Electrocoagulation as a green technology for phosphate removal from river water

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ABSTRACT

The current study investigates the removal of phosphate from water using a new baffle plates aluminium-based electrochemical cell (PBPR) taking consideration the influence of key operating parameters. This new cell utilises perforated baffle plates as a water mixer rather than magnetic stirrers that require extra power to work. As this unit is new, a comprehensive study has been carried to assess it performance. This study also includes preliminary estimates of the reactor's operating costs, the amount of H_2 gas produced and the yieldable energy from it. SEM (scanning electron microscope) was used to investigate the influence of the electrocoagulation process on the morphology of the surface of aluminium electrodes, and an empirical model developed to reproduce the phosphate removal process.

The results showed that 99% of phosphate was removed within 60 min of electrolysis at an initial pH (ipH) of 6, inter-electrode distance (ID) of 0.5 cm, current density (J) of 6 mA/cm^2, initial concentration of phosphate (IC) of 100 mg/L, and minimum operating cost of 0.503 US \$/m^3. The electrochemical cell produced enough H_2 gas to generate 4.34 kWh/m^3 of power.

Statistically, it was proved that the influence of the operating parameters on phosphate removal could be modelled with an R^2 of 0.882, the influence of these operating parameters on phosphate removal following the order: $t > J > IC > ipH > ID$. Finally, SEM images showed that after several electrolysing runs, the Al anode became rough and nonuniform which could be related to the production of aluminium hydroxides.

1. Introduction

Phosphorus is a non-metallic element with the atomic number 15 and an atomic mass of 30.974 amu [13]. It is an important nutrient for the growth of organisms [3]and it is not categorised as a harmful or toxic element for mankind at low concentrations [2]. Phosphorus occurs in the aquatic environment as dissolved phosphate forms such as orthophosphates, polyphosphates and organic phosphate [4,29]. However, the most thermo-dynamically stable and dominant form of phosphate is orthophosphate, which represents about 50% of the total amount of phosphate, other forms comprising the remaining 50% [13,49,51]. Due to the instability of polyphosphate in water, it undergoes chemical reactions converting to orthophosphate making orthophosphate the most commonly identified form of phosphate in the laboratories [13].

Although phosphate occurs naturally in the ecosystems due to the erosion of phosphate containing rocks, its natural cycle has been significantly altered, during the last 50 years, by human activities [6,13]. Since the turn of the last century, the world has witnessed an industrial and agricultural revolution, which has significantly increased the production of waste phosphates. For instance, the agricultural industry in China consumes 300,000,000 kg/year of pesticides to enhance the crop production [65], which in turn produces significant amounts of phosphate-contaminated drainage water. Furthermore, the global overuse of fertilisers and intensive farming practices have made agricultural effluent the major manmade source of phosphate [60,61]. In addition, with the increasing world population, many countries continue to import huge amounts of both animal feeds and phosphate fertilisers, this long history of phosphate-containing products use have built up phosphate levels in the freshwater ecosystems of some developed countries

to least 75% greater than preindustrial levels [6,7]. Beside the agricultural industry, other human activities, such as the consumption of fossil fuel, detergents, cosmetics, and other technical uses, have more than doubled the amount of wasted phosphate into the environment through the municipal and industrial wastewater [7,17].

The excessive concentration of phosphate in water is responsible for several environmental and industrial problems [4]. For instance, the excessive presence of phosphorus, 100 μg P/L, promotes the growth of alga (eutrophication phenomenon), which in turn substantially limits sunlight penetration and the flow of carbon dioxide, subsequently depleting dissolved oxygen in the aquatic environment [5,49]. Industrially, the presence of phosphorus compounds in water results in costly maintenance as it promotes the fouling of water pipes [2] as well as interrupting the removal of other dangerous pollutants such as arsenate [42]. In addition, presence of high concentration of phosphate in drinking water results in many negative human health impacts such as loss of habitat [7]. Therefore, the Environmental Protection Agency (EPA), limits the total phosphate concentration in streams, at the point where they discharge into lakes or reservoirs, to 0.05 mg/L [62]. In terms of drinking water limitations, the total phosphate concentration must not exceed 0.1 mg/L [13].

To meet these limitations, a broad range of technologies have been applied to remove phosphate from water and wastewater, such as adsorption [63,42], microalgae cultivation [61] and reverse osmosis [17]. Among this wide spectrum of phosphate removal methods, interest in electrocoagulation technology (EC) is growing as a promising alternative as it poses advantages that eliminate the drawbacks of traditional methods [27,8,23,9]. For instance, the EC method, which is a process of in-situ generation of coagulants by passing an electric current through metallic electrodes, is characterised by the ease of installation and operation, short treatment time, and the ability to remove very fine particles, as these are more easily attracted to the electric field when charged [35,10]. More importantly, EC technology does not require chemicals additives as the coagulants are freshly produced by eroding the sacrificial electrodes, which in turn prevents the generation of secondary pollutants and significantly reduces the sludge production [27,16,47]. Therefore, the EC method is classified as a green technology for water and wastewater treatment [39]. It has been well documented that EC technology is able to remove as much as 95–99% of various pollutants within a relatively short treatment time [15,46,21,38]. It has been successfully used to purify water of pathogens [46], strontium [40], heavy metals [33], phosphate [4,2], and organic matter [59].

However, the literature indicates that the EC method still has clear deficiencies in terms of both the lack of variety in reactor design and the availability of models for its performance. Its performance is also highly influenced by key operating parameters such as initial pH, current density [28,20].

The aim of the present project is therefore to address some of these gaps in the literature. Carrying out a comprehensive study regarding optimising, assessing and the modelling of the removal of phosphates from water by the EC technology.

2. Objectives

The specific objectives of the current study are:

- To investigate the feasibility of using a new aluminium (Al)-based EC reactor as a phosphate treatment method. This new reactor (PBPR) utilises perforated baffle plates as water mixers, which reduces the need for external magnetic and electrical stirrers that consumes extra power to work. The influence of electrolysis time (t) (0–60 min), initial pH value (ipH) (4–9), current density (J) (2–8 mA/cm^2), electrode spacing (ID) (5–15 mm) and initial phosphate concentration (IC) (50–150 mg/L), will be taking into considerations.
- The development of an empirical model to reproduce the removal

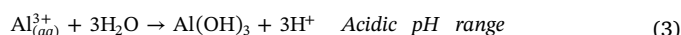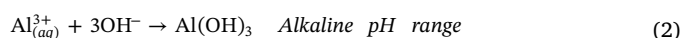process in terms of the influence of the above operating parameters.
- To conduct a preliminary estimation of the reactors' operating costs. This will provide a guide to the operating costs of the removal of phosphate from water by the Al-based EC reactor.
- To calculate how much hydrogen gas (H$_2$) can be produced during phosphate removal, and the yieldable energy from this gas.
- To carry out a SEM (scanning electron microscope) investigation of the influence of the electrocoagulation process on the morphology of the surface of aluminium electrodes.

3. Brief description of electrochemical phosphate removal

Electrocoagulation technology is an electrochemical process that depends on the in-situ generation of coagulants by passing an electric current through a sacrificial metallic anode to destabilise suspended pollutants in an aqueous media, the cathode producing hydrogen gas that floats the pollutants [12,58,24,20]. The type of coagulants generated depends on the material of electrodes, which is selected depending on the characteristics of the targeted pollutants, cost of material and oxidation potential. Although a number of materials have been used as electrodes material in EC reactors, a wide body of literature demonstrates that aluminium is one of the most effective and successful electrode materials [12,24]. Because of this, aluminium (Al) has been used, in the current study, as the electrode material.

As the electric current passes through the Al electrodes, the anode starts the corrosion process producing metal cations that instantly undergo more reactions to form different polymeric metal hydroxides, similar to coagulant salts in traditional chemical coagulation processes [12,4]. These reactions at the Al electrodes and in the solution, can be summarised by the following equations [4,53,1]:

Anode reactions:

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e \tag{1}$$

$$Al^{3+}_{(aq)} + 3OH^- \rightarrow Al(OH)_3 \quad \textit{Alkaline pH range} \tag{2}$$

$$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad \textit{Acidic pH range} \tag{3}$$

Cathode reactions:

$$3H_2O + 3e \Leftrightarrow \frac{3}{2}H_2\uparrow + 3OH^- \tag{4}$$

In case of phosphate present in the solution being treated, it could be precipitated according to the following reaction [5,2]:

$$Al^{3+}_{(aq)} + PO_4^{3-} \rightarrow AlPO_{4(s)} \tag{5}$$

4. Materials and methods

4.1. Reactor construction

The electrochemical phosphates removal experiments have been carried out using a new rectangular electrocoagulation reactor (PBPR), as shown in Fig. 1. This reactor consists of a Perspex rectangular container of net dimensions of length 10 cm, width of 9.5 cm and a height of 7 cm. It is supplied with six parallel-perforated rectangular baffle plates (electrodes) made from aluminium. Each electrode, width of 9.4 cm and a height of 8 cm, has 36 holes (0.4 cm in diameter) distributed in three rows and three 0.7 cm diameter holes distributed at the top and bottom to fix it in the required position. It can be seen from Fig. 1(A) that the three rows of holes in the anode are shifted by 0.4 cm in comparison with those in the cathode, this is to ensure that the water follows in a convoluted path, thereby efficiently mixing the water being treated. The electrodes were held in the required position inside the reactor by 0.3 cm diameter PVC (Polyvinyl chloride) supporting rods.