Renewable Energy 80 (2015) 101–108

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Optimization of process parameters in electrocoagulation treating chicken industry wastewater to recover hydrogen gas with pollutant reduction

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A R T I C L E I N F O

Article history:
Received 16 June 2014
Accepted 15 January 2015
Available online

Keywords:
Chicken industry wastewater
Electrocoagulation
Hydrogen gas
COD reduction
Box–Behnken design
Optimization

A B S T R A C T

Electrocoagulation process (EC) was performed in an upflow blanket reactor (UBR) applying response surface methodology (RSM) based on the Box–Behnken design (BBD) to produce hydrogen gas and reduce the chemical oxygen demand (COD) from chicken industry wastewater. The results showed that RSM based on the BBD was a well-matched method for optimizing of EC to treat chicken industry wastewater. The independent variables such as current density, hydraulic retention time, and electrode surface area of EC process were investigated. Under the optimum conditions such as current density of 15 A/m^2, hydraulic retention time of 30 min and electrode surface area of 5 m^2 resulted in maximum hydrogen gas production (0.8 mL/L) and COD reduction (99%).

1. Introduction

In today's energy demanding life style, there is a need for exploring and exploiting new sources of energy that are renewable, as well as, eco-friendly [1]. Many countries worldwide are still heavily dependent on petroleum as their main source of electricity and transportation fuel, and its price has been setting record highs in recent days [2]. Thus, the only possible solution to this crisis is to find a sustainable (renewable) and economically feasible source of alternative energy. Industrial wastewaters are the one of the low cost feed stocks for the recovery of energy in the form hydrogen gas using green technologies like electrocoagulation (EC). The main reactions occurring at aluminum electrodes during electrocoagulation process are as follows [3]

At the anode, aluminum oxidation occurs,

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

At the cathode, water reduction occurs,

$$3H_2O + 3e^- \rightarrow \frac{3}{2}H_2 + 3OH^- \quad (2)$$

At alkaline conditions,

$$Al^{3+} + 3OH^- \rightarrow Al(OH)_3 \quad (3)$$

At acidic conditions,

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad (4)$$

The standard potential of aluminum dissolution is lower (−1.662 V), than the standard potential of hydrogen evolution, −0.828 V. The dissolution of aluminum is thermodynamically favored ($E_2^o >> E_1^o$) and it should proceed spontaneously. The process occurs in steps during electrocoagulation are as follows; (i) anode dissolution, (ii) formation of OH^- ions and H_2 at the cathode, (iii) electrolytic reactions at electrode surfaces, (iv) adsorption of coagulant on colloidal pollutants, and (v) removal by sedimentation or flotation. The main advantages of EC include no generation of secondary pollution, and compact equipment [4]. Many studies have reported the potentials of electrocoagulation in treating a variety of wastewater; whereas hydrogen (H_2) is a main by-product of the electrocoagulation process as it is generated at the cathodes by water electrolysis. With an effective gas-liquid-solid separation process, high quality hydrogen gas can be

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http://dx.doi.org/10.1016/j.renene.2015.01.030
0960-1481/

recovered from the electrocoagulation process and used as an energy source or as a reactant for industrial processes [5].

In India, Chicken industry wastewater is recognized as one of the organic wastewater and its production was more than 25 billion liter per year. Discharge of this wastewater into the ecological system without pretreatment causes the harmful effects on receiving natural environmental sources [6,7]. Therefore, there is a critical need to find out the proper treatment technique to treat chicken processing industry wastewater. From the literature survey it was found that very limited physico-chemical treatment studies were reported for the treatment of chicken processing industry wastewaters such as chemical coagulation and biological treatment methods [8,9]. But, these treatment techniques were not sufficient to treat chicken processing industry wastewater effectively due its complicated treatment setup and their limited amount of pollutant removal efficiency. Therefore, there is a critical need to develop an effective treatment setup to treat chicken processing industry wastewater [10,11].

However, to our best knowledge, no publications are available on the treatment of chicken processing industry wastewater using electrocoagulation reactor for the recovery of hydrogen gas via response surface methodology (RSM). Hence the objective of the present study has been made to investigate and optimize the individual and interactive effect of process variables such as current density, hydraulic retention time, and electrode surface area on the maximum hydrogen gas recovery and chemical oxygen demand (COD) reduction from chicken processing industry wastewater using Box–Behnken response surface design (BBD) coupled with Derringer's desired function methodology. Response surface methodology (RSM) is a statistical technique for designing experiments, building models, evaluating the effects of several factors, and searching optimum conditions for desirable responses [12]. With RSM, the interactions of possible influencing parameters on treatment efficiency can be evaluated with a limited number of planned experiments.

2. Experimental

2.1. Materials

Wastewater was collected from the local chicken processing industry near Erode, TamilNadu, and was stored at 4 °C prior to the experiments. The characteristic of chicken processing industry wastewater was determined using APHA standard methods and they were shown in Table 1. All other chemicals used in this study were analytical grade and purchased from local suppliers, Erode.

2.2. Experimental procedure

The electrochemical reactor was a 3-L acrylic column with a height of 28 cm and a diameter of 15 cm. It contained a set of 2 pairs of electrodes made of aluminum, which reduced the working volume to 1.5 L. The electrodes were connected vertically with a gap distance of 15 mm. The electrodes were connected in monopolar parallel mode to a DC power supply and the electrochemical reactor was operated in continuous mode with upflow process. The chicken industry wastewater was fed in at the bottom of the reactor, flowed upward through the layers of the electrodes and drained out at the outlet located at the top of the reactor. At the top of the reactor, a conical-shape gas separator was installed and it connected to water displacement apparatus. After experiencing the specified electrocoagulation time, the wastewater was collected at the reactor outlet and it was allowed to stand for 30 min. The supernatant was collected for the analysis of COD reduction. Schematic diagram of the EC is shown in Fig. 1.

Table 1
Characteristics of chicken industry wastewater.

Composition of chicken industry wastewater	
pH	5.4
Turbidity (NTU)	750
BOD (mg/l)	785
COD (mg/l)	4250

2.3. Analytical methods

The volume of hydrogen gas was measured by the water displacement method and the COD reduction was calculated as follows [13]

$$R = \frac{Y_0 - Y}{Y_0} \times 100 \quad (5)$$

where, R is COD reduction (%), Y_0 and Y were initial and final concentrations of COD.

2.4. Experimental design

In this study, Box–Behnken response surface experimental design (BBD) with three factors at three levels was used to optimize and investigate the influence of process variables such as current density, hydraulic retention time, and electrode surface area on the treatment of chicken processing industry wastewater using EC reactor. Process variables and their ranges were determined based on the experimental analysis and they are shown in Table 2. After selection of process (independent) variables and their ranges, experiments were established based on a BBD and the complete design consists of 17 experiments with five center points (used to estimate the experimental error). The total number of experiments was calculated from the following equation [14]

$$N = 2K(K-1) + C_0 \quad (6)$$

where, K is number of factors and C_0 is the number of central point. For statistical calculations, the process variables were coded at three levels (−1, 0 and +1) and the coding was done by the following equation

$$x_i = \frac{X_i - X_z}{\Delta X_i} \quad i = 1, 2, 3 \ldots\ldots\ldots k \quad (7)$$

where x_i, is the dimensionless value of an independent variable; X_i, the real value of an independent variable; X_z, the real value of an independent variable at the center point; and ΔX_i, step change of the real value of the variable i. From the BBD experimental data, a second-order polynomial equation was fitted to correlate the relationship between independent variables and responses. Generalized mathematical form of second-order polynomial equation is given below [15]

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \quad (8)$$

where, Y is the response; X_i and X_j are variables (i and j range from 1 to k); β_0 is the model intercept coefficient; β_j, β_{jj} and β_{ij} are interaction coefficients of linear, quadratic and the second-order terms, respectively; k is the number of independent parameters (k = 3 in this study); and e_i is the error. All the statistical analyses were done with the help of Stat ease Design Expert 8.0.7.1 statistical