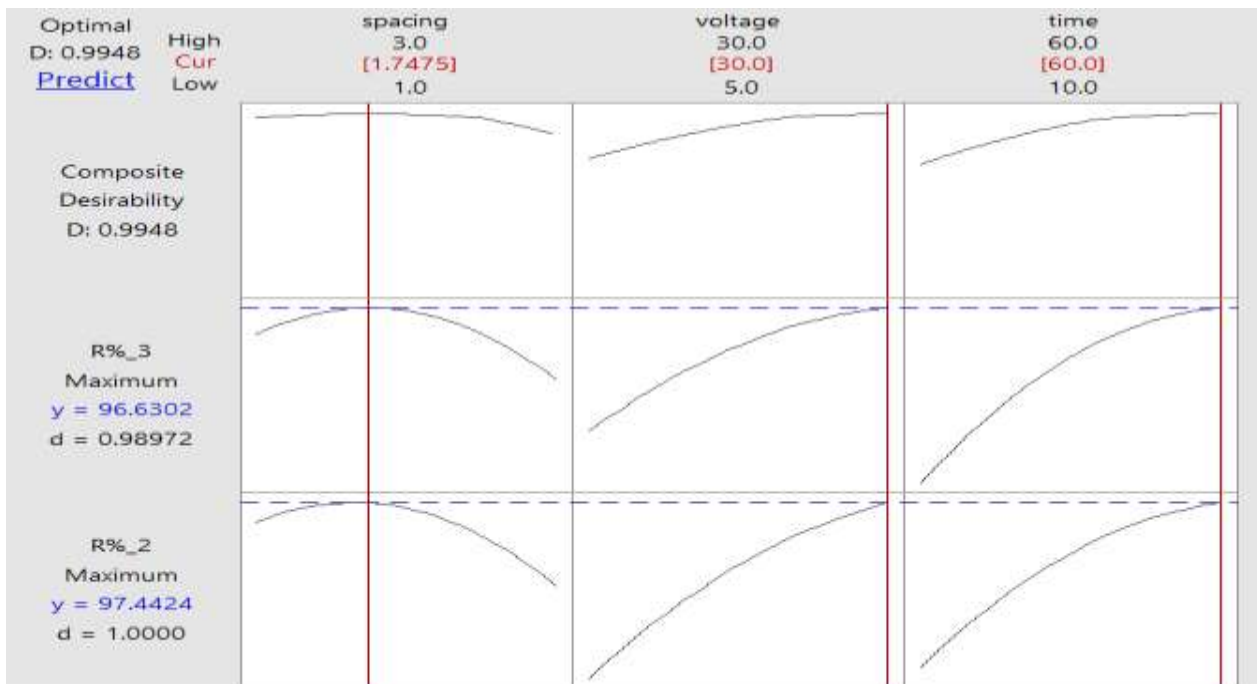


Figure.13 The optimal result for total suspended solids and turbidity



4. CONCLUSIONS

- 1- The water treatment using the electrocoagulation process was successfully achieved. It showed a dependence on time, the electrode spacing, and the applied voltage.
- 2- As the voltage increased from 5 to 30 volt, the maximum removal efficiency increased to 92% for the turbidity, and 95% for the total suspended solids removal at 2cm electrode spacing.
- 3- The 1st model for turbidity with a correction factor of 94.7%, and the 2nd for the TSS with a correction factor of 94.85%, were two models for predicting removal efficiency. Optimal results indicated that at 60 minutes, the voltage was 30V and electrodes 1.7 cm spaced, maximum removal effectiveness of 96% for turbid, and 97% for TSS was achieved.
- 4- The applied voltage shows the increase in the applied voltage led to an increase in removal efficiency.

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