Improving the Quality of Anaerobically-Pretreated Palm Oil Mill Effluent Using Electrocoagulation

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ABSTRACT

The palm oil extraction process generates large amounts of effluents with very high concentrations of pollutants, even though they are subjected to anaerobic pretreatment. Further treatment is needed in order to ensure that the effluent is safe for disposal or reuse. This work was conducted to evaluate the performance of an electrocoagulation process in removing pollutants from the anaerobically-pretreated palm oil mill effluent. A 1000 ml beaker glass equipped with a magnetic stirrer was used as an electrocoagulation reactor with four plates of aluminum electrode @ 12×2 cm and an effective area of 0.1 m^2 arranged in a bipolar configuration. The experiments run in a batch mode were carried out at various voltage levels and contact times, namely 10, 15, and 20 V for 15, 30, 45 and 60 min. The level of pollutant removal and electrical energy consumption were determined. The electrocoagulation process at 15 V for 30 min produced the highest level of pollutant removal for TSS, turbidity, color, COD, and BOD_5, i.e. 90%, 86%, 93%, 87%, and 97%, respectively. The estimated operating costs for these process conditions are 1.48 USD/m^3. A second order empirical model was developed to describe the TSS removal in the POME electrocoagulation process. The electrocoagulation with aluminum electrodes can significantly reduce various types of pollutants of anaerobically-pretreated POME, such as TSS, turbidity, color, COD, and BOD_5. The estimated cost of EC operation is cheaper than the chemical coagulation process.

Keywords: aluminum electrodes; electrocoagulation; empirical model; Palm oil mill effluent (POME); pollutant removals

INTRODUCTION

Palm oil (*Elaeis guinensis* Jacq.) is one of the most important commodities in the Indonesian economy. Indonesia's crude palm oil (CPO) production is growing at 11.5% per year. In 2020, the CPO production is estimated at 49 million tons and palm kernel oil (PKO) at 10 million tons, making Indonesia the highest CPO producer in the world (BPS, 2019). The palm oil industry generates various wastes including oil palm trunks (OPT), mesocarp fibres (MF), empty fruit bunches (EFB), palm fronds, palm pressed fibres (PPF), oil palm kernel shells (OPKS), and palm oil mill effluent (POME) (Liew *et al.*, 2018).The palm oil extraction process generates large amounts of effluents with very high concentrations of pollutants.

The process generates POME 3–4 m^3/ton CPO with COD 44,000–100,000 mg/L, BOD_5 25,000–66,000 mg/L, TSS 18,000–46,000 mg/L, and pH 3.4–5.2 (Wang *et al.*, 2015). POME is a polluted industrial wastewater that may cause harm to the environment if discharged directly due to its biological oxygen demand (BOD) and chemical oxygen demand (COD) (Hossain *et al.*, 2019). POME treatment is generally carried out in anaerobic open ponds. Although simple, inexpensive, low in energy, the systems have shortcomings in terms of long retention time, which is 116–192 days (Rahardjo, 2016), large space, and causing methane emissions. Some mills have implemented a methane capture system. Hasanudin *et al.* (2015) reported that this methane capture system is capable of producing renewable energy

around 25–41 kWh/ton fresh fruit bunch (FFB) and reducing the GHG emissions by 109–175 kg CO_2e/ton FFB. However, the treated effluent still contains high concentrations of pollutants, i.e. pH of 7.5–7.8, color 4,190 PtCo, COD 1,400 mg/L, BOD_5 800 mg/L, and turbidity of 650 NTU (Sidik *et al.*, 2019). These characteristics do not meet the effluent quality standards of the palm oil mill and therefore require further treatment. There are various treatments for managing POME in the palm oil industry. The coagulation method, by means of synthetic chemicals, has been frequently used for managing the effluents generated by a large number of industries. In this method, the colloidal particles are destabilized with chemical coagulants and separated from the liquid phase. However, synthetic or chemical coagulants have such disadvantages as the large amount of sludge produced and the remaining aluminium in treated water that caused the environmental impact (de Souza *et al.*, 2014). Electrocoagulation (EC) has been developed as an alternative which is more environmentally-friendly. In EC, coagulants are formed through electro-dissolution of the anode, commonly aluminium or iron, which causes the destabilization of the pollutants by hydrolysis (Verma and Kumar 2018). Recent studies have shown that electrocoagulation (EC) is an effective alternative to purifying various types of wastewater. This method has various advantages, such as short processing time, occupying less space, no need for chemicals, simple equipment requirement and ease to operation (Butler *et al.*, 2011; Rachmawati *et al.*, 2014; Bharath *et al.*, 2018). In this process metal anodes initiate the electrochemical reactions that provide active metal cations for coagulation, flocculation, and other physical-chemical processes that can eliminate various pollutants. This process has been proven successful in clarifying sugarcane juice (Noersatyo *et al.*, 2020), treating dairy wastewater (Markou *et al.*, 2017), purifying detergent wastewater (Suprihatin and Aselfa, 2020), decolorizing wastewater (Ibrahim *et al.,* 2018); eliminating heavy metals Cu, Cr, and Zn (Singh and Mishra, 2016), and conducting defluoridation of drinking water (Essadki *et al.*, 2010). The EC process is considered as a feasible and environmentally-friendly, as well as a cost-effective technology, with short startup period, simple operation, no addition of chemicals, high removal capabilities, easy collection of the produced sludge, and easy control (Al-Qodah *et al.*, 2020). EC is a combination of the electrochemical and coagulation processes (Kabdaşlı *et al.*, 2012). The process includes oxidation and reduction which can reduce the stability of suspended, colloids, dissolved pollutants, and emulsion breakdown. As a result of the electric current in the electrode cells which are connected to an external power source, the anode oxidation dissolves the electrodes to produce positive metal ions which function as coagulants together with the production of hydroxyl ions and hydrogen gas at the cathode, thereby triggering the formation of floc which easily settles or floats by the hydrogen gas formed. The mechanism for removing various types of pollutants from wastewater has been described and discussed in various publications (Mollah *et al.*, 2010; Marriaga-Cabrales and Machuca-Martínez, 2014; Brahmi *et al.*, 2019). The removal efficiency and electrical energy consumption depends on many factors, including current density, temperature, time, concentration, pH, and materials of electrodes (Islam, 2017; de la Luz-Pedro *et al.*, 2019). The aims of this study were to evaluate the performance of the EC process in further removing the pollutants contained in anaerobically-pretreated POME and to calculate the energy consumption and operating cost of the electrocoagulation method. The empirical models were also developed to describe the EC process for treating the anaerobically-pretreated POME. This study was carried out in Bogor, Indonesia, in 2020.

MATERIALS AND METHODS

Materials and EC reactor

The anaerobically-pretreated POME used in this study was obtained from a CPO processing plant in West Java in January 2020. Visually the effluent was brownish black and very turbid with the characteristics as presented in Table 1.

Table 1. Characteristics of anaerobically-pretreated POME used in this study

Parameter	Unit	Value
pH	-	8.17
TSS	mg/L	785 ± 20
Turbidity	NTU	457 ± 6
Color	PtCo	10,400 ± 70
COD	mg/L	6,000 ± 100
BOD_5	mg/L	2,740

A 1000 mL beaker glass equipped with a magnetic stirrer was used as an electrocoagulation reactor. Four plates of 12×2 cm aluminum electrode with an effective area of 0.1 m² were arranged in a bipolar configuration with the distance between the electrodes of 1 cm. Figure 1 shows the experimental set up that consists of the electrocoagulation reactor, a power supply, and a voltmeter.

Experimental method

All experiments were run in a batch mode. During the electrocoagulation process, the effluent was stirred using a magnetic stirrer at 100 rpm at an initial temperature of 33°C. Two independent variables were examined, namely the electric voltage and the contact time. Three levels of electric voltage, namely 10, 15, and 20 V and three levels of contact time, namely 30, 45 and 60 min were examined. Each experiment was carried out with two replications. After the electrocoagulation process was complete, stirring was stopped and the liquid was left for 1 hour to allow the floc to settle. Afterwards, the samples were taken from the supernatant to measure pH, TSS, turbidity, color, COD, and BOD$_5$. The analysis of the effluent characteristics was carried out by referring to standard procedures, namely TSS, turbidity, color, COD, BOD$_5$, and pH (APHA, 2017).

Data analysis

The experimental data were analyzed statistically and the results were expressed in terms of absolute removal (Ct – Co) or in percentage of pollutant removal, using Eq. (1).

$$R\ (\%) = \frac{(C_0 - C_t)}{C_0} 100 \qquad (1)$$

where: C_0 and C_t are the pollutant concentrations at time 0 and t, and R is the pollutant removal.

On the basis of the experimental results, an empirical model was developed to describe the pollutant removal characteristics which is useful for designing the EC process. In addition, the operational costs estimation of the EC process was also conducted by calculating the electricity and the electrode consumption.

RESULTS AND DISCUSSION

Pollutant removal
TSS removal and turbidity

The effect of electric voltage and contact time on the reduction of TSS is presented in Figure 2. The EC process drastically decreases TSS in the first 30 min, followed by a slight decrease up to 45 min, but there is no significant decrease afterward. The figure also shows that the removal rate of TSS increases along with electric voltage. Under 10 V operating conditions for 30 min there is a reduction in TSS by 76%, whereas at 20 V for 60 min the reduction of TSS can reach 99% with a final effluent TSS of 11 mg/L. The higher the voltage, the greater the electric current produced and the more Al^{3+} ions are formed. As a result, more flocks are formed and more suspended solids can be removed.

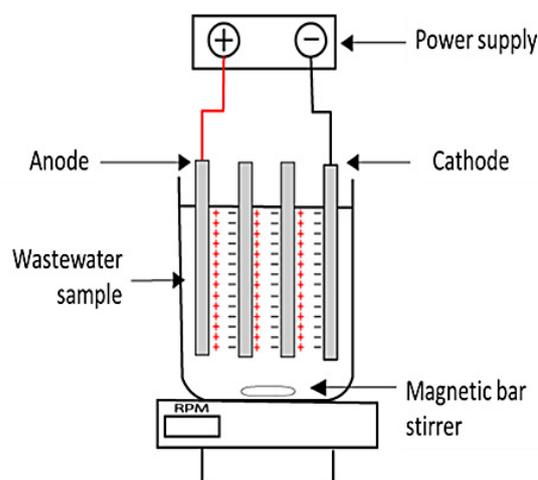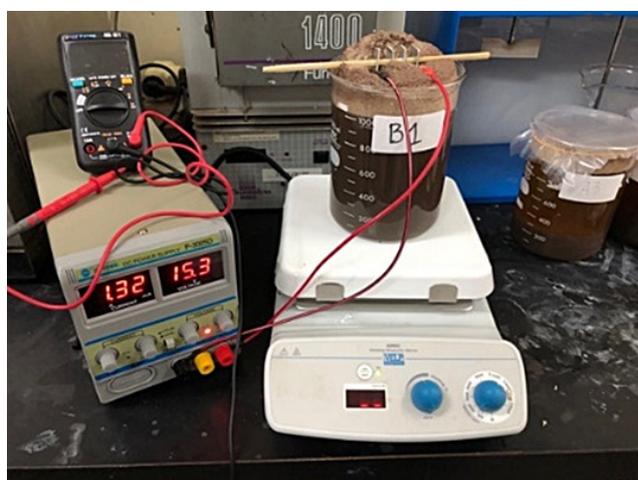Turbidity of wastewater is closely related to organic and inorganic suspended materials and

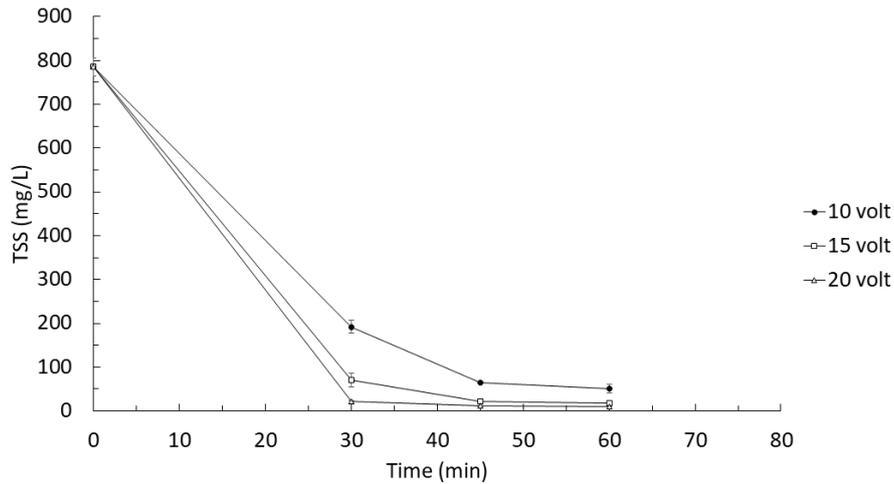**Figure 1.** A schematic diagram of the bipolar configuration of the EC reactor

Figure 2. The effect of electric voltage and contact time on the TSS removal

colloids. This explains that the reduction in TSS is proportional to the reduction in turbidity of wastewater. Figure 3 shows the turbidity reduction profile as a function of the applied voltage and contact time. Similar to the TSS removal profile, turbidity decreases very rapidly in the first 30–45 min of EC, afterwards it decreases only slightly. A similar effect also applies to electrical voltage levels; the higher the voltage, the faster the rate of turbidity decreases. At a voltage of 10 V for 30 min the rate of turbidity reduction is 54%, while at a voltage of 20 V for 60 min, the turbidity reduction can reach 98% which is 4.6 NTU. The same explanation of the TSS removal mechanism also applies to the reduction of turbidity. Cathode electrodialysis produces the Al^{3+} ions which trigger destabilization of suspensions or colloids, formation of larger, stable, insoluble complexes, and finally settle. On the other hand, the reduction of water at the cathode produces the H_2 gas, attaches to and lifts particles or flocs to the surface. As the current increases, higher concentrations of Al^{3+} occur, resulting in a faster removal of the TSS, turbidity, and other pollutants (Markou *et al.*, 2017).

Color

The color of wastewater is caused by the presence of dissolved organic and inorganic materials that can be visually observed or measured on a platinum cobalt (PtCo) scale by comparing the sample color and standard color. The color appearance is influenced by the colloidal particles present in wastewater (Malakootian and Fatehizadeh, 2010), so the decrease in the colloidal
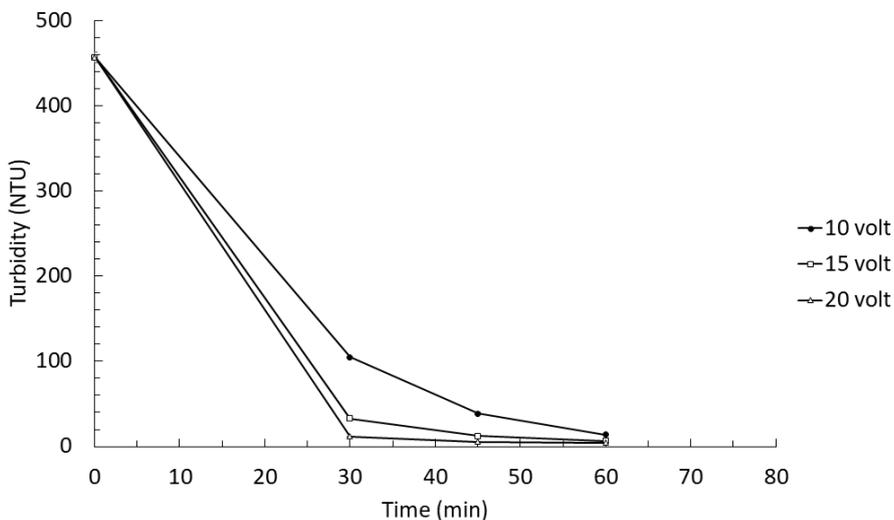

Figure 3. The effect of electric voltage and contact time on turbidity

particles due to coagulation and flocculation causes a decrease in color. The color sources of wastewater include iron ions, manganese oxide, tannins, lignin, and others (Spellman, 2008). As shown in Figure 4, the EC process reduces the color of wastewater by 70% at a voltage of 10 V for 30 min. The highest color reduction of 96% was obtained at a voltage of 20 V for 60 min, namely 375 PtCo. In general, the higher the voltage and contact time, the greater the color reduction. This is due to the higher voltage and longer contact time, which causes that the colloidal particle charge (which is generally negative) becomes neutralized by the Al^{3+} ion formed, so that the suspended particles or colloids are bound to one another. The colloidal particles that bond together will form lumps and settle at the bottom of the reactor more quickly (Islam *et al.*, 2011a; Islam *et al.*, 2011b). Color removal can also be caused by binding of the color-causing compounds by metals, adsorption by floc formed, or deposition of metals due to increased pH. The decrease in color intensity due to EC, visually, can also be seen in Figure 4. The removal of dissolved substances results in color reduction. On the other hand, the operating conditions (such as dissolved oxygen and pH) can oxidize or reduce the color-causing dissolved materials, and certain metals that cause the color of wastewater (Ibrahim *et al.*, 2018).

COD and BOD$_5$ removals

The effects of electrical voltage and contact time on the content of organic pollutants, which are quantitatively expressed in COD and BOD$_5$,

are presented in Figs. 5 and 6. The effluent COD and BOD$_5$ decrease with increasing contact time. The reduction in organic pollutants occurs as a result of colloidal destabilization by the Al^{3+} cations forming polyvalent polyhydroxides. This complex compound has a high adsorption capacity, thus encouraging aggregation with various dissolved pollutants to form larger flocks, which are easier to precipitate. A COD reduction of 80% is achieved at 10 V for 30 min and increased to 91% at 20 V with the same contact time, i.e. at COD 520 mg/L. In terms of BOD$_5$, the EC process at 20 V for 30 min can reduce the effluent BOD$_5$ by 99% or at 32 mg/L. The reduction of COD and BOD results from the removal of suspended and dissolved organic matter, colloid, and emulsion breakdown, complex formation of organic metals, oxidation by oxygen (Kabdaşlı *et al.*, 2012; Bharath *et al.*, 2018; Brahmi *et al.*, 2019).

pH

One important parameter of wastewater quality is pH because of its significant effect on the environment. Figure 7 shows the change in pH for the operating conditions under study. The pH value tends to increase along with voltage and contact time, with the highest value being 8.6 at 15 V for 60 min. increasing the pH of the solution is an advantage of this method compared to chemical coagulation (CC). The CC process tends to reduce pH, especially for wastewater with low alkalinity. The increase in pH in EC can be explained by the following
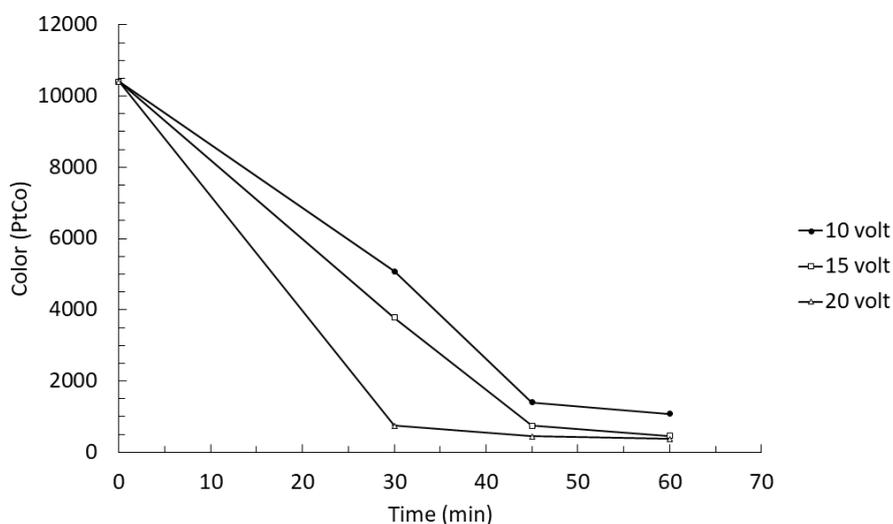

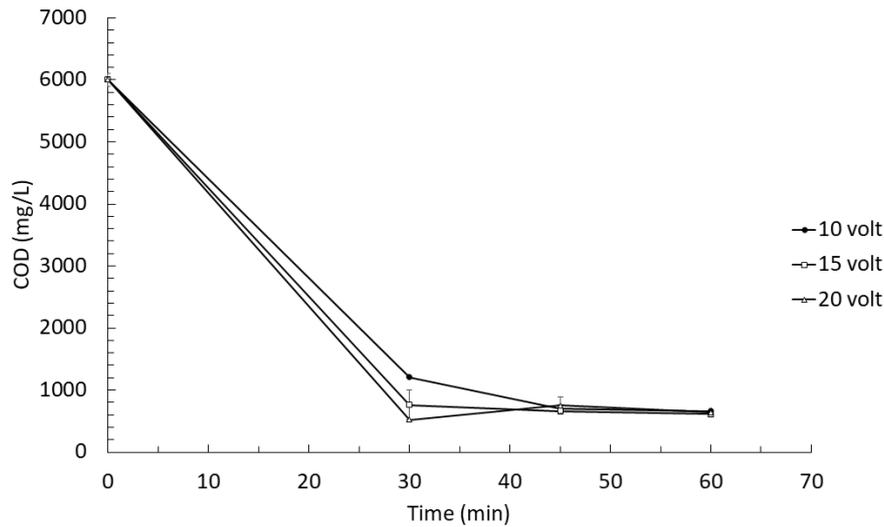**Figure 4.** The effect of electric voltage and contact time on color

Figure 5. The effect of electric voltage and contact time on effluent COD
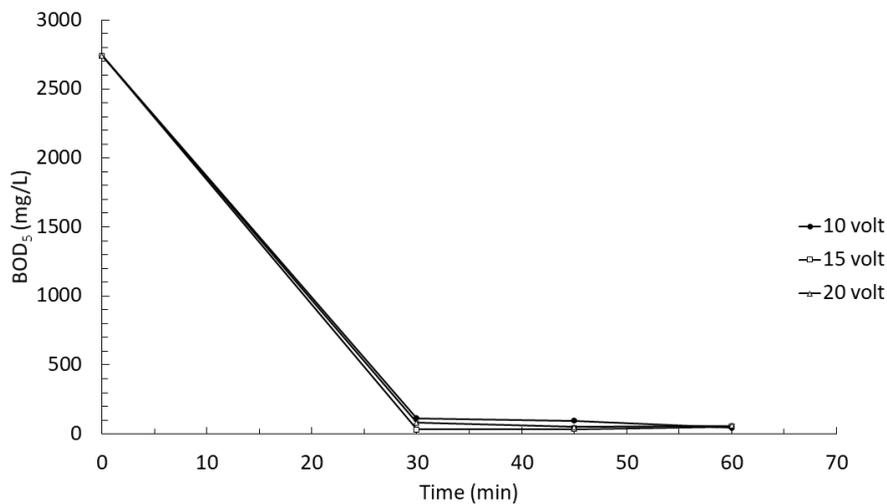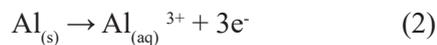

Figure 6. The effect of electric voltage and contact time on effluent BOD$_5$

reaction, where electrolysis of aluminum metal produces the trivalent aluminum ions (Al^{3+}) which also simultaneously produce the OH ions, causing an increase in alkalinity or pH of wastewater, in Eqs. (2) and (3).

$$Al_{(s)} \rightarrow Al_{(aq)}^{3+} + 3e^- \qquad (2)$$

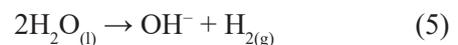$$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al(OH)_{3(s)} + 3H^+_{(aq)} \qquad (3)$$

Cathode electrolysis produces the OH$^-$ ions, tends to increase pH, and causes a variety of additional positive effects, such as decrease the solubility and precipitation of certain metals (Brahmi *et al.*, 2019).

The EC process uses aluminum electrodes in a combination of electrical voltage and contact time applied in this study, as described above, proven to eliminate suspended (insoluble) solids and dissolved pollutants simultaneously. On the basis of these experimental data, a correlation between the TSS reduction and reduced turbidity, color, COD, and BOD$_5$ can be made and the results are presented in Figure 8.

In the EC process with aluminum as an electrode, the electric current passed through the electrode oxidizes Al to its cation (Al^{3+}) and simultaneously reduces water to the OH$^-$ ions and hydrogen gas (H_2) at the cathode. The reactions are presented in Eqs. (4) and (5).

$$Al \rightarrow Al^{3+} + 3e^- \qquad (4)$$

$$2H_2O_{(l)} \rightarrow OH^- + H_{2(g)} \qquad (5)$$

Furthermore, the Al^{3+} cations react with water to form aluminium hydroxide, in Eq. (6).

$$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al(OH)_{3(s)} + 3H^+_{(aq)} \qquad (6)$$
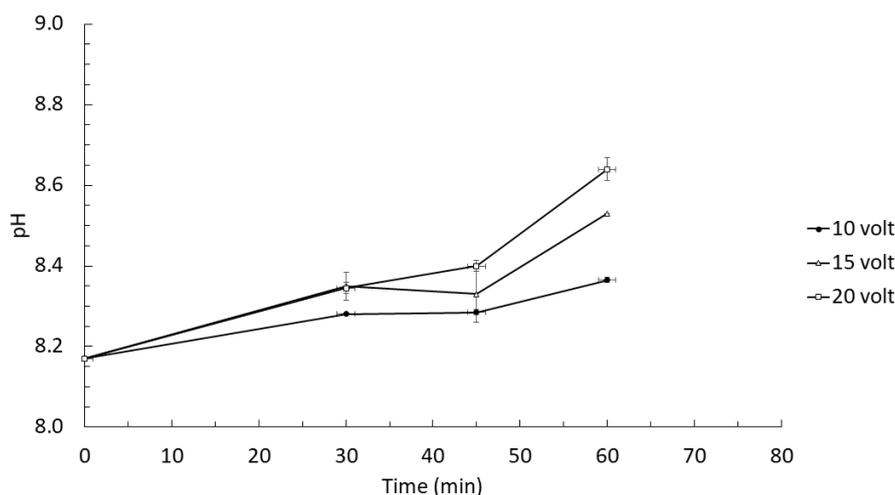
Figure 7. The effect of electric voltage and contact time on effluent pH
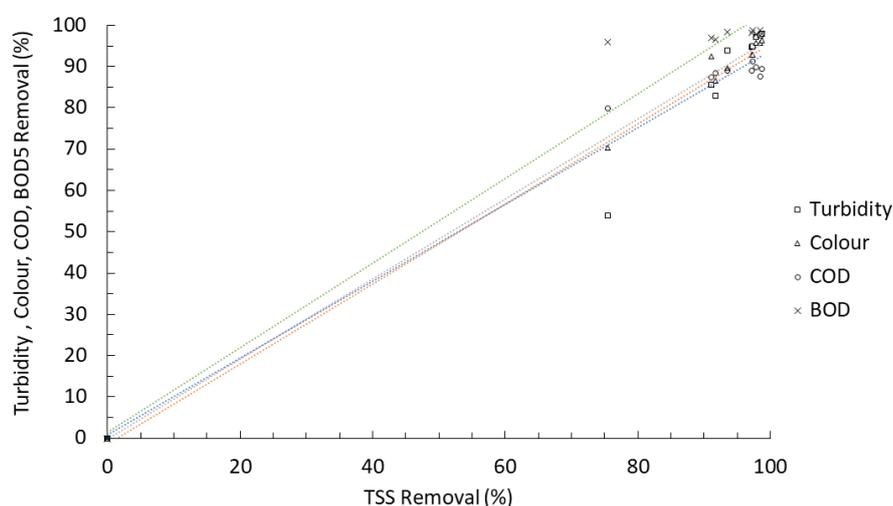

Figure 8. Correlation between the TSS reduction and removal of turbidity, color, COD and BOD$_5$

Aluminum hydroxide, which has a high adsorption capacity, will bind pollutants to form larger flocks and sweep out particles in water. Depending on the reaction conditions, such as oxygen concentration and pH, oxidation or reduction of pollutants can also occur (decolorization). Because H$_2$ is formed, these gas bubbles can also cause electroflotation and particle adhesion (Kabdaşlı *et al.*, 2012). The process of removing pollutants can take place sequentially or synergistically. The dominant process in removing pollutants depends on many factors, such as operating conditions, type of electrodes, and type of wastewater. The mechanisms and processes that might be involved in the removal of pollutants include coagulation, aggregation, flocculation of suspended particles, complexation with metals, precipitation, sedimentation or flotation by the H$_2$ gas.

Characteristics of the EC treated wastewater

The results of EC treatment in various combinations of the operating conditions studied are visually shown in Figure 9. The EC process has changed the appearance of the anaerobically-pretreated POME which was originally turbid and jet black to clear and brown. These figures also show the formation of large amounts of deposits at the bottom of the reactor. In general, the amount of deposits increases along with voltage and contact time. Table 2 presents the results of quantitative analysis of wastewater characteristics before and after EC treatment. It is clear from all the measured quality parameters that the EC process improves the wastewater quality.

Referring to Regulation of the Minister of Environment of the Republic of Indonesia No. 5/2014, except for COD, all parameters of the
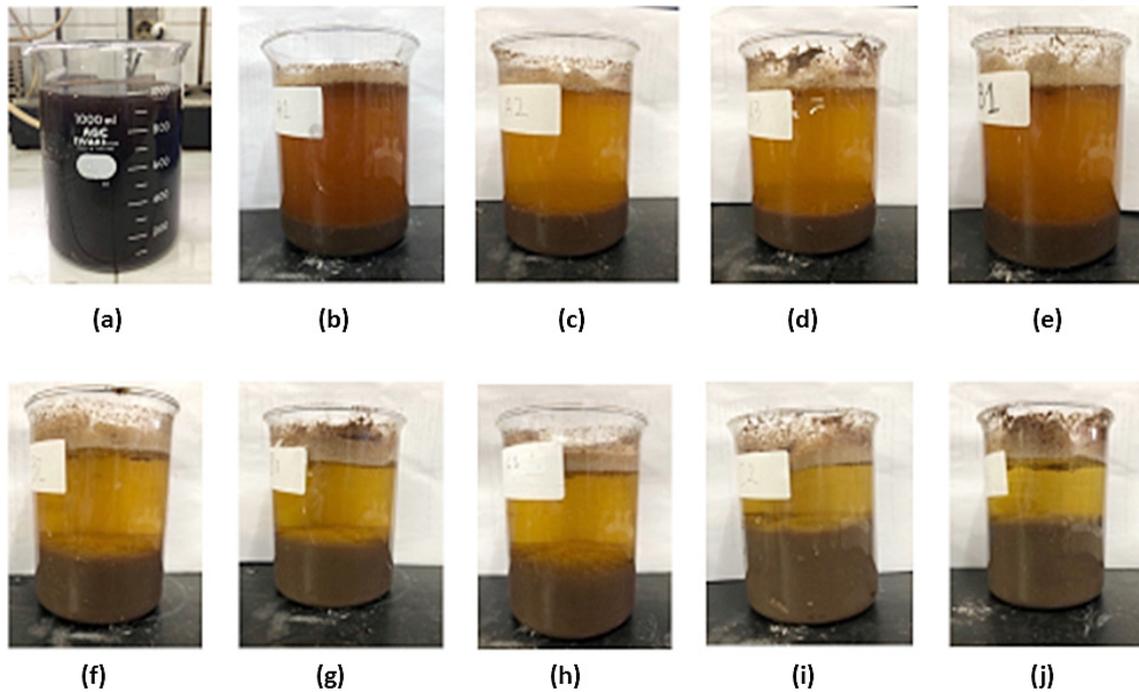
Figure 9. Visual appearance of the anaerobically-pretreated POME before and after EC treatment: (a) before treatment, (b) 10 V for 30 min, (c) 10 V for 45 min, (d) 10 V for 60 min, (e) 15 V for 30 min, (f) 15 for 45 min, (g) 15 V for 60 min, (h) 20 V for 30 min, (i)

wastewater quality have been met through the EC treatment. On the basis of the very small BOD_5/COD ratio ($\approx 0,1$), it is known that the remaining dissolved organic material is difficult to degrade biologically and cannot be removed by the EC process. In order to produce the effluents that meet the standards, further research is currently being conducted using an adsorption method with empty fruit bunches biochar, which is believed to be effective in removing the pollutant residues.

EC kinetic model

First and second order kinetics models developed by Singh and Mishra (2016) and Nwabanne *et al.* (2018) are used to describe the process of removing pollutants, specifically suspended solids. In a batch EC system, the level of pollutant elimination can be stated as Eq. (7).

$$-\frac{dC}{dt} = -r_D \qquad (7)$$

where: R_D is removal rate (mg/L.min) and t is time (min). With the first order model ($r_D = k_1 C$), the integration of equation (7) with the initial concentration (C_0) results in Eq. (8).

$$C_t = C_0 e^{k_1 t} \qquad (8)$$

where: k_1 is the first order-rate constant in min⁻¹. The k_1 is obtained from the plot of Ln C against time *t*, where the value of k_1 is the slope (Figure 10). By plotting the experimental data, the values of k_1 are determined as presented in Table 3.

Table 2. Characteristics of the anaerobically-pretreated POME before and after EC treatment

Parameter	Unit	Before Treatment	After Treatment (at 15 V for 30 min)	Indonesian Standard of Effluent Quality*
pH	-	8.2	8.4	9.0
TSS	mg/L	785 ± 20	70	250
Turbidity	NTU	457 ± 6	33	-
Colour	PtCo	10,400 ± 70	775	-
COD	mg/L	6,000 ± 100	760	350
BOD_5	mg/L	2740	80	100

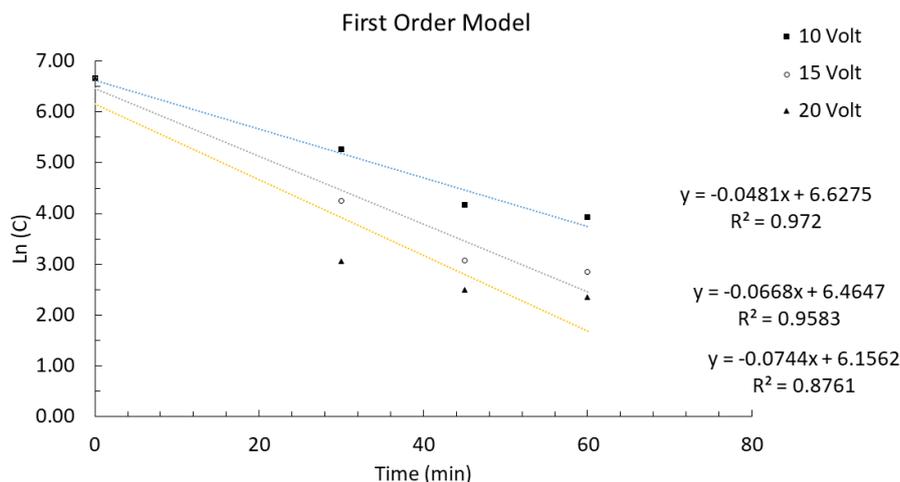* Minister of Environment Regulation No. 5/2014.

Figure 10. Plot of Ln C against time t to obtain k_1

For the second order kinetic model ($-r_D = k_2 C^2$), the concentration dependence on time can be expressed as Eq. (9).

$$\frac{1}{C_t} = \frac{1}{C_0} + k_2 t \qquad (9)$$

where: k_2 is the second order rate constant in $(mg/L)^{-1}min^{-1}$.

A plot of $-1/C$ against time (t) is used to obtain kinetics parameters of k_2, where k_2 can be obtained from the slope of the linear line (Figure 11), as presented in Table 3.

The level of fitting of the kinetic model to the experimental data is determined by using the linear regression coefficient (R^2). From Table 4 it can be seen that the R^2 values for the second order model are in general better than R^2 of the first order model. The R^2 values are more than 0.9 for all levels of the studied voltage. On the basis of these results, it is recommended that a second order kinetics model be used to describe the TSS removal from the anaerobically-pretreated palm POME for the applied voltages of 10, 15 and 20 V. The models can be written as Eqs. (10), (11), and (12).

$$\frac{1}{C_t} = \frac{1}{C_0} + 0.0003.t \qquad \text{for 10 V} \qquad (10)$$

$$\frac{1}{C_t} = \frac{1}{C_0} + 0.0010.t \qquad \text{for 15 V} \qquad (11)$$

$$\frac{1}{C_t} = \frac{1}{C_0} + 0.0016.t \qquad \text{for 20 V} \qquad (12)$$

Figure 12 shows the graphical presentation of second-order kinetics models of TSS removal. The model shows a quantitative relationship between C_o, C_t, and t for voltages of 10, 15, and
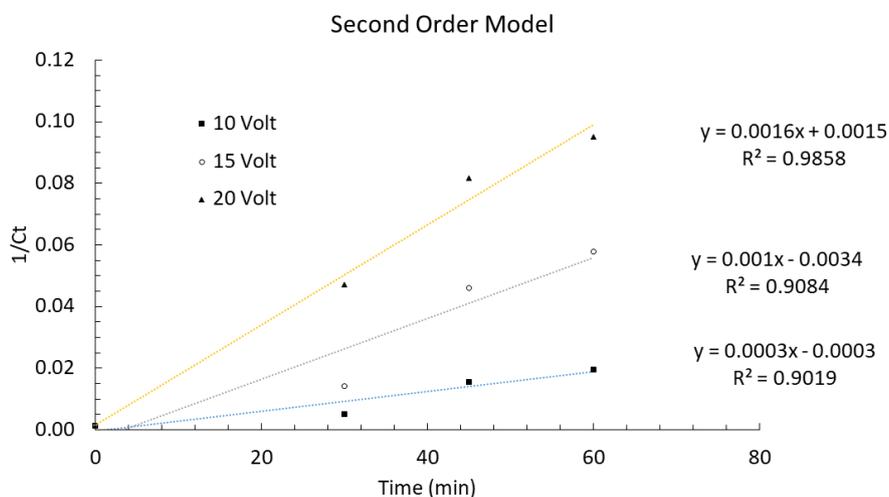

Figure 11. Plot of $-1/C$ against time (t) to obtain the kinetics parameter k_2

Table 3. Values of kinetic parameters of first and second order models with their regression correlation coefficient (R^2) for 10, 15, and 20 V

	First order kinetic model		
	10 V	15 V	20 V
k_1 (min^{-1})	0.0481	0.0668	0.0744
R^2	0.9720	0.9583	0.8761
	Second order kinetic model		
	10 V	15 V	20 V
k_2 (1/(mg/L)·min)	0.0003	0.0010	0.0016
R^2	0.9091	0.9084	0.9858

20 V. With the help of this model, the TSS removal efficiency and C_t can be estimated at various t. In other words, to achieve the value of C_t or certain efficiency, it can be estimated the contact time needed for EC, if C_o is known. With the known t required, the reactor volume (v) can be estimated, if the flow (Q) of effluent is known as Eq. (13).

$$v = Q.t \qquad (13)$$

Energy consumption and operating cost

In contrast to chemical coagulation, where the process for removing pollutants requires chemicals such as aluminum sulfate $Al_2(SO_4)_3$ or poly aluminum chloride (PAC), the EC process does not use coagulant chemicals. However, this process requires electrical energy and electrode replacement in its operations, which are the major operating cost components in the EC process. Electrical energy consumption for electrocoagulation can be estimated with the help of Eq. (14) (Geraldino *et al.*, 2015; Brahmi *et al.*, 2019).

$$W = \frac{V \times i \times t}{v} \qquad (14)$$

where: W is electrical energy consumption (kWh/m^3),
V is voltage (Volt),
i is electrical current (Ampere),
t is contact time (h), and
v is wastewater volume (m^3).

Electrode consumption is estimated using Eq. (15).

$$C = \frac{i \times t \times M}{F \times z \times v} \qquad (15)$$

where: C is electrode consumption (g/m^3),
i is electrical current (A),
t is contact time (s),
M is molecular mass (g/mol),
F is a Faraday constant (96,485 C/mol),
z is number of electron, and
v wastewater volume (m^3).

Thus, the operational costs of the EC process are the sum of the two costs (Eq. 16).
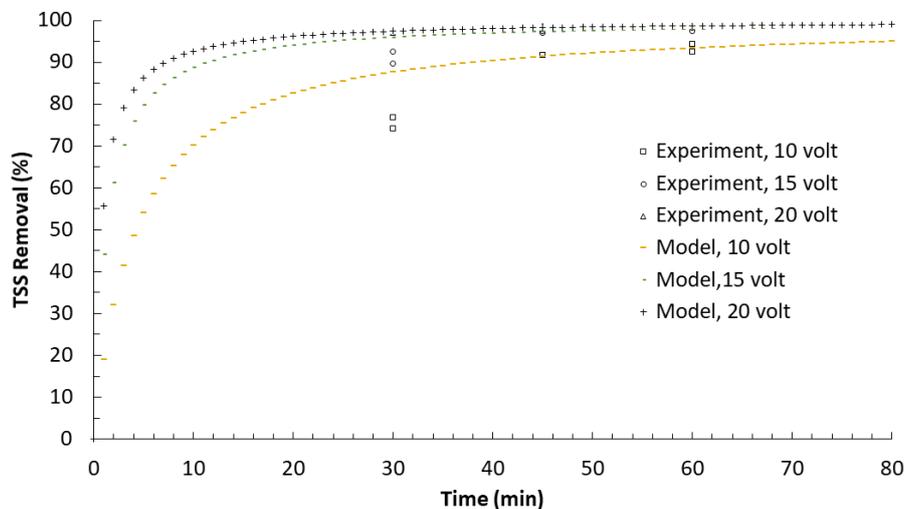

Figure 12. Graphical presentation of second-order kinetics model of the TSS removal

$$B_o = (a.W) + (b.C) \qquad (16)$$

where: B_o is the operational cost (USD/m³),

a is the price of electricity (USD/kWh),

W is the electricity consumption (kWh/m³),

b is the price of aluminum (USD/kg), and

C is the electrode consumption (kg/m³).

Table 4 shows the estimated electrical energy requirements, electrode consumption and operating costs calculated using Eqs. 14, 15 and 16 above. For example, to remove 87% COD, 97% BOD_5, 90% TSS, 93% color, and 86% turbidity with EC operated at 15 V for 30 min requires electrical energy of 10.58 kWh/m³ (0.71 USD) and electrode replacement of 0.2367 kg/m³ (0.76 USD). Thus the total operating costs for the EC process conditions studied range from 1.48 USD to 39480 per m³. Compared with the chemical coagulation method, the EC process requires lower costs and shows better efficiency in removing various pollutants. In comparison, Hassan and Puteh (2007) reported that the POME treatment using chemical coagulation method consumed 8 g/L alum (5.42 USD /m³) with a turbidity removal rate of 99%, COD 49%, and TSS 99%. As shown in Table 4, the electrode costs account for around 50% of the total operating costs. This cost can be reduced or even eliminated, if aluminum scrap is used as an electrode. Recycling and reuse can reduce the processing costs and also reduce the aluminum waste. Furthermore, because POME generally does not contain heavy metals or harmful synthetic organic materials in high concentrations, the precipitate formed from the EC process can be used as an organic fertilizer for agriculture. It should be emphasized here that the operating costs are highly dependent on the EC operating conditions, especially the voltage and contact time. The cost calculation presented in Table 4 is only a rough estimate using a number of assumptions. In order to obtain an accurate calculation, a more specific study need to be conducted by considering the actual local conditions.

CONCLUSION

Electrocoagulation has been developed as an alternative of POME treatment which is more environmentally-friendly and easy to operate. This study shows that electrocoagulation with aluminum electrodes can significantly reduce various types of pollutants of anaerobically-pretreated POME, such as TSS, turbidity, color, COD, and BOD_5. Electric voltage and contact time have been determined to evaluate the electrocoagulation performance in term of pollutants removal. The elimination rate of pollutants increases along with the electric voltage and contact time. The higher the voltage, the greater the electric current produced and the more Al^{3+} ions were formed. As a result, more flocks were formed and more suspended solids could be removed. The longer contact time, causing more suspended particles bound to one another and settle at the bottom of the reactor more quickly. The rate of pollutant reduction significantly occurs during the first 30 min, after which the rate of decline is no longer significant. The EC process at a voltage of 20 V and a contact time of 30 min can reduce TSS, turbidity, color, COD, and BOD_5 by 90%, 86%, 93%, 87%, and 97%, respectively. The removal of TSS from anaerobically-pretreated POME can be explained by a second-order kinetics model. From experimental data, the kinetic constant is calculated to have a value between 0.0003 to 0.0016 mg/L/min for a voltage range of 10–20 V, so that the relationship between the effluent TSS concentration, influent TSS concentration, and contact time can be determined quantitatively. This kinetic model can be used to evaluate the level of TSS removal in EC

Table 4. Estimation of EC operating costs

Component	Operating Condition 1	Operating Condition 2
Voltage (V)	20	15
Contact time (min)	30	30
Electrical current (A)	2.2	1.4
Energy consumption (kWh/m³)	22	10.6
Cost of energy (USD/m³)	1.49	0.71
Electrode Consumption (kg/m³)	0.37	0.24
Cost for electrode (USD/m³)	1.19	0.76
Operating cost (USD/m³)	2.67	1.48

* Electrode price: 3.22 USD/kg

systems and to determine the volume of reactors needed to treat wastewater with known flow rates and TSS levels. The cost analysis shows that the operating costs of the EC process are estimated to range 1.48 USD,- to 2.67 USD per m³ to achieve the desired level of pollutant removal. This cost is cheaper than that of chemical coagulation. The results of this study can be used as a basis for optimizing and scaling up on a continuous EC system. The development of more advanced effluent treatment methods is still needed, especially for the recycling purposes. Further research on the EC processes should consider other factors, including current density, temperature, and electrode materials.

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