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Treatment of Palm Oil Mill Effluent by an Integrated Aeration–Bipolar Electrocoagulation System

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Abstract

Electrocoagulation (EC) has increasingly been used in wastewater treatment, including palm oil mill effluent (POME), due to its ease of operation and less sludge production. In this study, POME was treated using an integrated aeration and EC process, which was conducted continuously at a constant flow rate of 500 mL.min^{-1}. The agitation process was applied in the EC reactor at a rotating speed of 20 rpm to shorten the electrolysis reaction time. The EC reactor was equipped with 6 electrodes as baffles. Two current densities (12 and 15A.m^{-2}) and electrode configurations (3A-3C and 2A-2C-2B) were used, and the resulting effluents were compared. The experimental results showed that the highest contaminant removal was achieved with the electrode configuration 2A-2C-2B and the current intensity was 15 A. The BOD removal efficiency was 91.36% (from 132 to 11.4 mg. L^{-1}), COD of 81.27% (from 386 to 72.3 mg. L^{-1}), TDS of 47.64% (from 645.5 to 338 mg. L^{-1}), TSS of 76.27% (from 43.7 to 10.4 mg. L^{-1}), and turbidity of 96.46% (from 59.65 to 2.11 NTU). Meanwhile, the total energy requirement was 21.33 kWh.m^{-3} with the pH of the effluent of 8.05. The combination of aeration-EC can be used as an alternative POME treatment to achieve high contaminant removal efficiency.

Keywords: Aeration, electrocoagulation, high-removal efficiency, POME treatment

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INTRODUCTION

Electrocoagulation (EC) has increasingly been used in wastewater treatment due to its ease of operation, less chemical addition, small space requirement, and lower sludge production compared to conventional chemical processes (Lu *et al*., 2021). The EC process involves an electrolysis reaction generated by the presence of an electric current and a pair of electrodes, namely anode and cathode (Nugroho *et al*., 2020). Numerous studies have been published on the advantages and disadvantages, reactions, and coagulation mechanisms that occur in the EC process (An *et al*., 2017; Naje *et al*., 2017; Sadik and Sadik, 2018). When using aluminum (Al) as electrodes, Al^{3+} ions are produced from the anodes and then transformed to amorphous aluminum hydroxide ($Al(OH)_{3(s)}$) as the coagulant. Al^{3+} destabilizes the pollutants by charge neutralization, which is adsorbed by the $Al(OH)_3$ to form flocs that are then precipitated (Rafiee *et al*., 2020). Researchers have conducted numerous studies to optimize operating conditions to achieve high efficiency of contaminant removal either in a single application or combined with other separation processes (Djajasasmita *et al*., 2022; Ika Pratiwi *et al*., 2021; Moradi and Moussavi, 2019; Nugroho *et al*., 2019).

In the palm oil industry, the EC process has been applied to reduce contaminant levels in palm oil milling effluent (POME), which is commonly measured by chemical oxygen demand (COD) and biological oxygen demand (BOD). Up to this time, numerous palm oil industries still rellied on biological treatments in an open ponding system for the POME treatment (Bello and Abdul Raman, 2017). Even though the ponding systems are simple and inexpensive, they are limited by the large area requirement and long hydraulic retention time (HRT), leading to an effluent that frequently fails to meet standard discharge limits. Anaerobic digestion followed by the aerobic ponding system requires an operating time up to 40 days for the POME treatment (Chan *et al*., 2010). However, Nasution *et al*. (2014) demonstrated that by using the EC process, a 42.94% COD removal efficiency could be achieved in just 6 hours of operation. Ibrahim *et al*. (2018) also successfully reduced the color of POME by 78% using the EC process with an applied voltage of 20 V, an electrode distance of 9.5 cm, and pH 5. The mentioned operating conditions resulted in 78% color removal. Further studies have continuously been carried out to shorten the operating time and to improve the removal efficiency of contaminants. Nasrullah *et al*. (2022) used steel wool electrodes in EC reactor to treat the POME at a high current density of 542 $mA.cm^{-2,}$ pH of 4.37, operating time of 45 minutes, and an electrode distance of 8.6 mm. The removal efficiency of chemical oxygen demand (COD), biological oxygen demand (BOD), and suspended solids (SS) of 97.21%, 99.26%, and 99.00%, respectively. By varying the current intensity from 1 to 20A and the space between the electrodes, (Nasrullah *et al*., 2020) studied the growth of the flocs during the POME treatment. They found that floc size increased with current intensity and decreased electrode spacing. In addition, the flocs formed a more substantial network when the operating time was increased. Despite its high removal efficiency, the application of high intensity is associated with high operational costs and energy consumption (Sakthisharmila *et al*., 2019).

In the wastewater treatment field, the EC processes have been combined with other techniques to improve the effluent quality. (Saad *et al*., 2022) investigated the performance and economics of the EC process when it is used as a single unit or in combination with a nylon 6.6 membrane for POME treatment. A pair of Fe electrodes were utilized at a current density ranging from 1.5 to 110 $mA.cm^{-2}$. The integrated EC membrane achieves higher contaminant removal efficiency and shorter operating time than the single EC system. Based on the economic analysis, the integrated EC membrane requires a higher capital cost than the single EC process but a much lower operating cost. Djajasasmita *et al*. (2022) combined EC with membrane processes (ultrafiltration/UF and reverse osmosis/RO) as a post-treatment for hospital wastewater. At the same current density of 8.8 $mA.cm^{-2}$, the EC-UF system resulted in lower COD and BOD_5 removal efficiencies (95.18 and 97.88%, respectively) than the EC-RO system (97.88 and 98.38 %, respectively). Optimizing operating conditions in integrated EC-membrane processes has been performed to obtain high-quality effluent (Nugroho *et al*., 2019; Nugroho *et al*., 2021; Aryanti *et al*., 2022).

Besides membranes, the integration of the EC process with an aeration system has also been applied to eliminate dissolved gases and to oxidize dissolved metals, such as iron, hydrogen sulfide, and some volatile organic chemicals (VOCs) (Mohd Remy Rozainy *et al*., 2015). In addition, aeration is often used to minimize the carbon dioxide liberated by a treatment process (Muthukrishnan *et al*., 2022). The aeration system is typically placed inside the EC reactor, and it is known as the aerated electrocoagulation process (Goren and Kobya, 2021). (Khalifa *et al*., 2020) studied the influence of the aeration process (at a flow rate of 1.5 $L.m^{-1}$) in the EC reactor for oily wastewater treatment. The Al-SS pair of electrodes was installed vertically with a 4 cm gap. They found that COD removal was higher with the aeration process (93.3%) than with non-aerated EC (84%) at a current density of 12 $mA.cm^{-2}$. Akansha *et al*. (2020) used aerated EC equipped with Al-Fe electrodes for treating dairy wastewater. The 120-min aeration time resulted in 97% COD removal.

In this paper, aeration was used as the pretreatment of the EC process, equipped with a combination of monopolar and bipolar electrodes. The aeration-EC process was used to treat POME from the palm oil industry in Indonesia, which had previously been treated in open sedimentation ponds. The effluent quality was evaluated in terms of TSS, TDS, COD, and BOD.

MATERIALS AND METHODS

Materials

The POME was obtained from one of the palm oil industries located in Garut, West Java, Indonesia, and collected after the sedimentation process. The cathodes and anodes were aluminum (Al), with dimensions of 30 cm × 5 cm × 3 mm.

Integrated Aeration-electrocoagulation process for POME wastewater treatment

The schematic of the experimental equipment used in this study is illustrated in Figure 1. An aeration system was installed at the bottom of the wastewater tank at a constant flow rate of 12 $L.min^{-1}$. After 1 hour of the aeration process, the feed wastewater was delivered to the destabilization and EC reactor at a flow rate of 500 $mL.min^{-1}$. In the EC reactor, 6 pieces of electrodes were installed with two configuration variations, namely 3 anodes 3 cathodes (code: 3A-3C)

Table 1. Electrode Configurations and Current Density

Electrode configurations	Current intensity (A)	Code	Current density ($mA.cm^{-2}$)
3A – 3C	10	3A-3C 10A	7.37
3A – 3C	15	3A-3C 15A	11.06
2A – 2C – 2B	10	2A-2C-2B 10A	11.06
2A – 2C – 2B	15	2A-2C-2B 15A	16.59

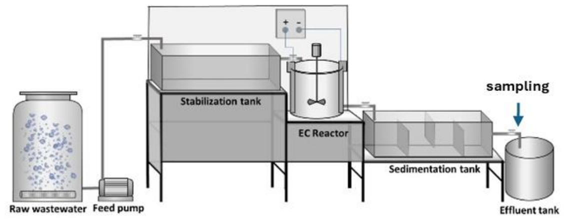


Figure 1. Experimental Set-Up of Integrated Aeration and Electrocoagulation Process

and 2 anodes 2 cathodes 2 bipolar (code: 2A-2C-2B). The current intensity of the EC process was set at 10 A or 15 A. The calculated current density of each configuration is presented in Table 1. The agitation process (50 rpm, six-blade turbine impeller) was used to improve the distribution of metal ions released from the anode and to enhance the growth of flocs. The effluent of the EC process flowed into the sedimentation tank to precipitate the remaining flocs, which were carried away by the EC effluent. In the sedimentation tank, further flocculation of flocs might occur with the amorphous $Al(OH)_3$. The final effluent quality was analyzed after 1 hour of the wastewater treatment process in terms of TDS, TSS, COD, BOD, and turbidity. Furthermore, electrode consumption and hydrogen production after 1 hour of the EC process were also calculated.

The electrode consumption was calculated by the following equation (Nugroho *et al*., 2021):

$$W_e = \frac{I \cdot t \cdot M_e}{n \cdot F \cdot V} \quad (1)$$

where W_e is the electrode (anode) consumption (in $g.cm^{-2}$. L^{-1}), I is the applied current density ($A.cm^{-2}$), t is the operating time (second), M_e is the molecular weight of the electrode (Al, g. $mole^{-1}$), n is the number of electrons transferred (e^-. $mole^{-1}$), F is Faraday constant (96,485.33 Coulomb.$mole^{-1}$), and V is the treated liquid volume (cm^3). The contact area of each electrode with the wastewater was 226 cm^2. Meanwhile, the hydrogen consumption was calculated by Equation (2) as follows (Aryanti *et al*., 2022):

$$Q_{H_2} = \frac{I \cdot A \cdot t}{F \cdot V} \quad (2)$$

where Q_{H2} is the concentration of H_2 gas from the cathode (in mole. L^{-1}), I is the applied current density (in $A.m^{-2}$), A is the surface area of cathodes that are contacted with the liquid (in m^2), t is the operating time (in second), F is Faraday's constant Faraday constant (96,485.33 Coulomb.$mole^{-1}$), and V is the treated wastewater volume (in m^3).

The energy consumption during 1 hour of the EC process was calculated by the following equation (Aryanti *et al*., 2022):

$$C_{power} = \frac{I \cdot V_{cell} \cdot t}{1000 \times V} \quad (3)$$

where C_{power} is the power consumption ($kWh.m^{-3}$), I is the applied current (A), V_{cell} is the cell potential (V), t is the operating time (h), and V is the treated liquid volume (m^3). The energy consumption of the EC process with and without the aeration process was compared.

RESULTS AND DISCUSSION

Influence of Electrode Configuration and Current Intensity on the Electrode Consumption and Hydrogen Production

The influence of the electrode configuration and current intensity on the electrode consumption is presented in Figure 2. The theoretical electrode consumption was calculated by multiplying the result in Eq. (1) by the total area of the anode used in the EC reactor. Meanwhile, the actual electrode consumption during 1 hour of operating time was determined by weighing the Al anodes before and after the wastewater treatment process. Based on Eq. (1), the electrode consumption is influenced by the current intensity in the EC process. In the 3A-3C configuration and without the aeration process, the electrode consumption was increased from 0.33 to 0.35 g. L^{-1} with the increase in current intensity (from 10 to 15 A). With the same electrode configuration of 3A-3C 10A, the aeration process resulted in a 39% reduction in electrode consumption. While at an applied current of 15 A, the electrode consumption was reduced by 37%. It is suggested that the passivation on the electrode surface may more easily form in the EC process without aeration, which triggers a greater consumption of electrodes (Al-Raad dan Hanafiah, 2021). The bipolar electrodes with an aeration process resulted in lower electrode consumption, i.e., 0.20 at a current intensity of 10A and 0.22 at 15A.

Table 2 describes the influence of the electrode configuration and current intensity on electrode consumption. The increase of current intensity from 10 to 15 A improved the H_2 gas production. The electrode configuration of 3A-3C 15A provided the highest H_2 production.

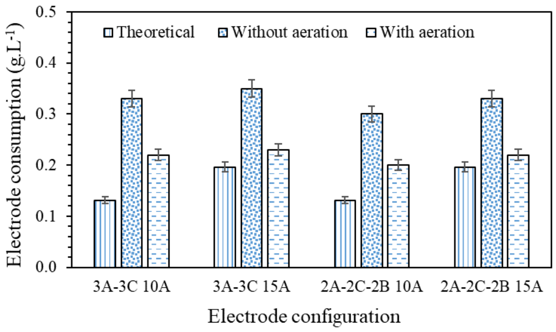


Figure 1. Electrode consumption during 1 hour of the electrocoagulation process

Table 2. Hydrogen production

Configuration of electrodes	QH_2 (mole.L^{-1})
3A-3C 10A	252.97
3A-3C 15A	379.46
2A-2C-2B 10A	168.65
2A-2C-2B 15A	252.97

It is known that the H_2 gas bubbles are produced near the anode and cathode surfaces due to the electro-dissolution of the anode and reduction of the cathode (Ensano *et al*., 2019). Based on Eq. (2), the H_2 gas production is related to the applied current and surface area of the electrodes. The H_2 gas production decreased when the configuration of 2A-2C-2B was used. Even though the current density was higher at 2A-2C-2B than 3A-3C, the number of cathodes also affected the amount of H_2 gas produced.

Influence of Electrode Configuration and Current Intensity on the Contaminants Removal

Figure 3 shows the removal efficiency of contaminants in terms of TSS, TDS, COD, and BOD. The increase of current intensity from 10 to 15 A improved the removal efficiency of the pollutants. It has been explained in Figure 2 that the increase in current intensity enhances the electrode consumption, which is related to the number of metal ions (Al^{3+}) released into the bulk solution. The rise in Al^{3+} ions in the bulk solution enhanced destabilization of pollutants and the formation of amorphous coagulants ($Al(OH)_3$). The electrode configuration of 2A-2C-2B 15A achieved a high TSS removal. The configuration of 3A-3C 15A also provided high TSS removal of 79%. Besides TSS removal, the aeration process improved the COD and BOD removal. The aeration may oxidize the dissolved metals and some VOCs before flowing to the EC reactor. The amount of Al^{3+} released into wastewater by the anodes was used to destabilize and agglomerate the remaining contaminants. Therefore, high COD and BOD removals were achieved. With aeration, the COD removal of 3A-3C at a current intensity of 10 and 15 A was equal to 89.055%. Meanwhile, the BOD removal was 82 and 85%, respectively. The configuration of 2A-2B-2C at 10 and 15 A with aeration resulted in COD and BOD reductions of 81.27 and 91.36%, respectively. Meanwhile, the TSS and turbidity removal were 76.27% and 96.46%, respectively. The opposite phenomenon occurs in TDS removal. TDS removal efficiency was higher in the non-aerated than in the aeration process. It is suggested that the high concentration of TDS was attributed to a higher concentration of Al^{3+} ions remaining in the aerated wastewater in the EC reactor compared to those without the aeration process.

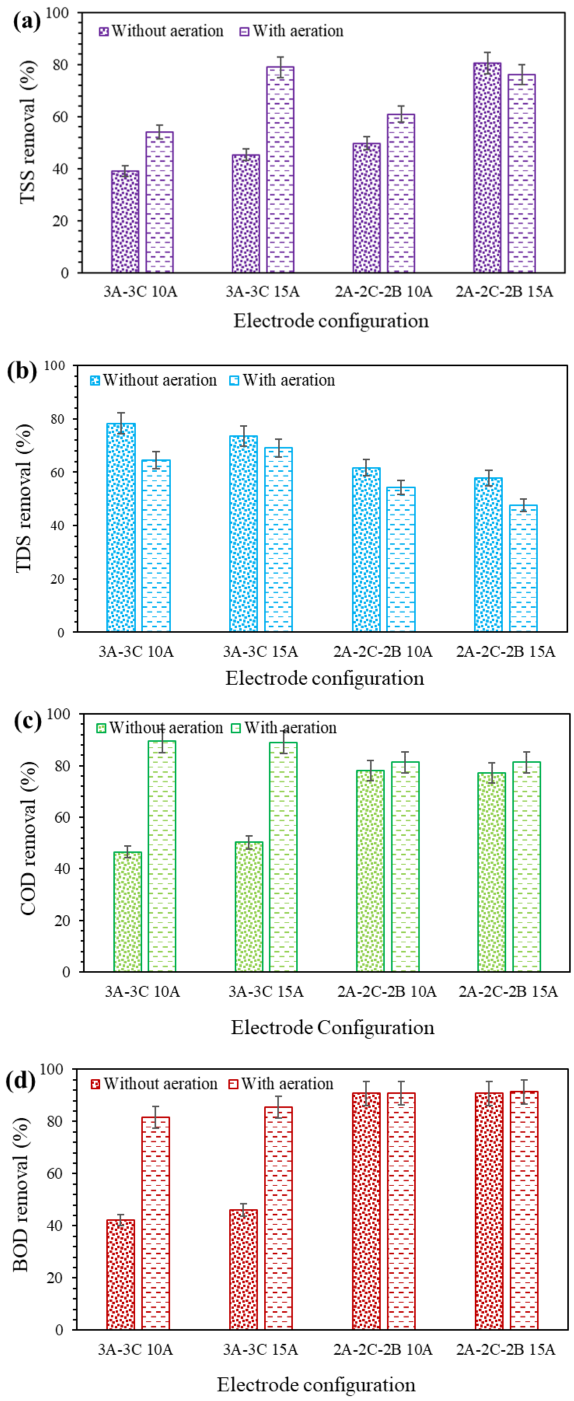
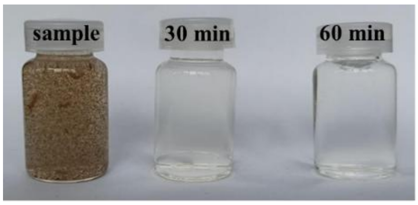
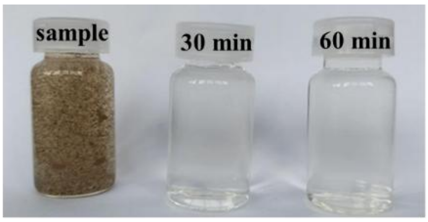


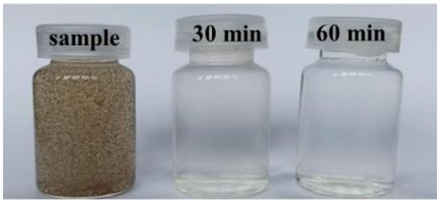
Figure 2. The removal efficiency of contaminants after 1 hour of the wastewater treatment: (a) TSS, (b)TDS, (c) COD, and (d) BOD removal.



(a) 3A-3C 10A (without aeration)



(b) 2A-2C-2B 10A (without aeration)



(c) 3A-3C 10A (with aeration)

(d) 2A-2C-2B 10A (with aeration)

Figure 3. The influent and effluent of EC without (a,b) and with aeration process (c,d)

The pH of the effluent was approximately 8.05. Clearer effluent resulted when the aeration process accompanied the EC process as pretreatment compared to the non-aerated wastewater (Figure 4).

Influence of Electrode Configuration and Current Intensity on Energy Consumption

The energy consumption during the EC process is shown in Figure 5. It shows that the increase in applied current intensity enhances the energy requirement for the POME wastewater treatment. The EC process with the aeration process requires lower energy than the non-aerated wastewater. The electrode configuration of 2A-2C-2B 10A with the aeration process offered the lowest energy requirement of 8.52 $kWh.m^{-3}$, followed by the 3A-3C 10A configuration (9.06 $kWh.m^{-3}$). At a current intensity of 15A, the 3A-3C and 2A-2C-2B configurations require energy of 20.68 and 16.13 $kWh.m^{-3}$, respectively. In all EC configurations, the aeration process provides an energy reduction between 16 to 26% from the non-aerated wastewater. The higher energy requirements of the non-aerated system may be initiated by the more severe passivation phenomenon on the electrodes

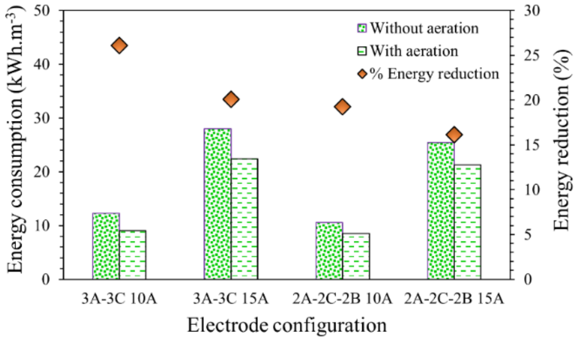


Figure 4. Energy consumption during wastewater treatment

compared to the aerated effluent. The presence of passivation on the electrode surface due to contaminants increases the resistance at the electrode-electrolyte interface. In contrast, the low concentration of contaminants reduces the passivation phenomenon, which reduces energy consumption during the EC processes.

CONCLUSION

The integration of the aeration and electrocoagulation (EC) process is successfully used for POME treatment. High contaminant removal was obtained when the electrode configuration was 2A-2C-2B and the current intensity of 15A. The BOD removal efficiency was 91.36% (from 132 to 11.4 mg. L^{-1}), COD of 81.27% (from 386 to 72.3 mg. L^{-1}), TDS of 47.64% (from 645.5 to 338 mg. L^{-1}), TSS of 76.27% (from 43.7 to 10.4 mg. L^{-1}), and turbidity of 96.46% (from 59.65 to 2.11 NTU). Meanwhile, the total energy requirement was 21.33 $kWh.m^{-3}$ with the pH of the effluent of 8.05. The combination of aeration-EC can be used as an alternative POME treatment to achieve high contaminant removal efficiency. Further research is needed to improve the quality of contaminants.

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AI DECLARATION

The authors declare that artificial intelligence tools were used solely for language editing. Specifically, Grammarly software was employed to improve grammar, spelling, and sentence clarity. No generative AI tools were used to create, analyze, or interpret the scientific content of this manuscript. All ideas, results, and conclusions presented are solely the work of the authors.

AUTHOR CONTRIBUTION

Febrianto Adi Nugroho: Conceptualization, investigation, methodology, validation, supervision, and writing – original draft.
Handoko Rusiana Iskandar: investigation, methodology, project administration, and supervision.
Nadiem Anwar: investigation, methodology, validation, and supervision.
Tiara Ariani Putri: writing – original draft, and methodology,
Putu Teta Prihartini Aryanti: Conceptualization, investigation, methodology, validation, supervision, writing – original draft, and writing – review and editing

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