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Experimental Studies on Continuous Electrocoagulation Treatment of Peat Water in Sarawak with Copper Electrodes

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Abstract: Electrocoagulation is an electrochemical wastewater treatment method, which coagulates impurities particles and ions by using electrical current. In Sarawak, freshwater peat covers around 1.698 million hectares whereas the other 154,000 hectares are mangrove. Peat water is the water or moisture produced from these peatland or peat soil. Clean water availability in the rural coastal regions are limited due to the high financial cost of distribution of essential clean water resources to sparse population in the remote areas. Therefore, a cost-effective standalone electrocoagulation system for the treatment of peat water in Sarawak is one of the suggested solutions to this water supply problem. The main aim of this research is to develop a continuous electrocoagulation water treatment system by using copper electrodes to treat peat water in Sarawak. The peat water treated is targeted to achieve at least standard quality for domestic usage and the parameters studied to measure the optimal design of the treatment system are the turbidity, total suspended solids (TSS), total organic carbon (TOC), pH and chemical oxygen demand (COD) of the water treated. The experimental results meet the standard for Raw Water Quality and Drinking Water Quality with an optimum parameter of 20 electrodes, 0.7 cm inter electrodes spacing, current density of 5.99A/m2 and treatment time of 100 minutes. The total operating cost for the optimize parameters is RM 0.11 per litre of peat water. Overall, the treatment of peat water by using continuous electrocoagulation with copper electrodes is feasible.

Keywords: Continuous electrocoagulation process, peat water, copper electrodes

1. Introduction

There are several regions in the rural coastal areas of Sarawak experience water scarcity problems. Despite Malaysia high quantity of water resources [1], water scarcity is still a big problem with no proper solutions. One of the initiatives is to utilize peat water especially for rural coaster areas of Sarawak where peat water is available abundantly.

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Peat water is associated with the surface water formed on peat soil or peatland. Peat soil is defined as highly organic soil that consists of a heterogeneous mixture of partially decomposed plant remains, sand silt content and clay under damp and anaerobic condition [2]. Peat is most commonly located in river valleys and estuaries [3]. The total area of peatland in Sarawak includes freshwater peat of 1.698 million hectare [4]. Fig. 1 shows the peat water of Sarawak which is red-brownish in colour.

Generally, there are three main types of water treatment technologies, which are chemical process, biological process, and physical process. A conventional water treatment plant usually combines the operation of these technologies. EC uses the concept of coagulation, flotation, and electrochemistry. Several advantages of EC overt other technologies are: (i) effective and rapid matter separation compared to coagulation, (ii) no necessary pH control, (iii) coagulant electrogenerated directly and (iv) low operating cost [5].

Studies had proved that using copper electrodes in EC treatment successfully remove various pollutants from water at high efficiency [6]–[8]. Copper electrodes are easy to be ionized in an electrolysis system and the sludge produced have high recycling potential [7]. A comparative study between copper and aluminium electrodes found out that copper has better pollutants removal efficiencies and corrosion at the surface of copper after EC is uniform which is easier to predict [9]. Referring to equations **(1)**, **(2)**, **(3)**, **(4)** and **(5)**, oxidation and reduction process occurred simultaneously during EC treatment using copper electrodes, at which copper cations and copper hydroxide are produced in situ to act as coagulant to remove pollutants [7].

Anodic electrochemical dissolution:

$$Cu_{(s)} \rightarrow Cu^{2+}{}_{(aq)} + 2e^{-} \quad \textbf{(1)}$$

Oxidation of copper electrode:

$$Cu^{2+}{}_{(aq)} + H^{+}{}_{(aq)} + \frac{1}{4}O_{2(g)} \rightarrow Cu^{2+}{}_{(aq)} + \frac{1}{2}H_2O_{(l)} \quad \textbf{(2)}$$

Hydrolysis reaction:

$$Cu^{2+}{}_{(aq)} + 2H_2O_{(l)} \rightarrow Cu\left(OH\right)_{2(s)} + 2H^{+}{}_{(aq)} \quad \textbf{(3)}$$

Cathodic electrochemical reaction:

$$2H^{+}{}_{(aq)} + 2e^{-} \rightarrow H_{2(g)} \quad \textbf{(4)}$$

Overall reaction:

$$2Cu_{(s)} + 3H_2O_{(l)} + \frac{1}{2}O_{2(g)} \rightarrow 2Cu\left(OH\right)_{2(s)} + H_{2(g)} \quad \textbf{(5)}$$

Fig. 1 - Peat water

The main aim of this research is to develop a continuous EC water treatment system using copper electrodes to treat peat water in Sarawak. The peat water treated is targeted to achieve standard quality for domestic use. The objectives of the research are to study and design the EC system to treat peat water, as well as fabricate small scale continuous EC water treatment system by using copper electrode and provide economic analysis of the continuous EC system.

Nomenclature	
COD	Chemical Oxygen Demand
TOC	Total Organic Carbon
TSS	Total Suspended Solids
EC	Electrocoagulation

2. Methodology

The research is conducted in several parts: (i) Literature review, (ii) Site visit and sampling, (iii) Sample analysis, (iv) Design and fabrication (v) Experimental studies and (vi) Data analysis.

2.1 Literature Review

Literature review focuses on the EC system and the peat water treatment system. Besides, this part of the study also discusses on the trend of the past research on EC, as well as identification of the weakness and strength of this system as well as, identifying the problems involving the lack of clean water resources and possible solution to meet clean water demand in rural areas in Sarawak is included in the research.

2.2 Site Visit and Sampling

Water samples are collected with consideration of the location of sampling points, the volume of samplings and proper containment of the samples. Kampung Sebangkoi Jaya, Simunjan district, Samarahan, is chosen as the study location due to its location which is accessible by roads and the community is not connected to the clean water supply. The community used peat water and rainwater for daily purposes.

2.3 Sample Analysis

Samples collected from the study location are analysed for the following parameters as listed in Table 1.

Table 1 - Parameter of peat water analysis with its respective method and apparatus

Parameter	Method	Apparatus name	Apparatus model
COD	Calorimetric method	Colorimeter	Hach DR 900
Turbidity	Absorptometric Method (Method 8237)	Colorimeter	Hach DR 900
Colour	Platinum-Cobalt Standard Method (Method 8025)	Colorimeter	Hach DR 900
TSS	Photometric Method (Method 8006)	Colorimeter	Hach DR 900
TOC	360°C combustion catalytic oxidation method	TOC analyser	Shimadzu TOC-L
pH	-	pH meter	AB150

2.4 Design and Fabrication of Electrocoagulation System

The desktop scale continuous EC system is divided into 3 parts: (i) peat water storage chamber, (ii) EC chamber and (iii) filtration system. Fig. 2 shows the fabricated continuous EC model. The continuous reactor is fabricated from perspex. The electrodes for EC process is powered by a DC power supply. The system also comprises of a small aquarium pump, turbidity sensor and level sensor. The level sensor is programmed to automatically switch off the pump when the level of water in the treated water tank reaches maximum. The turbidity sensor enables the user to view the treated water turbidity displayed on a digital LED display. The design of the system is based on these criteria: (a) Materials used are available readily in the local market; (b) Easy fabrication and maintenance process and (c) Low fabrication and operating cost.

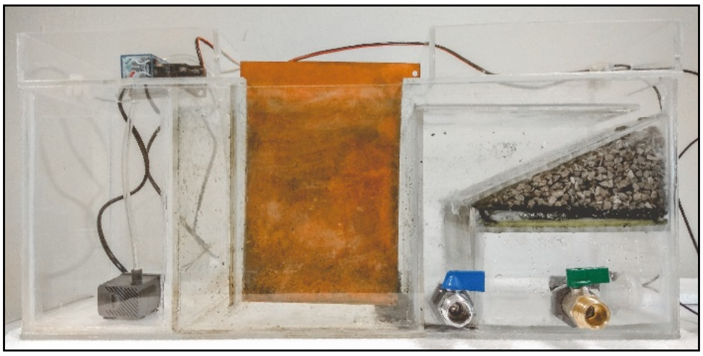


Fig. 2 - Fabricated treatment system front view

Autodesk Inventor is used to design the model of the system. The 3D drawing of the desktop scale EC system is as illustrated in Fig. 3(a) whereas the dimension of the system is as shown in Fig. 3(b). The system begins from the peat water chamber where water is pumped into the EC tank via an aquarium pump. The peat water will gradually enter the EC chamber with and upward movement. The treated water then flows into the filtration system. The filtration system consists of gravels, carbon and fibre sponge.

The overall dimension of the EC treatment system is 53.0 cm length, 15.0 cm width and 20.0 cm height. The maximum capacity for EC treatment is 4.75 litre with 3.6 litre for peat water storage whereas 2.25 litre for treated water storage. The system fabricated is small and portable.

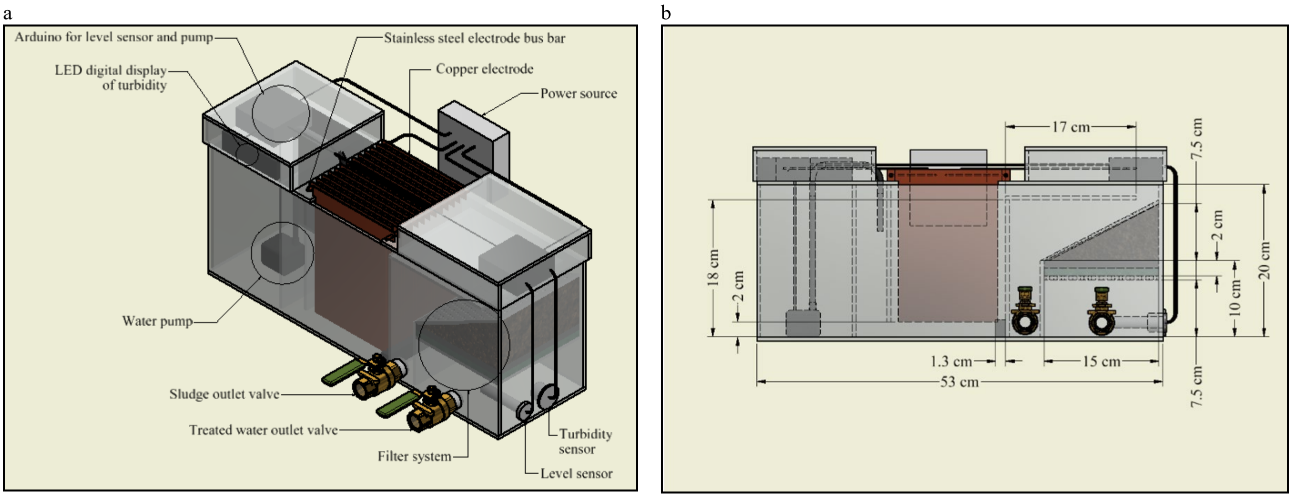


Fig. 3 - (a) 3D drawing electrocoagulation treatments system; (b) Front view of the system

2.5 Experimental Studies

Several sets of experimental studies are conducted by using copper electrode to study on the optimum design for the system including the inter-electrode distance, number of plates, current density and treatment time as shown in Table 2. The EC performance is investigated by analysing the final TOC, COD, TSS and turbidity after treatment of the peat water. 3 set of experiments are conducted as tabulated in Table 2. Experiments are conducted by using the fabricated continuous EC reactor.

Table 2 - Manipulated and constant operating parameters

Experiment	Manipulated variables	Constant variables
Set 1	Inter-electrode distances (0.7 cm, 1.0 cm, 1.5 cm)	1. 7.1 Liter per hour flow rate 2. 100-minute reaction time 3. 10 electrodes 4. 5 A current
Set 2	Number of plates (10, 15, 20 electrodes)	1. Optimum inter-electrode distance from experiment set 1 2. 7.1 Liter per hour flow rate 3. 100-minute reaction time 4. 5 A current
Set 3	Current density ($1.20 A/m^2$, $3.59 A/m^2$, $5.99 A/m^2$)	1. Optimum inter-electrode distance from experiment set 1 2. Optimum number of electrodes from experiment set 2 3. 7.1 Liter per hour flow rate 4. 100-minute reaction time

2.6 Data Analysis

Data analysis is done on; (i) removal efficiency, (ii) amount of coagulant dissolved and (iii) operating cost.

(i) Removal Efficiency

The removal efficiency in percentage for each of the parameters studied is calculated by using equation **(6)** [10]. The result of this experiment is interpreted in graph form.

$$R = \frac{C_0 - C_1}{C_0} \times 100 \quad \textbf{(6)}$$

Where,
R = Removal efficiency (%)
C_0 = The concentration of pollutant before treatment
C_1 = The concentration of pollutant after treatment

(ii) Amount of Coagulant Dissolved

As learned from the previous chapter, dissociation of anode serves as coagulants when current pass through the cell. Faraday's Law can be used to calculate the dissolution of coagulant into the solution as shown in equation **(7)** [11].

$$EMC = \frac{ItM}{ZF} \quad (7)$$

Where,
EMC = Electrode Material Consumption (kg/m^3)
I = Current intensity (A)
t = Time (s)
M = Molecular weight of metal (g/mol)
Z = Number of electrons involved in the oxidation or reduction reaction
F = Faraday's constant (96485 C/mol)

(iii) Operating cost

Electrical energy used and the electrode material affects the operating cost of EC. The electrical energy consumption can be calculated using equation **(8)**, while operating cost can be obtained using general equation **(9)** [12].

$$C_{energy} = \frac{U \times I \times t}{60 \times V} \quad (8)$$

$$\text{OC} = a\ C_{energy} + b\ C_{electrode} \quad (9)$$

Where,
U = is applied voltage in volt (V)
I = applied current in ampere (A)
t = treatment time in minutes
V = volume of treated water (dm^3)
C_{energy} = energy consumption per cubic meter of water (kWh/m^3)
$C_{electrode}$ = consumed electrode for treatment of a cubic meter water (kg/m^3)
a = average cost of copper material (RM/kg)
b = cost of electricity (RM/kWh)

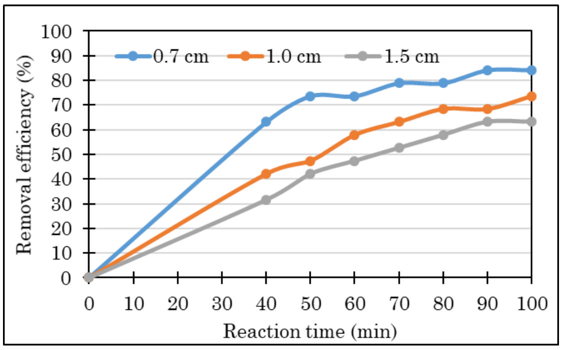
3. Results and Discussion

There are parameters that affect the performance of EC in term of removal efficiency of turbidity, TSS, COD and TOC. The effect of electrode distance, the effect of current density and the effect of treatment time on the performance of batch EC are discussed.

3.1 Effect of Inter-electrode Distance

The constants used in the experiment are 5 A current equivalent to 5.99 A/m^2 current density and 10 electrodes. Three inter-electrode distances are studied which are 0.7 cm, 1.0 cm and 1.5 cm. Fig. 4 shows the result of removal efficiencies against reaction time for 3 different inter-electrode distance. The result shows that by reducing the inter-electrode distance, the removal efficiencies increase with treatment time. The highest removal efficiency is achieved by using 0.7 cm inter-electrode distance where the removal efficiency of 84.21% for turbidity, 83.33% for TSS, 72% for COD and 95% for TOC are achieved after 100 minutes. Apart from that, the experiment resulted in a total removal of peat water colour from a high 459 TCU to 0 with a final pH of 7.

a



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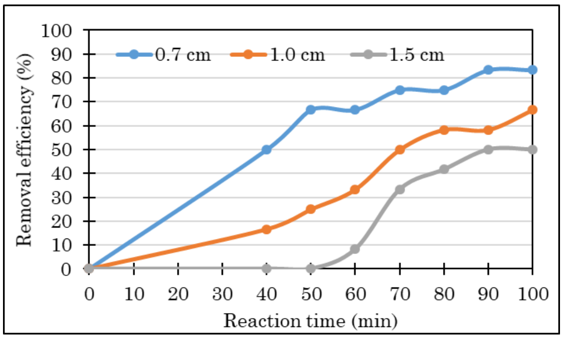

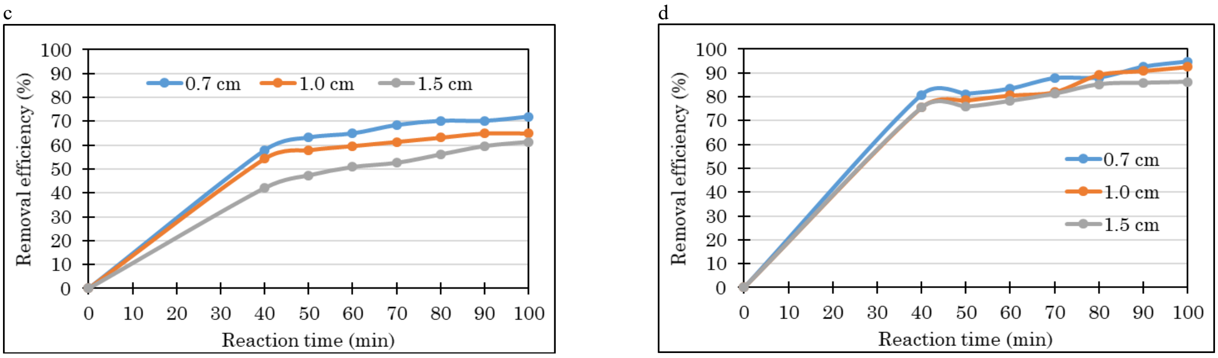

Fig. 4 - Removal efficiency of (a) turbidity; (b) TSS; (c) COD; (d) TOC for different inter electrode distance

Resistance due to copper oxide layer on the surface of anode electrodes affect the removal efficiency. The resistance increases with electrode spacing which is due to the increase in the oxide layer. Increasing of resistance resulted in inquiring greater potential subsequently increasing treatment cost [13]. Ohmic loss is related to the distance travelled by electrons, thus, larger distance, subsequently leads to higher ohmic loss [14]. The interaction of ions with hydroxide polymers is lesser with increasing electrode distance [15]. This suggested that smaller spacing is to be used for the electrodes. Thus, the smallest spacing of 0.7 cm is the most optimized operating parameters for the system.

3.2 Effect of Number of Electrodes

The study is conducted with 10, 15 and 20 electrodes. The best electrode distance of 0.7 cm from the previous experiment is set as the new constant with current of 5 A or 5.99 A/m^2 current density. Flow rate of 6.075 L/hour is maintained. Fig. 5 shows the results for the removal efficiency of different parameters in comparison with the number of electrodes. The higher number of electrodes resulted in better removal efficiencies for all the parameters studied. 20 electrodes able to remove 100% for turbidity, 78% for TSS, 76% for COD and 97% for TOC after 100 minutes of treatment. The treatment system is also able to reduce the pH of peat water from slightly acidic of pH 6.0 to pH 7.0 that is neutral. Hydroxide ions produced from the reaction neutralizes the acidity of water. Other than that, colour is completely removed from 459 TCU to 0 TCU after treatment due to successful coagulation of particles to be removed from the water.

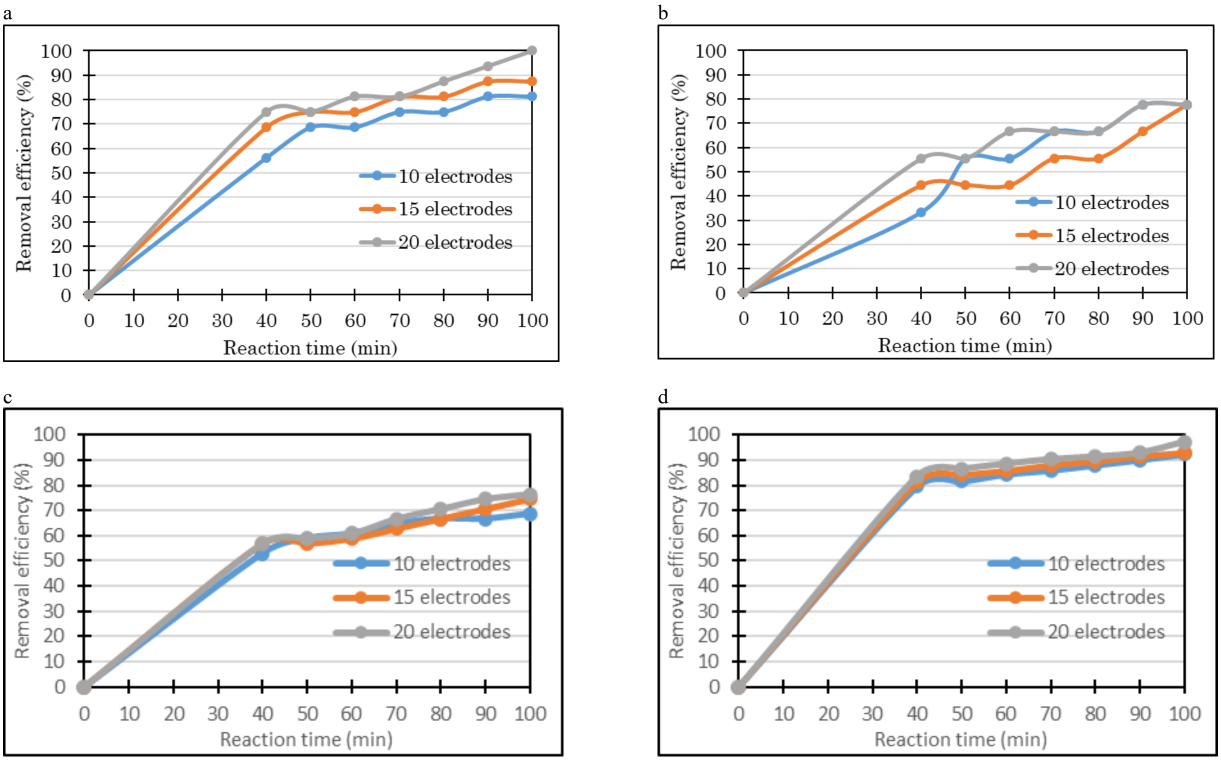

Fig. 5 - Removal efficiency of (a) turbidity; (b) TSS; (c) COD; (d) TOC for different number of electrodes

The increase in the number of electrodes used in a system, increases the effective areas, which then increases the removal efficiency of contaminants. Other than that, the number of electrodes also affected the current density, mass transfer rate on anode surfaces, time of electrolysis and removal percentage [16]. Multiple electrodes provide larger surface area which enhances more anodic oxidation compared to single electrode [17]. These prove that 20 electrodes gives the best efficiency and optimized the performance of the system.

3.3 Effect of Current Density

The optimum parameters from previous experiments are set as the constant of this experiment. The constants are 20 electrodes with 0.7 cm inter-electrode spacing. The current density manipulated are 1.20, 3.59 and 5.99 A/m^2. Fig. 6 shows the results for the removal efficiency of parameters against reaction time for respective current density. The highest current density, 5.99 A/m^2 shows the highest in performance where it successfully removed 100% for turbidity, 90% for TSS, 78% for COD and 97% for TOC. A positive result can also be observed in term of colour removal from peat water whereby the final colour after treatment reaches total removal of 0 TCU. Meanwhile, the pH of initial peat water of acidic pH 6.0 can be reduced to a neutral pH 7.0 after treatment of 100 minutes. The hydroxide ions produced by the reaction neutralizes the acidic peat water.

Current density of a treatment system is the key to control the reaction rate and adjust bubble production in term of size and distribution [18]. Anodic dissolution of copper electrodes is associated with the current density whereby current flow allows redox reaction that produced copper cations and hydroxide which is responsible for the coagulation of contaminants. reported that the current density influences the growth of flocs which subsequently influence the treatment efficiency of the system [16]. In accordance with Faraday's Law (refer to equation **(7)**), current density is directly proportional to the amount of coagulant produced. Higher formation of copper hydroxides increases the removal efficiency due to the occurrence of precipitation and sweep coagulation [19]. Based on the result discussed, it is proven that the higher current density gives better efficiency. Thus, the optimum current density is 5.99 A/m^2 by using 5 A current.

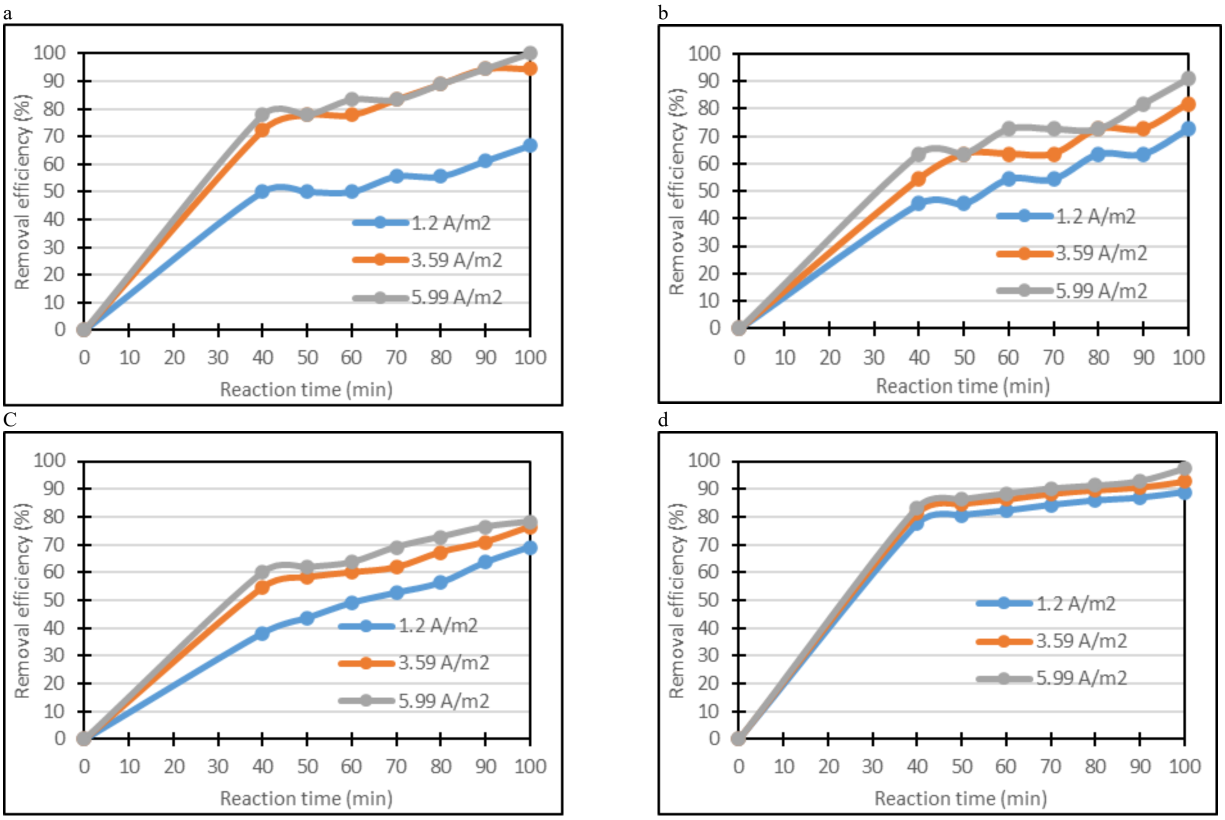

Fig. 6 - Removal efficiency of (a) turbidity; (b) TSS; (c) COD; (d) TOC for different current density

3.4 Comparison to Water Standard Limits

The best result obtained from 20 electrodes with an inter-electrode spacing of 0.7cm, 5.99A/m^2 of current 5A and 30V is compared to the related parameters limit in drinking water standard, recommended raw water standard and water classes standard limits. Table 3 represented the comparisons with drinking water standard by the Ministry of Health [20] while Table 4 shows the comparisons with National water quality standards for Malaysia by Department of Environment [21]. Water sources for drinking must comply with the National Drinking Water Quality Standards guidelines [22].

Table 3 - Comparison of water before and after treatment with drinking water quality standard

Parameter	Before treatment	After treatment	Recommended raw water quality Acceptable value (mg/L unless otherwise stated)	Drinking water quality standards Maximum acceptable value (mg/L unless otherwise stated)
Turbidity (NTU)	18	0	1000	5
TSS (mg/L)	11	2	NA	NA
COD (mg/L)	54	12	10	-
TOC (mg/L)	99	2.7	-	-
Colour (TCU)	459	0	300	15
pH	6	7	5.5 – 9.0	6.5 – 9.0

Table 4 - Comparison of water before and after treatment with national water quality standards for Malaysia

Parameter	Before treatment	After treatment	Class				
			I	IIA/IIB	III	IV	V
Turbidity (NTU)	18	0	5	50	-	-	-
TSS (mg/L)	11	2	25	50	150	300	300
COD (mg/L)	54	12	10	25	50	100	> 100
TOC (mg/L)	99	2.7	NA	NA	NA	NA	NA
Colour (TCU)	459	0	50	150	-	-	-
pH	6	7	6.5 - 8.5	6 - 9	5 - 9	5 - 9	-

Based on Table 3, the parameters such as turbidity, TOC, colour and pH are all within the standard limits of both raw water and drinking water quality. COD and copper metal content, on the other hand, exceed the limits set. COD exceed the limit of raw water quality by 2 mg/L while to be acceptable as drinking water standard, the COD should be completely removed. TSS concentration limit is not listed in the drinking water standard. The treated water quality does not achieve drinking water standard for the parameters studied. Apart from that, to study the suitability of water for drinking, all parameters stated in the drinking water quality standard need to be tested.

Referring to Table 4, turbidity, TSS, colour and pH is lower than the limits set for Class I water and the concentration are much lower compared to limits of water in Class II and above. However, COD exceeded limits in Class I water but lower than the limit set in Class IIA/IIB. Overall, the treated water needs further treatment especially for COD and based on water classes and uses, the treated water is suitable for water supply.

4. Conclusion

The EC treatment process is mainly affected by inter-electrode distance, current density, treatment time and the number of plates. The smaller electrode spacing achieved greater efficiency. The best electrode spacing is 0.7cm. Greater number of plates give a greater removal efficiency and the cost increase is not significant. Thus, the optimum number of plates for the fabricated EC cell tank is 20 plates. Longer treatment time resulted in greater removal efficiency due to the ability to provide sufficient time for particles to coagulate. However, the operating cost is dependent on treatment time whereby cost increases in time. The optimum time is 100 minutes to achieve the highest removal efficiency. The cost to treat the highest treatment time is still very low at RM 0.11 per litre water. Higher current density can achieve a higher removal efficiency as compared to lower current density. However, using a higher current density cost more compared to lower current density. The optimum current density is 5.99A/m^2 of current 5 A and 30 V voltage. The overall cost for operation is below RM 0.11 per litre of peat. The capacity of the EC reactor is 4.7 litres. The pH of initial peat water is pH 6 which is slightly acidic, and the EC treatment can increase the pH to pH 7. Overall, the EC treatment system is feasible to reduce several studied contaminants in peat water. The system that is fabricated using materials available locally is economic.

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