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Modelling of electrochemical phosphate removal from water

Hayfaa A. Mubarak ^{1*}

¹ Chemical Engineering Department, College of Engineering, University of Babylon, Iraq; haifaadnan_81@uobabylon.edu.iq

Corresponding Author: haifaadnan_81@uobabylon.edu.iq

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Abstract: Phosphate contamination in surface water is a common problem that still needs a dependable solution because the presence of phosphate is the main motivator of the eutrophication of surface water which leads to many economic and health problems. In terms of the economy, eutrophication ruins the quality of the water inhibits tourism activities and requires expensive treatments and management plans. While in terms of health, eutrophication results in the generation of toxins via algal activities. The present article presents the results of phosphate removal from water using an electrocoagulation unit supplied with aluminium electrodes, and also it presents the results of modelling of phosphate removal by the electrocoagulation method. The experimental work focused on the effects of distance between electrodes (D), current density (CD) and contact time (Time), and the modelling process was developed using Response Surface Methodology (RSM) (a three-factor Box-Behnken design). The results of both experimental and modelling studies were agreed with an R² of 0.9779, and it was noticed that the 20 mg/L of phosphate was removed after 55 minutes of electrolysis at CD of 5 mA/cm² and D of 3 mm. The results encourage the use of this method for phosphate removal from domestic wastewater or use the method as a pre-treatment for industrial wastewater because the latter is usually highly loaded with phosphate.

Keywords: Water; electrocoagulation; RSM; phosphate.

1. Introduction

The presence of phosphate in water occurs naturally due to the contact between the surface or ground water and the geological formations with high phosphate concentrations. Additionally, the runoffs wash the phosphate from the banks of the rivers and lakes into the surface water [1]. Usually, the groundwater contains a higher concentration of phosphate than the surface waters due to the long-term contact between water and soils or rocks [2]. However, nature has a minor contribution to water phosphate contamination and does not require extensive treatments. The main root of phosphate pollution in water is industrial and agricultural wastewater that contains elevated phosphate concentrations. It has been reported that the phosphate concentration in freshwater sources has increased by 75% during the last century due to industrial and agricultural wastewater discharge. In addition, the phosphate-based dete



Several solutions for phosphate pollution have been developed since this problem was triggered in the last century, such as biological lagoons, chemical precipitation, and adsorption. The majority of these methods are efficient in the removal of phosphate from water, but each one of these methods has its own disadvantages/limitations. For example, biological treatments are based on the natural digestion processes of living cells or plants to remove phosphate from water or wastewater. Besides the long treatment time, biological treatment requires a controlled environment. Delgadillo-Mirquez, et al. [3] found that the microalgae convert phosphate in the wastewater into biomass and bio-products efficiently, and the conversion rate depends on a number of factors such as the temperature of wastewater and the availability of light, and the best removal of phosphate was obtained at a temperature of 25 °C. Chemical precipitation is also efficient in the removal of phosphate, but the extensive use of chemicals in the treatment is the major limitation of this type of treatment.

The current focus of the research regarding phosphate removal is the use of bio- or eco-friendly adsorbents due to the minor environmental effects of these materials, availability and cost-effectiveness. Many materials were used for this purpose; for example, Ajmal, et al. [4] used three different oxides of iron (ferrihydrite (F), goethite (G), and magnetite (M)) as adsorbents to remove phosphate from water at different contact times, pH and temperatures; the results indicated that the best adsorption capacity was for the ferrihydrite (66.6 mg/g), followed by the magnetite (57.8 mg/g) and the goethite has the lowest capacity (50.5 mg/g). Natural materials were also used to remove phosphate from water; for example, Hamdi and Srasra (2012) removed phosphate from water using two clay minerals, kaolinitic and smectic, and also used synthetic zeolites. The adsorption capacity of these minerals was studied in different pH scales. The results showed the good capacity of these minerals to remove phosphate on a pH scale of 4-6, and the best capacity was for the zeolite (52.9 mg/g). The by-products were another potential material for phosphate from water, Li, et al. [5] used the sludge of water treatment to remove phosphate from water, and the wasted sludges were used in constructed treatment wetland. The sludges were collected from 5 plants in several cities in China. It was found the 5 sludges were removed at 20.408 mg/g, 15.625 mg/g, 15.385 mg/g, 90.909 mg/g and 4.167 mg/g. However, the quick depletion of the adsorbents is a problem that faces the use of the adsorption method; additionally, the high precision of the manufactured adsorbents is another problem that needs a solution.

Opposite to the traditional methods, the electrocoagulation method has acquired good attention over the last few years in the removal of phosphate from water. The electrocoagulation method is cheap, fast and safe compared with the traditional methods. For example, electrocoagulation with graphite anode and air cathode was able to remove 98% of phosphate in 15 min from domestic wastewater at a current density of 1 mA/cm², an energy consumption of 0.14 kWh/m³. Similar results were noticed in other studies, such as the study of Bakshi, et al. [6], who used aluminium electrodes to remove phosphate and found that the electrocoagulation unit can remove 90% at pH 7 and Voltage of 11.23 V and costs of 0.22 \$/m³. Also, the authors modelled the phosphate removal using the central composite design and noticed the modelling process was very useful in the prediction of the removal of phosphate and gave valid values.

The above studies clearly showed the electrocoagulation method is dependable and cost-effective for phosphate removal from water, and also, the materials that can be used as electrodes are available and cheap. Therefore, the electrocoagulation process will be used in this study to remove phosphate from water; the unit's electrodes will be aluminium. Additionally, the removal of phosphate will be modelled using Response Surface Methodology



(RSM) (a three-factor Box-Behnken design) to facilitate the prediction of the removal efficiency in future studies.

2. Materials and Methods

The phosphate solution was prepared by weighing a suitable amount of the KH_2PO_4 powder (286.574 mg) and then dissolving it in 10.0 liter of deionised water to get a stock solution with an initial concentration of phosphate of 200 mg/L.

The solution was kept in a cold place (4 °C) and used when needed in the experiments by taking 100 mL of the stock solution and mixing it with 800 mL of deionised water to get the initial concentration of phosphate of 20 mg/L.

The diluted solution was modified in terms of conductivity by adding a suitable amount of the NaCl to get a conductivity of 0.34 mS/cm, while the pH of the solution was changed into the required values using either HCl acid or NaOH particles (after dissolving the particles in deionised water).

The electrocoagulation unit consists of a cylinder glass beaker with a volume of 1000 mL and two electrodes made from aluminium. The electrodes are rectangular in shape, and they were partially submerged in water to get an effective area of 100 cm² per electrode. The electrodes were supplied with the DC current using a solar panel (Sunyma-12W, China). The unit is shown in Figure 1.

The experiments were conducted using 1.0 L of the diluted solution, and the effects of the distance between electrodes (D), current density (CD) and treatment time (Time) were considered to get the best removal efficiency.

The considered ranges for the D, CD and Time were 1-5 mm, 1-5 mA/cm², and 5-55 minutes, respectively. A small sample (5 mL) was collected after every 10 minutes from the unit, filtered on a paper filter (0.45 µm) and then used to measure the phosphate concentration using a UV-spectrophotometer (DR2800-Hach Lange) and LCK348-349 cuvettes (Hach Lange).

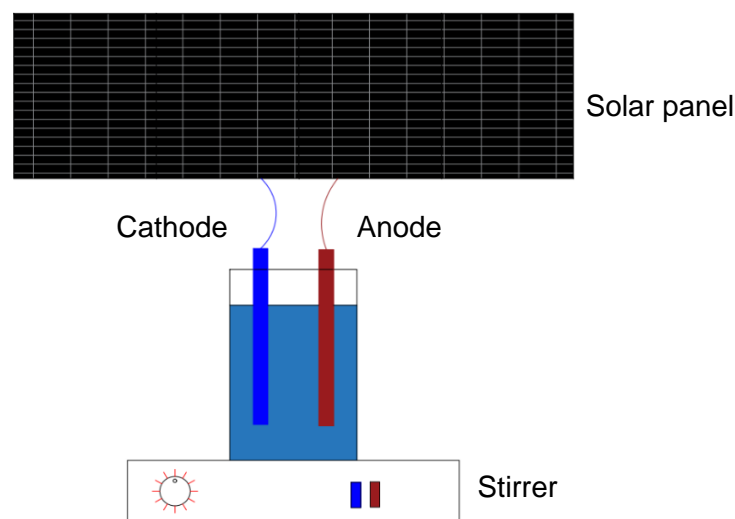


Figure 1. The Electrocoagulation unit.

The experiments were optimised before starting the work to avoid unnecessary experiments and also to obtain the required data for the modelling process. The optimisation and modelling processes were conducted using the Response Surface Methodology (RSM)



(a three-factor Box-Behnken design) because this method is commonly used for such purposes. The required experiments (15 experiments) for the optimisation are shown in Table 1, produced by the three-factor Box-Behnken design.

Table 1. Optimisation experiments according to the three-factor Box-Behnken design.

No.	D	CD	Time
1	3	1	5
2	5	3	5
3	5	5	30
4	3	3	30
5	5	3	55
6	1	5	30
7	1	3	55
8	3	3	30
9	5	1	30
10	1	1	30
11	3	3	30
12	3	1	55
13	3	5	55
14	1	3	5
15	3	5	5

3. Results

The experimental investigation was started by treating 1.0 L samples of diluted water using the electrocoagulation unit. Each experiment in Table 1 was conducted separately according to the specified conditions in the table. The results of the 15 experiments are shown in Table 2.

It can be observed that the electrocoagulation method can remove 99.8% of the 20 mg/L of phosphate when the CD is 5 mA/cm², D is 3 mm, and the Time is 55 minutes. At the same time, it can be seen the lowest removal of phosphate was 50.2% when the CD was low (1 mA/cm²), the Time was short (5 minutes), and the D was 3 mm. The results can give a set of conclusions, which are:

- 1- Increasing the CD is useful for the removal of phosphate.
- 2- Increasing the Time increases the removal of phosphate.
- 3- The long D is not useful for the removal of the phosphate.

These conclusions are agreed with the literature such as [7], [8] and [9].



Table 2. Results of phosphate experiments.

No.	D	CD	Time	Removal of phosphate %
1	3	1	5	50.2
2	5	3	5	75.2
3	5	5	30	98.7
4	3	3	30	92.2
5	5	3	55	95.2
6	1	5	30	93.2
7	1	3	55	85.6
8	3	3	30	90.2
9	5	1	30	60.1
10	1	1	30	59.5
11	3	3	30	88.7
12	3	1	55	80.5
13	3	5	55	98.8
14	1	3	5	72.6
15	3	5	5	92.8

It can be seen the obtained results in Table 3 are very close to the results of Table 2. This similarity between the predicted and actual removal efficiencies was tested using the R^2 that is shown in Figure 2. It can be seen the R^2 value is 0.9979, which is a very good agreement. The relationships between the removal efficiency and the D, CD and Time are shown in Figure 3.

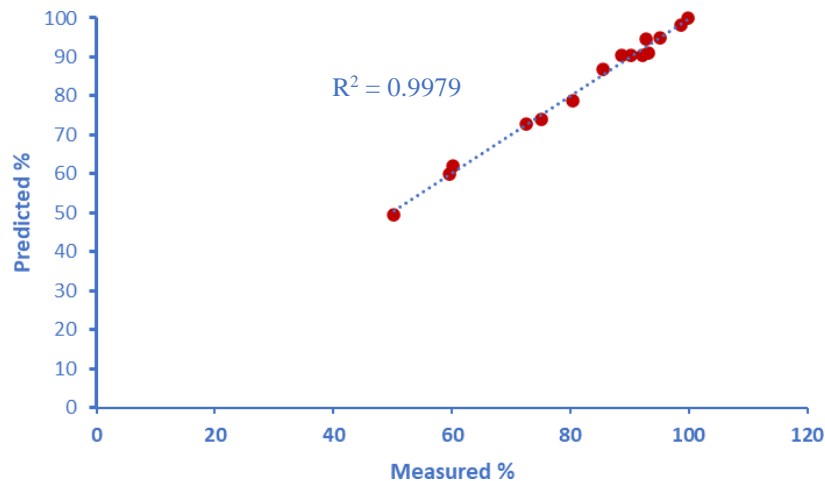


Figure 2. Relationship between predicted and actual removal efficiencies.

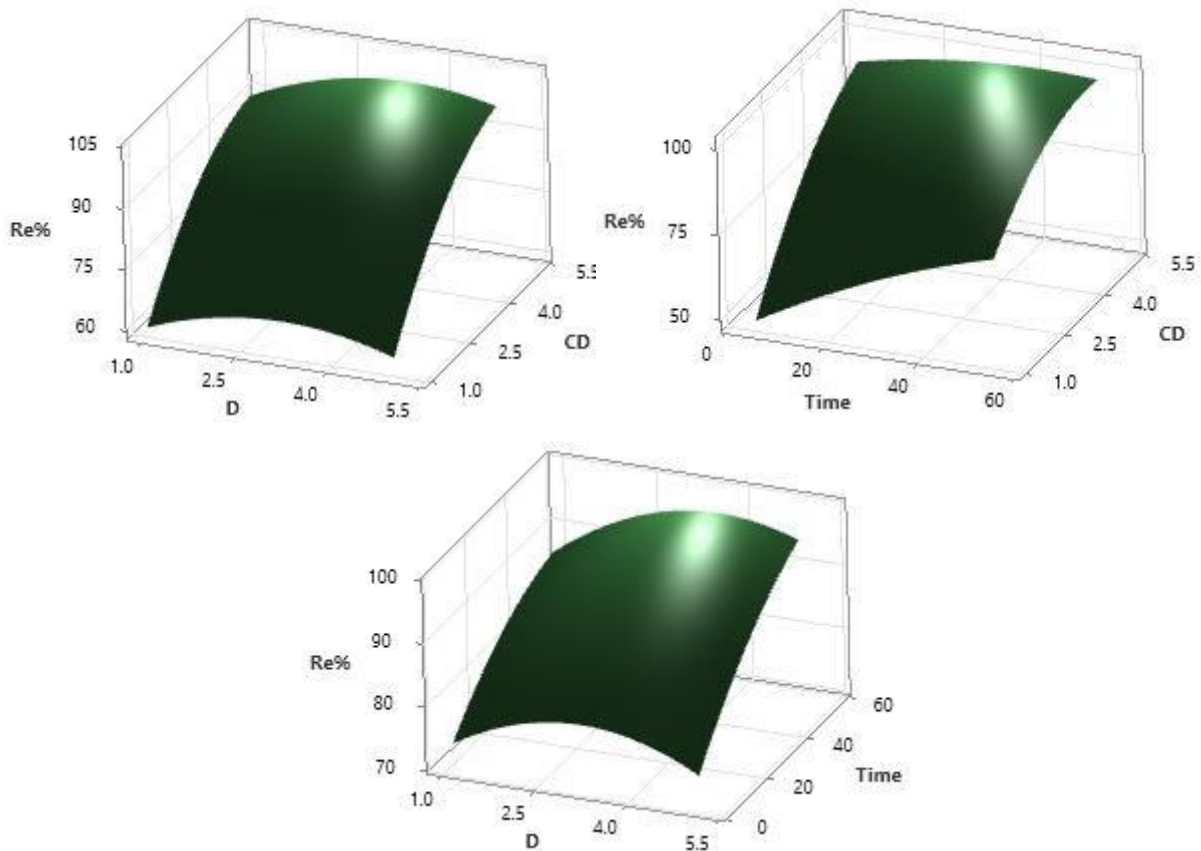


Figure 3. Relationship between the removal efficiency and D, CD and Time.

1. Conclusions

The present experimental and theoretical study investigates the removal of phosphate from water using the electrocoagulation method, considering the effects of the current density, distance between electrodes and treatment time. The results of this study showed that electrocoagulation removes 99.8% of the 20 mg/L of phosphate when the CD is 5 mA/cm², D is 3 mm, and the Time is 55 minutes. The results can give a set of conclusions: the increase in the CD and Time is useful for the removal of phosphate, but the increase in the long D is not useful for the removal of the phosphate. It was also found that the removal of phosphate by the electrocoagulation can be modelled using the Response Surface Methodology (RSM) (a three-factor Box-Behnken design) with R^2 is 0.9779.

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