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Remediation of phosphate-contaminated water by electrocoagulation with aluminium, aluminium alloy and mild steel anodes

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ABSTRACT

The present study provides an electrocoagulation process for the remediation of phosphate-contaminated water using aluminium, aluminium alloy and mild steel as the anodes and stainless steel as the cathode. The various parameters like effect of anode materials, effect of pH, concentration of phosphate, current density, temperature and co-existing ions, and so forth, and the adsorption capacity was evaluated using both Freundlich and Langmuir isotherm models. The adsorption of phosphate preferably fitting the Langmuir adsorption isotherm suggests monolayer coverage of adsorbed molecules. The results showed that the maximum removal efficiency of 99% was achieved with aluminium alloy anode at a current density of 0.2 A dm^{-2}, at a pH of 7.0. The adsorption process follows second-order kinetics.

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1. Introduction

As is well known, eutrophication is one of the main problems nowadays encountered in the monitoring of environmental water sources in industrialized countries. This phenomenon, which is responsible for the dramatic growth of algae occurring in drinking water, is caused by the excess phosphate concentration in the effluents from municipal or industrial plants discharged to the environment. In the countryside, where agriculture and animal husbandry are the main industries, wastes from these activities will contribute to the accumulation of phosphorus in soil and water bodies. These phosphorus compounds, dissolved in surface or groundwaters, are responsible for eutrophication in closed water systems, especially in lakes and enclosed bays where the water is almost stagnant [1]. The U.S. discharge limit of phosphate is 0.5–1.0 mg/L P. The Indian discharge limits for phosphate is 5 mg/L as P [2].

To meet water quality standards, further treatment of water is required. Phosphate removal from wastewater has received considerable attention since the late 1960s [3]. Phosphate removal techniques fall into three main categories: physical, chemical, and biological. Physical methods have proven to be either too expensive, as in the case of electrodialysis and reverse osmosis, or inefficient, removing only 10% of the total phosphate [4]. Chemical treatment is widely used for phosphate removal. The common chemicals used for treatments are aluminium sulfate and ferric chloride. At present, chemical treatments are not used due to disadvantages like high costs of maintenance, problems of sludge handling and its disposal, and neutralization of the effluent [5–7]. In a biological treatment plant, it is necessary to transfer phosphate from the liquid to the sludge phase, and the removal efficiency usually does not exceed 30%, which means that remaining phosphate should be removed by another technique [8]. The phosphate removal from wastewater by adsorption using different materials has also been explored. The major disadvantages of this studied adsorbent are low efficiency and high cost [9–15].

Recent research has demonstrated that electrochemistry offers an attractive alternative to above-mentioned traditional methods for treating wastewaters [16–22]. Electrochemical coagulation, which is one of these techniques, is the electrochemical production of destabilization agents that brings about charge neutralization for pollutant removal, and it has been used for water or wastewater treatment. Usually, aluminium or iron plates are used as electrodes in the electrocoagulation process. Electrochemically generated metallic ions from these electrodes can undergo hydrolysis near the anode to produce a series of activated intermediates that are able to destabilize the finely dispersed particles present in the water/wastewater to be treated. The destabilized particles then aggregate to form flocs [23].

The advantages of electrocoagulation include high particulate removal efficiency, a compact treatment facility, relatively low cost,

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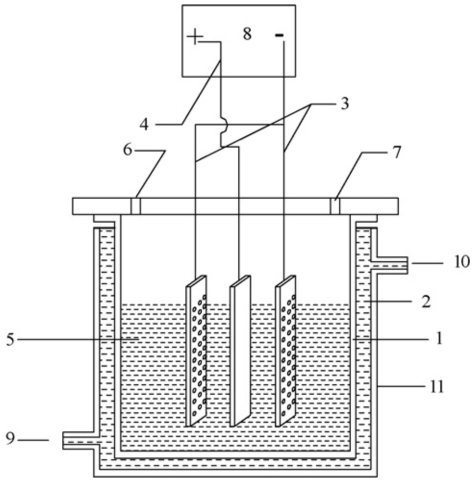

Fig. 1. Laboratory scale cell assembly. (1) Cell, (2) thermostatic water, (3) stainless steel cathode, (4) anode, (5) electrolyte, (6) and (7) holes to introduce pH sensor and thermometer, (8) DC source, (9) inlet of thermostatic water, (10) outlet of thermostatic water and (11) thermostat.

and the possibility of complete automation [24,25]. This method is characterized by reduced sludge production, a minimum requirement of chemicals, and ease of operation [26]. Although there are numerous reports related with electrochemical coagulation as a means of removal of many pollutants from water and wastewater, there is limited work on phosphate removal by the electrochemical method. This article presents the results of the study undertaken on the electrochemical removal of phosphate using aluminium alloy, aluminium and mild steel as the anodes and stainless steel as the cathode. To optimize the conditions, different parameters like effect of the anode materials, effect of initial phosphate concentration, effect of temperature, pH, effect of current density and effect of co-existing ions were studied. The equilibrium adsorption behavior is analyzed by fitting model of Langmuir isotherms. Adsorption kinetics of the electrocoagulants is analyzed using first- and second-order kinetic models.

2. Materials and methods

2.1. Cell construction and electrolysis

The electrolytic cell (Fig. 1) consisted of a 1.0 L Plexiglas vessel that was fitted with a poly-(vinyl chloride) (PVC) cell cover with slots to introduce the electrodes, pH sensor, a thermometer and the electrolytes. Aluminium alloy (consisting of Zn (1–4%), In (0.006–0.025%), Fe (0.15%), Si (0–.15%) (Patented material, CECRI, India), aluminium (Commercial Grade, India) and iron plate (Commercial Grade, India) with a surface area of 0.02 m^2 acted as the anode. The cathodes were a stainless steel (SS 304; SAIL, India; consisting of <0.08% C, 17.5–20% Cr, 8–11% Ni, <2% Mn, <1% Si, <0.045% P and <0.03% S) sheets of the same size as the anode is placed at an interelectrode distance of 0.005 m. The temperature of the electrolyte was controlled to the desired value with a variation of ±2 K by adjusting the rate of flow of thermostatically controlled water through an external glass-cooling spiral. A regulated direct current was supplied from a rectifier (10 A, 0–25 V; Aplab model).

The phosphate (KH_2PO_4) (Analar Reagent) was dissolved in water for the required concentration; A 0.90 L portion of solution was used for each experiment, which was used as the electrolyte. The pH of the electrolyte was adjusted, if required, with 1 M HCl and 1 M NaOH solutions before adsorption experiments.

2.2. Analytical method

The analysis of phosphate was carried out using the yellow vanodomolybdophosphoric acid method by a double beam spectrophotometer according to the Standard Methods for Examination of Water and Wastewater [27].

3. Results and discussion

3.1. Effect of anode materials for the removal of phosphate from drinking water

It is reported that, water treatment with coagulants such as aluminium alum ($Al_2(SO_4)_3 \cdot 18H_2O$), ferric chloride ($FeCl_3$) and ferric sulfate ($Fe(SO_4)_3 \cdot 7H_2O$) are effective in removing phosphate from drinking water. It is also reported that calcium and magnesium salts were tried for removal of phosphate from ground water. Phosphate present in the water will be removed by the adsorption with metal hydroxides produced from the respective coagulants. The main disadvantage for the above process is the presence of anions like chloride and sulfate will reduce the removal efficiency and will increase the total dissolved solids (TDS) in the treated water. So to overcome the above difficulties, in present investigation, aluminium, aluminium alloy, and mild steel are used as anode (for the generation of the coagulants) and stainless steel is used as cathode material. The electrochemical ion generation has several distinct advantages. Coagulants introduced without corresponding sulfate or chloride ions is more efficient at removing contaminants from water. By eliminating competing anions and using a highly pure coagulant source, lower metals residuals are obtained and less sludge is produced than when metal salts are utilized. A contaminant free ion source allows maximum adsorptive removal of the various dissolved forms of metals that could be present and require treatment. Contaminants present in industrial grade ferrous sulfate and aluminium salts end up in either the treated effluent or sludge cake. If flow rates or contaminant loads fluctuate, chemical treatment systems are difficult to operate but it is not in the case of electrochemical process.

During the electrolysis of aluminium (or) aluminium alloy (or) iron, hydroxides of micro-flocs are formed rapidly by anodic dissolution. After the electrolysis process, the water is gently stirred for few minutes for agglomeration of micro-flocs into larger easily setlable flocs. During this flocculation process all kinds of microparticles and negatively charged ions are attached to the flocs by electrostatic attachment. Phosphate is also adsorbed onto coagulated flocs. The possible chemical equations of aluminium and mild steel for the formation of hydroxides are as follows.

At aluminium anode,

Aluminium dissolution:

$$Al \rightarrow Al^{3+} \tag{1}$$

Table 1
Effect of different anode materials for the removal of phosphate from drinking water.

Anode material	Voltage (V)	Concentration of PO_4-P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
Aluminium alloy	1.5	100	1.0	99	7.3
Mild steel	1.8	100	13.0	87	8.1
Aluminium	1.8	100	15.0	85	8.0

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

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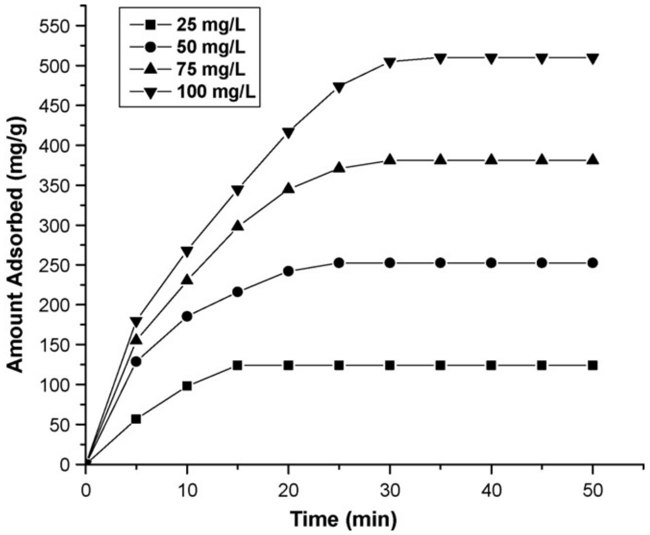

Fig. 2. Effect of agitation time and amount of phosphate adsorbed. Conditions: electrolyte pH: 7.0; electrolyte temperature: 305 K; current density: 0.2 A dm^{-2}.

Aluminium precipitation:

$$Al^{3+} + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ \qquad (2)$$

Like aluminium, mild steel will form hydroxide. Phosphate adsorbed on hydroxide flocs and removed by filtration. From Table 1, it is found that the phosphate removal efficiency is higher in the case of aluminium alloy electrode than aluminium and mild steel. The removal efficiencies for aluminium alloy, mild steel and aluminium are 99, 87 and 85%, respectively. The lower removal efficiency of phosphate in the case of aluminium anode is due to the disadvantages like passive film formation, lower dissolution efficiency, un-uniform dissolution and higher operating voltage with time. These results very much agreed with the earlier results obtained by others, where the aluminium hydroxide was more effective for the removal of phosphate. Hence aluminium alloy is used as anode material for further studies.

3.2. *Effect of initial concentration of phosphate*

As seen from Fig. 2, the adsorption of phosphate is increased with an increase in phosphate concentration and remains constant after the equilibrium time. The equilibrium time was 30 min for all of the concentrations studied (25–100 mg-P/L). The amount of phosphate adsorbed (q) increased from 24 to 97.9 mg as the concentration was increased from 25 to 100 mg-P/L. The figure also shows that the adsorption is the rapid in the initial stages and gradually decreases with the progress of adsorption. The plots are single, smooth and continuous curves leading to saturation, suggesting the possible monolayer coverage to phosphate on the surface of the adsorbent [28].

3.3. *Effect of pH*

It has been established that the initial pH of the electrolyte is one of the important factor affecting the performance of electrochemical process particularly on the performance of electrocoagulation process. To evaluate its effect, a series of experiments were performed, using 100 mg-P/L phosphate-containing solutions, with an initial pH varying in the range 2–10. As illustrated in Table 2, it can be seen that the removal efficiency of phosphate was increased with increasing the pH and the maximum removal efficiency of 99.0% was obtained at pH 7.0. The minimum removal efficiency of phosphate was 61% at pH 10.

Table 2
Effect of pH of the electrolyte for the removal of phosphate from drinking water.

Initial pH of the electrolyte	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
3.0	1.7	100	34.0	66	6.0
4.0	1.7	100	30.0	70	6.5
5.0	1.7	100	23.0	77	6.8
6.0	1.8	100	18.0	82	7.0
7.0	1.5	100	1.0	99	7.3
8.0	1.8	100	16.0	84	8.0
9.0	1.7	100	20.0	80	7.8
10.0	1.7	100	39.0	61	7.9

Conditions: temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}.

The decrease of removal efficiency at more acidic and alkaline pH was observed by many investigators [29,30] and was attributed to an amphoteric behavior of $Al(OH)_3$ which leads to soluble Al^{3+} cations (at more acidic pH) and to monomeric anions $Al(OH)^{4-}$ (at alkaline pH). It is well known that these soluble species are not useful for water treatment. When the initial pH was kept in neutral, all the aluminium produced at the anode formed polymeric species ($Al_{13}O_4(OH)_{24}{}^{7+}$) and precipitated $Al(OH)_3$ leading to more removal efficiency [31–34]. In the present study, the results agree well with the results presented in the literature and the maximum amount of phosphate removal occurred at pH 7.0.

3.4. *Effect of current density*

The amount of phosphate removal and the removal rate have increased by increasing the current density. The removal efficiencies are 68, 72, 88, 92 and 99% for current densities of 0.02, 0.04, 0.06, 0.08 and 0.2 A dm^{-2}, respectively. The results are presented in Table 3. Further, the amount of phosphate removal depends upon the quantity of adsorbent generated, which is related to the time and current density [35,3]. As expected, the amount of phosphate adsorption increases with the increase in adsorbent concentration, which indicates that the adsorption depends upon the availability of binding sites for phosphate.

3.5. *Effect of temperature*

The effect of temperature on the removal efficiency is presented in Table 4. From the results, it is found that, at low temperatures (<305 K) the removal efficiency is less by 29% than that at room temperature. At lower temperatures the dissolution of anode is less and the amount of formation of hydroxide is very low for complexation for phosphate.

Table 3
Effect of current density for the removal of phosphate from drinking water.

Current density (A dm^{-2})	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
0.02	1.0	100	32.0	68	7.1
0.04	1.1	100	28.0	72	7.1
0.06	1.3	100	12.0	88	7.2
0.08	1.3	100	8.0	92	7.2
0.20	1.5	100	1.0	99	7.3

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; duration: 30 min.

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Table 4
Effect of temperature of the electrolyte for the removal of phosphate from drinking water.

Temperature of the electrolyte (K)	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
293	2.2	100	30.0	70	7.8
305	1.5	100	1.0	99	7.1
313	1.4	100	1.0	99	7.2
323	1.2	100	1.0	99	7.2
333	1.15	100	1.0	99	7.3

Conditions: pH of the electrolyte: 7.0; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

3.6. *Effect of co-existing anions*

3.6.1. *Carbonate*

Effect of carbonate on phosphate removal was evaluated by increasing the carbonate concentration from 5 to 250 ppm in the electrolyte. The results are presented in Table 5. From the results it is found that the removal of the phosphate is not affected by the presence of carbonate below 150 ppm. Significant reduction in removal efficiency was observed above 250 ppm of carbonate concentration is due to the passivation of anode (hindering the dissolution process).

3.6.2. *Fluoride*

The concentration of fluoride ion was increased from 2 to 10 ppm, the contaminant range of fluoride in the ground water. The removal efficiency for phosphate was 99, 97, 80 and 77% for 0, 2, 5 and 10 ppm of fluoride ion, respectively. There is no change in removal efficiency of phosphate below 2 ppm of fluoride in the electrolyte. At higher concentrations (above 5 ppm) of fluoride, the removal efficiency decreases drastically. This is due to the preferential adsorption of fluoride over phosphate as the concentration of fluoride increase. The results are presented in Table 6.

3.6.3. *Silicate*

The effect of silicate on the removal efficiency was presented in Table 7. From the results it is found that no significant change in phosphate removal was observed, when the silicate concentration was increased from 0 to 10 ppm. The respective efficiencies for 0, 5, 10 and 15 ppm of silicate are 99, 98, 92 and 88%. The removal of phosphate decreased with increasing silicate concentration from 10 to 15 ppm. Further increase in silicate concentration decreases the removal efficiency. In addition to adsorption, silicate can interact with aluminium hydroxide to form soluble polymers and highly dispersed colloids that are not removed by normal filtration.

Table 5
Effect of addition of carbonate in the electrolyte for the removal of phosphate from drinking water.

Carbonate ion concentration (mg/L)	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
Nil	1.5	100	1.0	99	7.3
5.0	1.8	100	17.0	83	8.1
65.0	2.0	100	22.0	78	8.1
150.0	2.2	100	30.0	70	8.5
250.0	2.7	100	45.0	55	8.9

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

Table 6
Effect of addition of fluoride in the electrolyte for the removal of phosphate from drinking water.

Fluoride ion concentration (mg/L)	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
Nil	1.5	100	1.0	99	7.3
2.0	1.8	100	17.0	83	8.1
5.0	1.9	100	20.0	80	8.2
10.0	1.9	100	33.0	77	8.2

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

3.6.4. *Arsenate*

The effect of arsenate on the removal efficiency was presented in Table 8. From the results it is found that the efficiency decreased form 99 to 80% by increasing the concentration of arsenate from 0 to 15 ppm. This is because arsenate ions are similar with phosphate. Orthophosphoric acid has similar pK_a values (As (V) $pK_{a1} = 2.19$, $pK_{a2} = 6.94$ and $pK_{a3} = 11.5$: H_3PO_4 $PK_{a1} = 2.1$, $pK_{a2} = 7.2$ and $pK_{a3} = 12.3$) and structure properties as that of As (V), which explains the poor removal efficiency of phosphate. So, when arsenate ions are present in the water to be treated arsenate ions compete greatly with phosphate ions for the binding sites.

3.7. *Adsorption kinetics*

The Adsorption kinetic data of phosphate are analyzed using Lagergran rate equation. The first-order Lagergran model is [36]:

$$\frac{dq}{dt} = k_1(q_e - q) \qquad (3)$$

where q is the amount of phosphate adsorbed on the adsorbent at time t (min) and k_1 (min^{-1}) is the rate constant of first-order adsorption. The integrated form of the above equation is

$$\log(q_e - q) = \log(q_e) - \frac{k_1 t}{2.303} \qquad (4)$$

where q_e is the amount of phosphate adsorbed at equilibrium. The q_e and rate constant (k_1) were calculated from the slope of the plots of $\log(q_e - q)$ versus time (t). A straight line obtained from the plots suggests the applicability of this kinetic model. It was found that the calculated q_e values are not agreed with the experimental values (figure not shown here). So the adsorption does not obey the first-order kinetics adsorption.

The Second-order kinetic model is expressed as [37]:

$$\frac{dq}{dt} = k_2(q_e - q)^2 \qquad (5)$$

Table 7
Effect of addition of silicate in the electrolyte for the removal phosphate from drinking water.

Silicate ion concentration (mg/L)	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
Nil	1.5	100	1.0	99	7.3
5.0	1.8	100	2.0	98	8.5
10.0	1.8	100	8.0	92	9.0
15.0	1.9	100	22.0	88	9.2

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

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Table 8
Effect of addition of arsenic in the electrolyte for the removal of phosphate from drinking water.

Arsenate ion concentration (mg/L)	Voltage (V)	Concentration of PO_4–P (mg/L)		Removal efficiency (%)	Final pH
		Initial	Final		
Nil	1.5	100	1.0	99	7.3
5.0	1.5	100	10.0	90	7.5
10.0	1.9	100	15.0	85	7.7
15.0	2.0	100	20.0	80	8.3

Conditions: pH of the electrolyte: 7.0; temperature: 305 K; anode: aluminium alloy; cathode: stainless steel; current density: 0.2 A dm^{-2}; duration: 30 min.

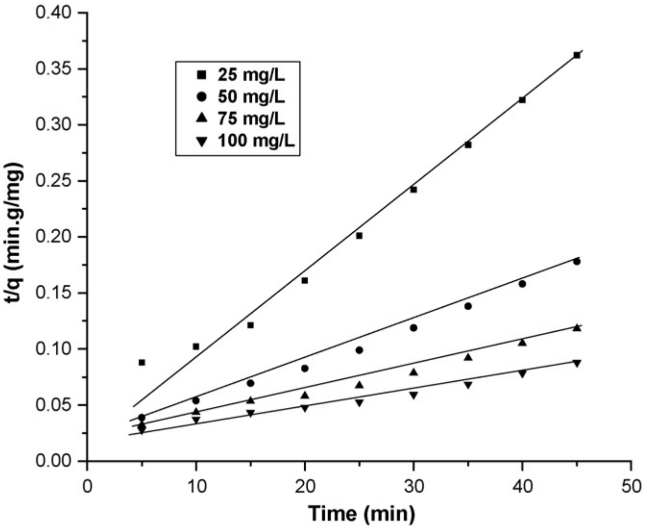

Fig. 3. Second-order kinetic model plot of different concentrations of phosphate. Conditions: electrolyte pH: 7.0; electrolyte temperature: 305 K; current density: 0.2 A dm^{-2}.

where k_2 is the rate constant of the second-order adsorption. The integrated form of Eq. (10) is

$$\frac{1}{q_e - q} = \frac{1}{q_e} + k_2 t \tag{6}$$

Eq. (11) can be rearranged and linearized as

$$\frac{t}{q} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \tag{7}$$

The plot t/q versus time (t) (Fig. 3) shows the straight line. The second-order kinetic values of q_e and k_2 were calculated from the slope and intercept of the plots t/q versus t. The plot shows that the correlation coefficient for the second-order kinetic model obtained in all of the concentrations studies were above 0.99 and also the calculated q_e values agree with the experimental q_e values. Table 9 depicts the computed result obtained from the second-order kinetic model. These results indicate that the adsorption system studied belongs to the second-order kinetic model.

Table 10
Frendlich Constants for the adsorption of phosphate at temperature 305 K and pH 7.0.

Concentration of phosphate (PO_4–P) (mg/L)	K_f (mg/g) (L/g)^n	N	R^2
25	5.4	1.03	0.999
50			
75			
100			

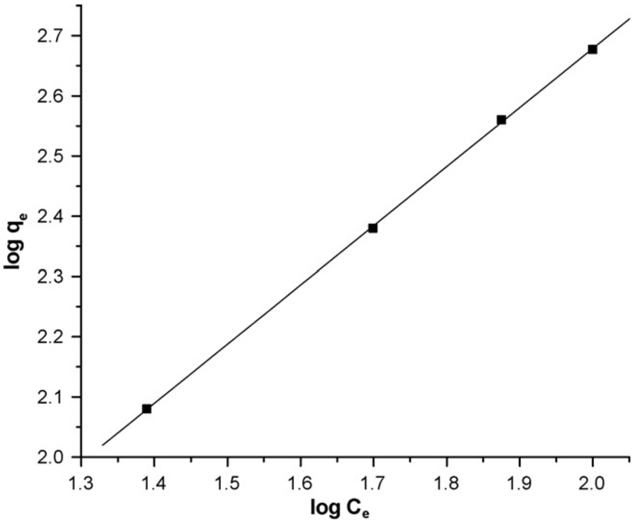

Fig. 4. Freundlich plot (log q_e vs. log C_e). Conditions: electrolyte pH: 7.0; concentration of phosphate: 100 mg-P/L; current density: 0.2 A dm^{-2}.

3.8. Adsorption isotherm

The adsorption capacity of the adsorbent has been tested using Freundlich [38] and Langmuir [28] isotherms. To determine the isotherms, the initial pH was kept at 7.0 and the concentration of phosphate used was in the range of 25–100 mg-P/L. The general form of Freundlich adsorption isotherm is represented by [38]:

$$q_e = KC^n \tag{8}$$

Eq. (9) can be linearized in logarithmic form and the Freundlich constants can be determined as follows [39]:

$$\log q_e = \log k_f + n \log C_e \tag{9}$$

where k_f is the Freundlich constant related to adsorption capacity, n is the energy or intensity of adsorption, and C_e is the equilibrium concentration of the phosphate (mg/L). To determine the isotherms, the phosphate concentration used was 25–100 mg-P/L at initial pH 7.0. The Freundlich constants k_f and n values are presented in Table 10. Fig. 4 shows the Freundlich plot with experimental data. From the analysis of the results it is found that the Freundlich plots fits satisfactorily with the experimental data obtained in the present study.

Table 9
Comparison between the experimental and calculated q_e values for different initial phosphate concentrations in second-order adsorption isotherm at temperature 305 K and pH 7.0.

Concentration of phosphate (PO_4–P) (mg/L)	q_e Experimental (mg/g)	$k_2 \times 10^3$ (g/(mg min))	q_e Calculated (mg)	R^2
25	124	1.78	122.4	0.9929
50	252.6	0.70	242.0	0.9973
75	381	0.22	360	0.9934
100	505	0.01	475.4	0.9915

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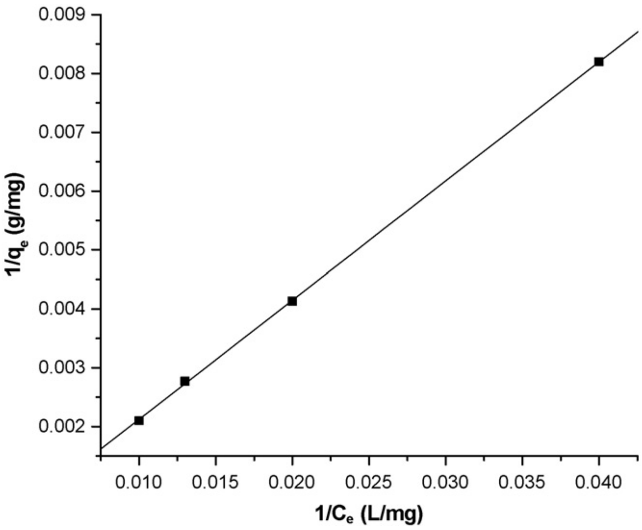

Fig. 5. Langmuir plot $(1/q_e)$ vs. $(1/C_e)$. Conditions: electrolyte pH: 7.0; electrolyte temperature: 305 K; current density: $0.2\,\mathrm{A\,dm^{-2}}$.

Langmuir isotherm is expressed as [40]:

$$\frac{C_e}{q_e} = \frac{1}{q_o b} + \frac{C_e}{q_o} \qquad (10)$$

The linear form of above equation is [41]:

$$\frac{1}{q_e} = \frac{1}{b\,q_e}\frac{1}{C_e} + \frac{1}{q_e} \qquad (11)$$

where C_e is the concentration of the phosphate solution (mg/L) at equilibrium, q_o is the adsorption capacity (Langmuir constant) and b is the energy of adsorption. Fig. 5 shows the Langmuir plot with experimental data. Langmuir plot is a better fit with the experimental data. The value of the adsorption capacity q_o as found to be 10.16 g/g, which is higher than that of other adsorbents studied [28]. The lower value of the adsorption capacity of the adsorbent studied is due to the pH of the solution, which was found to >8.0. This condition is not favorable for the adsorption of phosphate.

The essential characteristics of the Langmuir isotherm can be expressed as the dimensionless constant R_L [42]:

$$R_L = \frac{1}{1 + bc_o} \qquad (12)$$

where R_L is the equilibrium constant, which indicates the type of adsorption b and c_o is the Langmuir constant. The R_L values between 0 and 1 indicate the favorable adsorption. The R_L values were found to be between 0 and 1 for all the concentration of phosphate studied. The results are presented in Table 11.

In the case of mild steel electrode, electrocoagulation-byproduct showed the well crystalline phase such as iron phosphate hydrate, magnetite and iron hydrogen phosphate (Fig. 6). Fig. 7 shows the microscopic image of the anode before and after treatment. The microscopic image indicates the presence of ultrafine particular at micron size on the surface.

Table 11
Langmuir constants for the adsorption of phosphate at temperature 305 K and pH 7.0.

Concentration of phosphate (PO_4–P) (mg/L)	q_0 (g/g)	b (L/g)	R_L
25	10.16	0.494	0.075
50			0.039
75			0.026
100			0.019

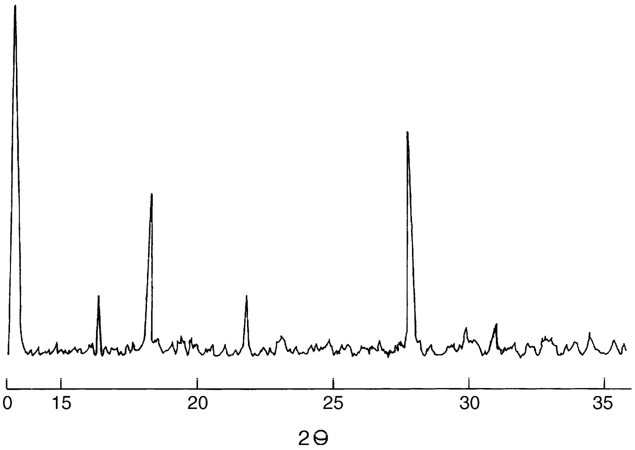

Fig. 6. XRD diffractogram of electrocoagulation-byproduct.

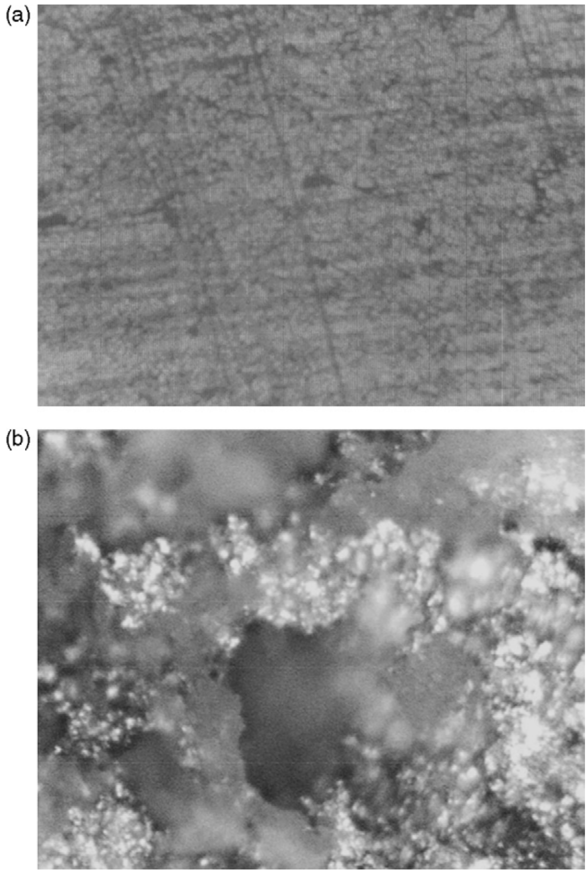

Fig. 7. Microscopic image of the anode (a) before and (b) after treatment.

4. Conclusion

Experiments were carried out to remove phosphate from synthetic solution using tap water. Different operating parameters such as, the anode materials, current density, initial concentration of phosphate, electrolyte pH, and temperature were studied in detail. Electrocoagulation was carried out for 30 min for phosphate concentration as high as 100 mg-P/L and satisfactory removal of 99 was obtained. The results showed that the maximum removal efficiency of 99% was achieved with aluminium alloy anode at a current density of $0.2\,\mathrm{A\,dm^{-2}}$, pH of 7.0. The adsorption of phosphate prefer-

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ably fitting the Langmuir adsorption isotherm suggests monolayer coverage of adsorbed molecules. The adsorption process follows second-order kinetics.

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