Experimental study of batch electrocoagulation treatment of peat water in Sarawak with aluminium electrodes

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Abstract. Peat water is commonly found in the coastal areas of Southern and Central Sarawak. About 39% of the rural communities in Sarawak are yet to receive clean water supply. As such the rural communities depend excessively on rainwater and peat water for domestic usage. However, the usage of untreated peat water for domestic usage may cause harm to human health and well-being as it contains natural organic matters such as humic substances. Electrocoagulation is an environmentally friendly and simple process of water treatment. This research aims to develop a batch electrocoagulation process for treatment of peat water in Sarawak using Aluminium electrodes. The research includes the study on electrocoagulation for peat water treatment, design, and fabrication of batch electrocoagulation process using Aluminium, experimental study for optimum performances of the electrocoagulation, and economic analysis of the electrocoagulation system. Several parameters that affect the performances of the electrocoagulation system are studied such as the inter-electrode distance, number of electrodes, current density and treatment time. The performance of the system is evaluated based on the removal efficiency on turbidity, colour, Chemical Oxygen Demand (COD), Total Organic Content (TOC) and Total Suspended Solid (TSS). The system successfully removes 100% of colour, 93.35% of turbidity, 89.80% of COD, 88.22% of TOC, and 87.50% of TSS by using a current density of 25 A/m² in 80 minutes and 8 Aluminium electrodes with inter electrode spacing of 2 cm. The final quality of treated peat water is determined to be suitable for domestic usage which falls under Class 1 water of the National Water Quality based on the parameters analyzed. The operating cost of 25 A/m² current density for 80 minutes of treatment time by using 8 electrode plates is RM 4.32 per m³ of peat water.

1. Introduction

Electrocoagulation, which is characterized by the in-situ generation of coagulant and hydroxide flocs with high absorption ability, is an environmentally-friendly process for treating wastewater with heavy metal ions and toxic organics [1]. Aluminum is usually used as electrodes and their cations are generated by dissolution of sacrificial anodes upon the application of a direct current [2]. The process is an alternative method to chemical coagulation for many reasons in which the electrocoagulation system capable of reducing the need for additive chemicals [3]. Several reactions occur during electrocoagulation as shown in the Equation (1), Equation (2) and Equation (3).

\[
\text{Al} \rightarrow \text{Al}^{3+} + 3e^- \quad (1)
\]
Sarawak is the largest state in Malaysia with approximately 1.7 million hectares of freshwater peat and approximately 154,000 hectares of mangrove area [4]. Peat water is typically slightly acidic and colored, and contains nutrients such as humic substances and total solids [3, 5]. In Sarawak, the water distribution systems are through the gravity feed water supply streams in which the water are channeled to households through polyethylene (PVC) pipe. Although the water supply by the Water Supply Authority in Sarawak is throughout the state, currently, there are about 61% of the rural areas which are yet to receive clean water [6]. Consequently, some rural communities opt for rainwater and peat water which is available abundantly in Sarawak. Figure 1 shows peat water in Simunjan district, Sarawak.

Figure 1. Peat water in Simunjan, Sarawak

This aim of this research is to develop batch electrocoagulation process for treatment of peat water in Sarawak with Aluminium electrodes. The objectives of the study are to design and fabricate a batch electrocoagulation processing system with selected Aluminium electrodes and conduct experimental analysis for optimum performance of the system. The operating condition such as the electrode spacing, electrode number, current density, and the treatment time of the system is studied based on the removal efficiency of a contaminant in peat water. The presence of heavy metal before and after electrocoagulation treatment is analyzed and the estimation of operating cost of the system is also attempted.

2. Methodology
This section discusses the (i) design and fabrication of electrocoagulation system, (ii) experimental study and (iii) data analysis for the study.

2.1. Design and fabrication of electrocoagulation system
The system is in batch mode and it is comprised of an electrocoagulation reactor with Aluminum electrodes, one electrocoagulation chamber, with one inlet for incoming peat water, two outlets each for treated peat water and cleaning process, DC power supply, one small aquarium pump, a turbidity sensor, and water flow sensor. Figure 2 shows the cross-sectional design of the batch electrocoagulation system by using Autodesk Inventor. The system is designed to ease fabricate and require simple maintenance if it is to be adopted by the local community. The electrocoagulation system design criteria are as follow:
1. Materials are affordable and readily available in the local market.
2. System is easy to be fabricated and maintained.
3. Low fabrication and operating cost.

The base of the electrocoagulation tank is designed in a cone shape so that the sludge and flocs formed can be drained off from the tank easily at the bottom of the cone. The faucet for treated water is
placed at the tank itself, facing front, while the flocs and sludge faucet facing the opposite. The tank is supported with the square acrylic base holder. The dimension of the acrylic base holder is 20 x 20 x 20 cm with a thickness of 0.5 cm. The electrocoagulation tank has a volume capacity of 13 liters. Figure 3 shows the fabricated batch electrocoagulation treatment reactor.

Figure 2. Cross-sectional design of the batch electrocoagulation system

Figure 3. Fabricated batch electrocoagulation reactor

2.2. Experimental study

The experiments are carried to study several factors affecting the electrocoagulation process such as electrode distance, number of plates, current density and treatment time. The experiments are performed in a batch reactor as shown by Figure 3. Peat water is pumped into the tank directly and electrodes are arranged parallel in the tank. Peat water samples are collected from Kampung Sebangkoi Jaya, Simunjan, Samarahan, Sarawak. The volume of peat water is set constant at 10 liters for every experiment and voltage of 30V. Table 1 shows the manipulated variable for each experiment.

Table 1. Manipulated and constant variables for experimental study

| Experiment | Manipulated Variables | Constant Variables |
|------------|-----------------------|--------------------|
| Set 1      | Electrode Distance (cm): 1.0, 1.5 and 2.0 | 1. 80 minute reaction time  
2. 8 electrodes  
3. 5A current  |
| Set 2      | Number of Plates: 3, 5 and 8 | 1. Optimum electrode distance from experiment 1  
2. 80 minute reaction time  
3. 5A current  |
| Set 3      | Current Density (A/m²): 5, 15 and 25 | 1. Optimum number of plates from experiment 2  
2. Optimum electrode distance from experiment 1  
3. 80 minute reaction time  |
| Set 4      | Treatment Time (min): 20, 40, 60 and 80 | 1. Optimum current density from experiment 3  
2. Optimum number of plates from experiment 2  
3. Optimum electrode distance from experiment 1  |

2.2. Data analysis

There are several parameter analyses for treated peat water such as the pH, turbidity, colour, chemical oxygen demand (COD), total suspended solids (TSS), total organic content (TOC), and heavy metals. The tools and equipment used to analyze the parameter are summarized in Table 2.

Table 2. Parameter Analysis

| Parameter | Tools/ Equipment | Method |
|-----------|-----------------|--------|
| pH        | AB150 pH Meter  | -      |
| Turbidity | Hach DR900 Colorimeter | Absorptometric Method |
| Colour    | Hach DR900 Colorimeter | Absorptometric Method |
| COD       | COD Reactor and DR900 | Calorimetric Method |
| TSS       | Hach DR900 Colorimeter | Absorptometric Method |
The performance of the electrocoagulation treatment is measured through the removal efficiency, which can be calculated using then Equation (4) [7]:

\[
\text{Removal Efficiency} = \frac{C_0 - C_i}{C_0} \times 100
\]

(4)

Where,

- \(C_0\) = Initial Concentration in mg/L
- \(C_i\) = Final Concentration in mg/L

Apart from removal efficiency, the economic analysis also is done by calculating the amount of specific electrical energy consumed (SEEC), the amount of electrical energy consumed (EEC), the amount of electrode material consumed during the electrocoagulation, and the operating cost. The specific electrical energy consumed (SEEC) is the amount of electrical energy consumed per unit mass of organic load removed. The equation of SEEC is given as in Equation (5) [8]:

\[
\text{SEEC} = \frac{VIt}{(C_0 - C)Q}
\]

(5)

Where,

- \(V\) = Voltage in Volts, V
- \(I\) = Current in Amperes, A
- \(t\) = Time in Hours, hr
- \(Q\) = Volume of wastewater in Litres, L

The equation to calculate the EEC is given as in Equation (6) [8]:

\[
\text{EEC} = \frac{UIL}{60V}
\]

(6)

Where,

- \(U\) = Applied Voltage in Volts, V
- \(I\) = Current in Amperes, A
- \(t\) = Time in Hours, hr
- \(V\) = Volume of Water in Litres, L

The consumption of electrode material (EMC) is calculated by applying Faraday’s Law [8]. The formula for calculating the EMC is as shown as follows:

\[
\text{EMC} = \frac{ItzM}{ZF}
\]

(7)

Where,

- \(I\) = Current in Amperes, A
- \(t_s\) = Treatment Time in Second, s
- \(M\) = Molecular Mass of Electrode Material
- \(F\) = Faraday’s constant (96485 C/mol)
- \(Z\) = The Valency Ions of the Electrode

The operating cost of the electrocoagulation process is calculated as in Equation (8) following.

\[
\text{OC} = a \times \text{EEC} + b \times \text{EMC} + c \times \text{SEC}
\]

(8)

Where,

- \(a\) = Current Market Prices of Electricity per Kilowatts Hours
- \(b\) = Current Market Prices of Electrode Material per Kilogram
- \(c\) = Current Market Prices of Supporting of Electrolyte per Kilogram

### 3. Result and discussion

This section is divided into 3 parts; (i) effect of inter-electrode distance, (ii) effect of number of electrodes, (iii) effect of current density, (iv) effect of treatment time and (v) comparison of treated water. The optimized parameter is evaluated in term of removal efficiencies due to the differences in initial peat water values for each parameter. Peat water is obtained from the studied location where the water quality varied due to some circumstances. Initial values of peat water are as shown in Table 3.

| Parameter                       | Initial value |
|---------------------------------|---------------|
| Turbidity                       | 15 NTU        |
| Chemical Oxygen Demand          | 49 TCU        |
3.1. Effect of inter-electrode distance

The inter-electrode distance is one of the factors affecting the electrocoagulation treatment process. Figure 4 depicts the trend of the removal efficiency for colour, COD, TOC, TSS and turbidity for different inter-electrode distance. The result shows that a greater gap between the electrodes provides a better reduction in the investigated parameters. The turbidity, which is one of the parameters used to indicate the cloudiness or haziness of the water due to the existent of suspended particles in water also shows declination in the removal percentage of the turbidity. The turbidity of the peat water is reduced from 100%, 92.86%, to 80% when inter-electrode spacing is reduced from 2 cm, 1.5 cm, to 1 cm. The TOC removal efficiency is 86.14% at an inter-electrode distance of 1 cm, 86.29% at 1.5 cm, and 88.22% at 2 cm while the removal efficiency for COD is 93.83% at an electrode spacing of 1 cm, 95.16% at 1.5 cm, and 96.49% at 2 cm as shown in Figure 4. As for the TSS, the removal efficiency increases from 80% to 89.47%, before further increases to 100% of removal at an electrode distance of 2 cm. Thus, an inter-electrode spacing of 2 cm is the most optimal operating condition. The increase in distances between electrodes has reduced the hindrance effect that likely occurred due to the interaction between colloidal particles. The interaction has likely contributed to the poor settling and floatation of the flocs itself. Thus, the best electrode spacing is chosen as the optimum electrode spacing as it provides the best removal efficiency of pollutants from peat water. This result is in correlation to the studies conducted by Shankar et al. [9] and it is further supported by Fadali et al. [10].

### Table 1: Water Quality Parameters

| Parameter          | Value  |
|--------------------|--------|
| Colour             | 451 mg/L |
| pH                 | 6.2    |
| Total Suspended Solids | 8 mg/L  |
| Total Organic Carbon | 73.4 mg/L |

3.1. Effect of number of electrodes

The experiment is conducted with a constant current of 5A, a voltage of 30V and treatment time of 80 minutes. The electrodes are arranged in Monopolar Parallel mode with electrode spacing of 2 cm. Figure 5 shows the removal efficiency against the number of electrodes for COD, colour, TOC, TSS and turbidity. The higher number of plates provide better removal of the studied parameters. This is due to the high total effective area which resulted in higher production of metal ions and hydroxyl at both anode and cathode surfaces. The total effective area increases as the number of electrodes increases. The highest percentage of removal for colour, turbidity, and TSS achieved are all 100%, while the removal percentage of COD and TOC are 96.49% and 88.22% respectively when 8 electrodes are used. While highest pollutant removal efficiency achieved at 8 electrodes, the lowest pollutant removal efficiency is achieved when using only 3 electrodes with 66% of colour removal, 80% of turbidity removal, 93.83% for COD removal, and 86.14% of TOC removal. The removal efficiency increases as the number of plate increases. This is due to the increase of effective area of electrodes in the system which improve the removal efficiency of pollutants. The number of plates affect the current density, mass transfer rate on anode surfaces, rate of evolution of hydrogen on cathode, rate of aluminium ion generation, time of electrolysis and removal percentage [11]. Multiple electrodes provide larger surface area which enhance more anodic oxidation as compared to single configuration of electrodes [12]. Thus, it can be concluded that at electrode spacing of 2 cm, a greater number of electrodes used during the electrocoagulation process provides greater pollutant removal efficiency within the 80-minute treatment time. More metal ions contribute to a greater amount of coagulant generated which aided the coagulation process.
3.3. Effect of current density
Another main factor affecting the performance of an electrocoagulation process is current density. Current density is determined by the current applied and effective electrode areas. Figure 6 illustrates the results of different current densities. The highest percentage of removal is achieved at 25 A/m². This is due to the production of coagulant at the anode electrodes increases when the current density increases. The generation of the coagulant such as Aluminium Hydroxide facilitates the formation of the floc, which is the reason for the improvement in pollutant removal efficiency. The percentage of colour removal from the peat water is 92.27% at a current density of 5 A/m² and increases to 99.26% and 100% when the current density increased to 15 A/m² and 25 A/m² respectively. For the percentage of turbidity removal, the percentage increase from 82.35% to 86.67% when the current density increased from 15 A/m² to 25 A/m² respectively. The result implies that even at lower current density, the considerably high removal efficiency of colour and turbidity from the peat water can be achieved. However, for COD, TOC, and TSS, the results show a similar trend where the pollutant removal percentage increases with the increases in current density. However, at lower current density, the percentage of removal efficiency does not even reach 80%. The removal efficiency of TOC, COD, and TSS when the current density is at 5 A/m² are 72.09%, 43.55%, and 62.50% respectively. From the result, 25 A/m² is chosen as the optimum current density as it provides the highest percentage of pollutant removal efficiency. The increase of current density will increase the formation of Al(OH)₃ coagulant [13]. Current density also influence the growth of flocs which then influence the treatment efficiency of the system [11]. Increasing of current density also decreases the bubble size which helps in resulting a quicker removal of pollutants by hydrogen flotation [14]. Thus, higher current density is favourable.

3.4. Effect of treatment time
The effect of electrocoagulation treatment time is also observed and analyzed. The amount of time used to treat the peat water is highly related to the amount of coagulant being added to treat the peat water. The changes in the water properties such as its turbidity, colour, COD, TOC, and TSS are analyzed and the results are presented in Figure 7. For the first 20 minutes, about 59.87% of colour and 50% of total suspended solids are removed from the peat water. This shows a relatively low percentage of removal efficiency due to the low amount of coagulant produced at the anode electrodes in a short time. The result also shows a much lower percentage of pollutant removal for turbidity COD, and TOC which are 13.33%, 12.24%, and 31.74% respectively. The coagulant generated is insufficient to treat peat water. Due to insufficient coagulant generated in the water at a short period of time, there is a low reaction of coagulant with pollutant to form flocs. As the treatment time increases, more coagulant is being generated at the anode electrodes, while the volume of peat water remained constant throughout the experiment. This explains the increased in the pollutant removal efficiency as more coagulant facilitates the coagulation and flocculation of pollutants in the peat water. By the time when treatment time reaching 80 minutes, the colour of the peat water is removed 100%, while the percentage of removal efficiency for turbidity, COD, TOC, and TSS increased to 93.33%, 89.8%, 88.22%, and 87.50%.
respectively. The concentration of the colour, turbidity, COD, TOC, and TSS in the water reduced significantly for treatment time of 80 minutes. At shorter time, the amount of floc produced is not sufficient to remove the contaminants [15]. Longer treatment times shows a better result due to the sufficient time of reaction.

3.4. Water Quality Standards

The comparison of treated peat water quality is made between the Drinking Water Quality Standard set by the Ministry of Health, Malaysia, and the Malaysia National Water Quality Standards for Class 1 water. Table 4 shows the water quality standard as well as the quality of peat water before and after the electrocoagulation treatment. It is observed that the final concentration of turbidity, colour, and pH for peat water is below the standard limit for drinking water and Class 1 water except for COD and TSS. A longer treatment time would be needed to completely reduce the COD and TSS of the treated water. Based on the result obtained, the final treated water is deemed to be suitable for domestic use especially for cleaning and hygienic purpose as it is within the standard limit for Class 1 water sets by the Department of Environment. The final treated water also shows potential for drinking water for investigated parameters.

Table 4. Result of Treated Water

| Parameter      | Drinking Water [16] | Class 1 [17] | Before Treatment | After Treatment |
|----------------|---------------------|--------------|------------------|-----------------|
| Turbidity (NTU) | 5                   | 5            | 15               | 1               |
| COD (mg/L)     | 0                   | 10           | 49               | 5               |
| Colour (TCU)   | 15                  | 15           | 451              | 0               |
| pH             | 6.5 - 9.0           | 6.5 - 8.5    | 6.2              | 7.0             |
| TSS (mg/L)     | 0                   | 25           | 8                | 1               |
| TOC (mg/L)     | Not Available       | Not Available| 73.4             | 8.65            |

3.6. Economic analysis of electrocoagulation system

The operating cost for the system depends on the current supplied, the voltage supplied, treatment time, and the prices of the electrode material. In this section, the effect of current density and treatment time on operating cost for electrocoagulation treatment is shown in Table 5 and Table 6. The greater current density cost more as higher current being supplied to the system for the treatment process. Meanwhile, in case of different treatment time, the operating cost is directly proportional to the treatment time. This is due to the continuous usage of the power supply during the treatment process.

Table 5. Operating Cost at Different Current Density.

| Current Density, A/m² | Electrical Energy Consumed, kWh/m³ | Electrode Material Consumed, kg/m³ | Operating Cost, RM/m³ |
|-----------------------|-----------------------------------|-----------------------------------|----------------------|
| 5                     | 4.80                              | 0.00000149                        | 0.86                 |
| 15                    | 14.40                             | 0.0000446                         | 2.59                 |
| 25                    | 24.00                             | 0.0000744                         | 4.32                 |

Table 6. Operating Cost at Different Treatment Time.
| Treatment Time, Minutes | Electrical Energy Consumed, kWh/m³ | Electrode Material Consumed, kg/m³ | Operating Cost, RM/m³ |
|-------------------------|----------------------------------|-----------------------------------|----------------------|
| 20                      | 6.00                             | 0.0000194                         | 1.08                 |
| 40                      | 12.00                            | 0.0000388                         | 2.16                 |
| 60                      | 18.00                            | 0.0000583                         | 3.24                 |
| 80                      | 24.00                            | 0.0000777                         | 4.32                 |

4. Conclusion
The performance of the batch electrocoagulation system using Aluminum electrodes is evaluated based on the removal efficiency of several parameters such as colour, turbidity, COD, TOC, and TSS. The result shows that the electrocoagulation process is affected by the inter-electrode spacing, the number of electrodes used during the treatment process, the usage of current density, as well as the treatment time. The best condition to run the electrocoagulation system is found at 2 cm inter-electrode distance using 8 electrode plate, at a current density of 25 A/m², and the treatment time of 80 minutes. The electrical energy consumed at optimum condition is 24 kWh per litres with an operating cost of RM 4.32 per m³. Overall, the electrocoagulation treatment of peat water using the Aluminum electrodes is capable of treating peat water into domestic water within Class 1 water standard set by the Department of Environment.

References
[1] Lu J, Wang Z, Ma X, Tang Q and Li Y 2017 Chemical Engineering Science 165 165-76
[2] Tezcan Un U, Koparal A S and Bakir Ogunveren U 2019 Journal of Environmental Management 90 428–33
[3] Butler E, Hung Y T, Yeh Y L and Ahmad M S 2011 Water 3 495-525
[4] Department of Irrigation and Drainage Sarawak 2018 Resource Centre - Peat Swamp Development
[5] Kuokkanen V, Kuokkanen T, Ramo J and Lassi U 2015 Water Research 79 79-87
[6] The Sun Daily 2018 Sarawak needs RM17b to implement water supply programmes under 11MP and 12MP
[7] Kuokkanen V, Kuokkanen T, Ramo J, Lassi U and Roininen J 2013 Green and Sustainability Chemistry 16 5232-44
[8] Kuokkanen V, Kuokkanen T, Ramo J and Lassi U 2015 Water Research 79 79-87
[9] Shankar B, Singh L, Mondal P and Chand S 2013 Desalination and Water Treatment 52 7711-22
[10] Fadali O A, Ebrahimi E E, El-Gamil A and Alhauer H 2016 Journal of Environmental Science and Technology 9 62-74
[11] Elmenay A E M H, Nassef E, Malash G F and Magid M H A 2017 Egyptian Journal of Petroleum 26 203-8
[12] Kartikaningsih D, Shih Y J and Huang Y H 2016 Sustainable Environment Research 26 150-5
[13] El-Shazly A H, Al-Zahrani A A and Alhamed Y A 2013 Int. J. Electrochem. Sci. 8 3176-85
[14] Can O T and Bayramoglu M 2010 Journal of Hazardous Materials 173 731-6
[15] Nandi B K and Patel S 2017 Arabian Journal of Chemistry 10 2961-8
[16] Ministry of Health Malaysia 2018 Drinking Water Quality Standard
[17] Department of Environment Malaysia 2018 National Water Quality Standards

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