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Electrocoagulation Applications in Managing Palm Oil Mill Effluent Pollution

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Palm oil mill effluent (POME) is characterized by high amounts of pollutants that are harmful to the environment when left untreated. Treatment methods for POME are necessary to reduce potential risks before discharge. Several technologies have been adopted for POME treatment. Most fall short of effectively addressing simultaneously the efficiency and cost-effectiveness of the treatment. Electrocoagulation (EC) has gained traction for its cost-effectiveness and high levels of pollutant removal efficiency. This paper reviewed studies about currently applied methods and their disadvantages with emphasis on how EC is advantageous over the other methods. There are limitations in currently employed methods, some of which EC sufficiently addresses. Comparative studies revealed that EC is more efficient in terms of hydraulic retention times, straightforward operations, and the variety of pollutant types it can treat in comparison with ponding system, membrane anaerobic systems (MAS), microbial fuel cells (MFC), and supercritical water gasification (SWCG). Through analysis of treatment efficiencies, it is evident that when compared to other methods with almost the same conditions, EC is much more effective in reducing pollutants. This study also explored how EC can be further optimized in its eventual application on large-scale operations and palm oil mills around the world.

1. Introduction

The palm oil sector is a vital contributor of fats and oils to the global market (Rodriguez-Mateus et al., 2016). Its by-products are economically relevant and suitable for various uses in different fields. Palm oil production reached a global output of over 79,464,000 t in 2023 (Philippine Coconut Authority et al., 2023). It is led by Indonesia (59 %), Malaysia (24 %), Colombia (≤5 %), Thailand (≤5 %), and Nigeria (≤5 %). Its milling operations involve the production of palm oil mill effluent (POME) (Adegbola and Simeon, 2020). POME is an oily wastewater characterized by its foul smell and capacity to decrease water quality. Its untreated effluent consists of 95 % to 96 % water, 4 % to 5 % total solids, 2 % to 4 % suspended solids (SS), 0.6 % to 0.7 % oil and grease, and a pH of 4 to 5 (Ahmed et al., 2015). POME contains elevated levels of organic content, biological oxygen demand (BOD), and chemical oxygen demand (COD) that have significant environmental consequences if discharged untreated (Mohd et al., 2023). Proper management and treatment of POME are vital to reducing its impact. The adverse effect of untreated POME necessitates the exploration of alternative treatment methods.
POME treatment technologies such as ponding systems, MFC, SCWG, and MAS have been employed to address the environmental concerns posed by POME (Tan and Lim, 2019). The subpar treated concentration, massive energy use, costly large-scale application, and generation of air pollutants lead to investigating alternatives for POME treatment. EC has been a subject of interest due to its efficiency in treating wastewater. EC is a wastewater treatment technique that involves applying direct current to sacrificial electrodes submerged in an aqueous solution (Kalsido et al., 2022). Its effectiveness lies in its operating conditions that can be optimized to increase treatment efficiency and minimize operating costs (Nasrullah et al., 2022). EC is a viable method for POME treatment due to its decreased sludge formation, reduced chemical use, high contaminant removal, cost-effectiveness, and low area requirement (Efluen et al., 2015). Extensive exploration has been conducted on EC as a treatment for general wastewater. Its targeted application in treating POME continues to

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be relatively marginal specific to efficiency, cost-effectiveness, and sustainability. This review explored the application of EC for POME treatment and outlined the latest developments in EC technology. It discussed key operational parameters influencing EC performance and its leverage over other treatment technologies in terms of efficiency, cost-effectiveness, and sustainability. This review contributes to advancing knowledge on EC as a treatment technology for POME by supporting its effective management in the palm oil industry. It also provides a foundation for future investigations in the field.

2. Palm Oil Mill Effluent

POME is a byproduct of the palm oil production process (Garritano et al., 2018). It is a thick brown-colored colloidal mixture (Lee et al., 2019) that exist in the forms of high solid, grease, oil, BOD, and COD (Mohammad et al., 2021). POME is a highly polluting residue that is generated from the three principal production processes in palm oil extraction, including condensate sterilization (36 %), clarification (60 %), and hydrocyclone processes (4 %) (Ahmed et al., 2015). Its high organic content and elevated BOD and COD levels have significant environmental consequences if discharged untreated (Mohd et al., 2023). Kamyab et al. (2018) reported that 25,000 mg/L BOD in POME is dangerous to aquatic surroundings and organisms if released widely. Mohd et al. (2023) highlighted that the high levels of COD and BOD lead to water pollution. Sari et al. (2019) added that the deterioration of organic compounds from the POME allows methane (CH_4) gas emission. This accelerates global warming and climate change. The impact of CH_4 in shifting the climate is 23 times more devastating than that of carbon dioxide (CO_2) (Hosseini and Wahid, 2015). POME treatment is essential to eliminate the pollution brought by the effluent from palm oil production. The generated pollution alarmed palm oil manufacturers and led to the application of biotreatment technologies as part of their waste management (Rana et al., 2017). Present POME management is often inadequate due to reliance on less effective methods such as open ponding. Proper treatment of POME mitigates pollution and contributes to renewable energy production. This can enhance the overall sustainability and efficiency of palm oil production worldwide (Oseghale et al., 2017).

3. POME Treatments

Effective POME treatment is crucial to mitigate its environmental impact. The ponding system is a conventional biological treatment for POME (Jusoh et al., 2023). It consists of several stages with varied hydraulic retention time (HRT), including a cooling pond (1 d), anaerobic pond (45 d), facultative pond (20 d), and aerobic pond (7 d). It is favored for its minimal capital expenditure and low operating cost. The system can eliminate an average of 70 % to 90 % of pollutants such as 77.6 % ammoniacal nitrogen removal (AN), 91.4 % oil and grease, 96.1 % total nitrogen (TN), and 75.3 % total phosphorus (TP). However, the sludge generated in the facultative pond resulted in poor color removal. The treatment failed to satisfy discharge standards due to high initial BOD and COD levels despite their reduction by 99.7 % and 98.9 %. The systems extended HRT and massive land use also necessitate alternative methods.

Membrane anaerobic system (MAS) has also shown considerable potential in POME treatment. Studies have shown that MAS can achieve high COD removal, with efficiencies ranging from 94 % (Hybat et al., 2019) to 98.4 % (Abdurahman et al., 2023). MAS technology can treat high-strength wastewater while also producing methane gas. Results indicated 94 % to 97 % COD removal and recovered 67.8 % to 70.3 % CH_4 (Hybat et al., 2019). It performs at elevated solids retention time (SRT) and adjusts to varied COD loadings. The HRT was significantly reduced from 150 d to 10 d making it suitable for high-strength wastewater like POME.

Microbial fuel cell (MFC) represents a novel approach to POME treatment that simultaneously treats wastewater and generates electricity. It utilizes microbes to break down organic pollutants and produce electrons to generate electricity (Roy et al., 2023). Ng et al. (2024) explored the capacity of MFC to generate electricity while treating POME with carbon cloth anodes. This resulted in 39.94 % COD removal at 4 d HRT with a generated power of 504.1 ± 8.7 mW m^{-3}. MFC is an environmentally friendly and energy-efficient alternative for POME treatment. However, improving its performance may increase cost and energy use. Further research is needed to develop its economic designs.

Supercritical water gasification (SCWG) is a thermochemical process that can convert biodegradable waste into useful gas (Mainil and Matsumura, 2019). It employs water at temperatures above 374 °C and pressure lower than 22.1 MPa to obtain fuel gases and nutrients in high-cost reactors. SCWG can gasify POME into carbon monoxide (CO), CH_4, CO_2, hydrogen gas (H_2), inorganic phosphorus, and solid carbon under conditions of 500 °C to 600 °C, 25 MPa, and 5 s to 50 s. This conversion provides a disposal option along with energy recovery. The release of gasification byproducts in the atmosphere promotes air pollution and emissions of greenhouse gases. The solid carbon produced, and phosphorus recovery have risks and contribute to environmental contamination if not appropriately managed.

Electrocoagulation (EC) is an efficient method that offers advantages over ponding systems, MAS, MFC, and SCWG treatments. EC does not rely on microbial activity as biological systems do which makes it less sensitive to changes in effluent characteristics. It avoids the extreme conditions required in SWCG while treating POME more efficiently.

Table 1: Summary of Studies for POME Treatment Technologies

Reference	Methods	Parameters	Highlights	Sludge Volume	Energy Consumption
Hybat et al. (2019)	MAS	COD removal, reduction in HRT, and CH_4 production.	Attained 94 % to 97 % COD removal with HRT (150 d to 10 d) reduction; CH_4 at 67.8 % to 70.3 %.	Low	Not quantified; estimated ~0.4–1.2 kWh/m³ based on MAS literature (Smith et al., 2015)
Ng et al. (2024)	MFC	Reduction of COD, HRT, and production of power.	39.94 % of COD was removed and 504.1 ± 8.7 mW m^{-3}; power was generated in 4 d of HRT.	Low	Very low input; generates 504.1 mW/m³
Mainil and Matsumura (2019)	SCWG	Gas composition	POME was gasified into CH_4, CO, CO_2, and H_2, inorganic phosphorus, and solid carbon.	Minimal (solid char)	Very high (>1000 kWh/m³)
Jusoh et al. (2023)	Ponding system	Removal of AN, TN, TP, COD, BOD, color, and oil and grease	Removal of 77.6 % AN, 91.4 % oil and grease, 96.1 % TN, 75.3 % TP; 99.7 % BOD and 98.9 % COD.	High	Very low (0.01–0.05 kWh/m³; relies on sunlight and natural microbial activity, no heating required)

Table 1 highlights the present treatment methods for POME. The effective management of POME is necessary to balance environmental sustainability and economic feasibility. Several treatment technologies provide solutions with complexity, cost, and efficiency trade-offs. The ponding system is a conventional method favored for its cost-effectiveness. It can remove pollutants and reduce COD and BOD at extended retention times (Jusoh et al., 2023). It produces high sludge volumes and has low energy demand, while color removal remains limited. MAS offers high COD removal and CH_4 recovery while reducing HRT (Hybat et al., 2019). It generates low sludge and has moderate energy consumption at around 0.4 to 1.2 kWh/ m³, but its strict control of organic loads and SRT increases operational complexity and cost. MFC treats wastewater and generates electricity (Ng et al., 2024). It produces minimal sludge and requires low energy input but efforts to improve COD removal beyond 39.94 % can lead to increased cost and energy consumption. Mainil and Matsumura (2019) reported that SWCG can convert POME into valuable gases such as CH_4, CO, CO_2, and H_2, as well as inorganic phosphorus and solid carbon. It produces negligible sludge but requires very high energy input (>1000 kWh/m³). Its uncontrolled emissions, leaks, and mismanagement pose risks and operational complexity. A treatment technology that offers efficiency and cost-effectiveness is necessary to manage POME better.

4. Electrocoagulation

EC is a wastewater treatment technique that involves applying direct current to sacrificial electrodes submerged in an aqueous solution (Kalsido et al., 2022). This involves the release of metal cations from the anodes (commonly iron or aluminum) which interact with hydroxyl ions to form coagulants that destabilize and aggregate pollutants for efficient removal (Elabbas et al., 2016). The EC process combines chemical, electrochemical, and physical mechanisms (Papadopoulos et al., 2020). This proves its capacity to be highly effective in removing various contaminants from wastewater. A study conducted by Ibrahim et al. (2018), achieved POME decolorization through the application of electric current to aluminum plates submerged in water. This induced Al^{3+} ions discharge, which interacted with hydroxide ions present in water. The reaction promoted the formation of aluminum hydroxide (Al $(OH)_3$) flocs that bound and captured organic colorants in the wastewater. It was also highlighted that the quantity of sludge generated from floc settlement in an EC process is relatively lower. This is dependent on the in-situ establishment of coagulants without chemical additives. This contributes to cost minimization of sludge handling and repurposing sludge for construction materials.

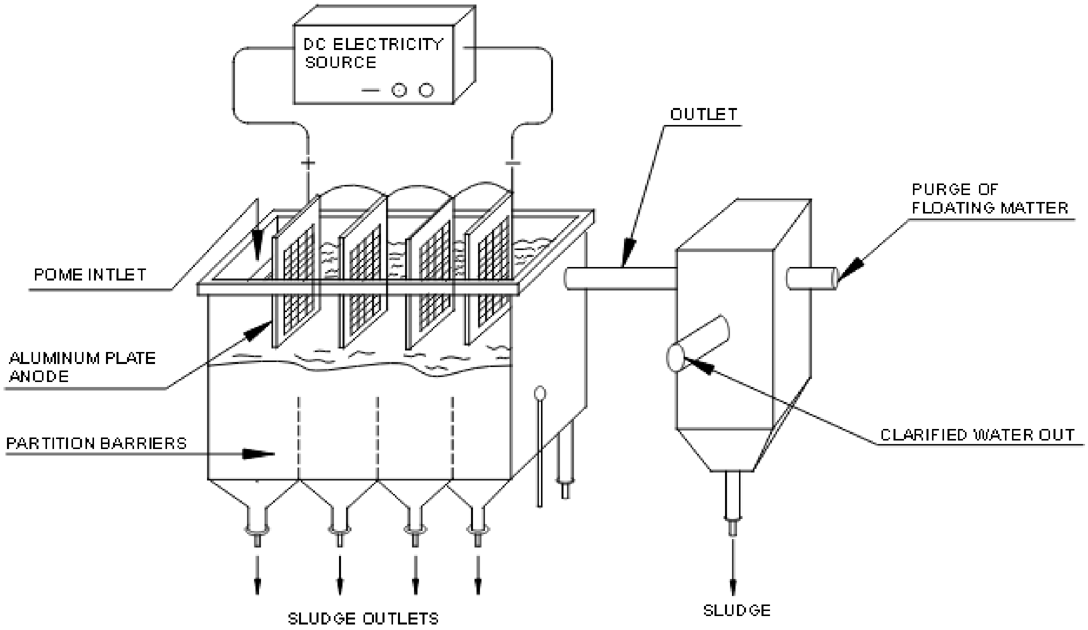

Figure 1: Electrocoagulation reactor

Figure 1 illustrates a typical EC reactor setup commonly used for wastewater treatment. While EC has gained popularity due to its low maintenance cost, effectiveness, and ability to treat a wide range of pollutants (Dehghani et al., 2014), its treatment over POME is limited. It has lower performance in degrading biodegradable pollutants and soluble organic substances (Ghaffarian Khorram and Fallah, 2020). High electricity use at longer treatment times also limits its practicality (Mohamad et al., 2022). Electrodes used in the EC process are prone to degradation which reduced pollutant removal over time (Al-Qodah et al., 2019). The sludge by-product also requires further treatment and disposal (Rakhmania et al., 2022). In overcoming such challenges, effective application of EC to complex wastewaters like POME necessitates the optimization of its operational parameters. This optimization would ensure the process can effectively address a wider array of pollutants. The performance of EC depends on several factors such as current density, voltage, pH, treatment time, and electrode setup. Current density directly affects the rate of coagulant production and pollutant removal, with higher current often leading to better treatment but also higher energy use and operational cost (Zailani and Zin, 2018). Voltage and treatment time also play important roles, with optimal removal achieved at 12 V for 150 min in POME treatment (Rusdianasari et al., 2017). pH influences the solubility of the coagulants formed during the process, where neutral to slightly acidic conditions often result in better removal of organic matter and suspended solids (Akhbari et al., 2019). Electrode material and distance also impact treatment efficiency. Aluminum and iron remain common choices due to their effectiveness and lower cost (Kalsido et al., 2022). Wider electrode gaps can lower removal performance by reducing current flow, while smaller gaps can increase resistance and maintenance needs (Susanto et al., 2022).

Nasrullah et al. (2022) optimized the EC process for POME treatment by applying high current intensities within a Box–Behnken design (BBD) framework. The study evaluated the influence of current strength, treatment time, electrode spacing, and pH on the removal of COD, BOD, and SS. The experiment achieved optimal removal at 19.07 A of current intensity, 8.60 mm of electrode spacing, 44.97 min of reaction time, and a pH of 4.37. Under these conditions, removal efficiencies reached 97.21 % for COD, 99.26 % for BOD, and 99.00 % for SS. The statistical analysis showed high R^2 values for all parameters, indicating strong model reliability. This result highlighted the crucial effect of current intensity on the formation of coagulants and pollutant destabilization during treatment.

Mohamad et al. (2022) introduced a photovoltaic-assisted EC system for POME treatment. This method used sunlight as a power source for EC which led to energy cost reduction. The system was operated under optimal sunlight and temperature conditions which enhanced electrochemical reactions. The POME contained high levels of contaminants prior to its coagulation process where COD concentration was at 25,952 mg/L and 15,612 mg/L for BOD. These were reduced to 2,114 mg/L for COD and 459 mg/L for BOD after 8 h. This emphasized the critical role of current intensity and coagulant dosage in achieving pollutant reduction, with

kinetic models showing a first-order reaction dependence on the concentration of metal ions during the process. This finding further supports the feasibility of using photovoltaic-based EC systems for POME treatment.
Susanto et al. (2022) studied the continuous treatment of POME using a column plate EC reactor. The system operated under varying flow rates, voltages, and electrode plate distances to determine their effects on the removal of total suspended solids (TSS), total dissolved solids (TDS), and COD. The influent sample showed initial concentrations of 2,150 mg/L TSS, 1,634 mg/L TDS, and 1,310 mg/L COD. Optimum removal was observed at a flow rate of 0.3 L/min, a voltage of 28 V, and a 2 cm gap between plates. Under these conditions, the system achieved removal efficiencies of 49.30 % for TSS, 49.40 % for TDS, and 60.30 % for COD. The study explained that voltage played a positive role in enhancing system performance due to increased coagulant formation, while greater electrode distances and faster flow rates reduced treatment efficiency due to lower residence time and current resistance. These findings highlight the importance of reactor configuration in improving EC performance.

Table 2: Summary of Studies for Electrocoagulation Technologies

Reference	Methods	Parameters	Findings
Nasrullah et al. (2022)	EC optimization with high current application using BBD	Operating time, electrode gap, initial pH, and current intensity.	Optimal electrocoagulation conditions (44.97 min, 8.60 mm gap, pH of 4.37, and 19.07 A) attained 97.21 % COD, 99.26 % BOD, and 99.00 % SS removal.
Mohamad et al. (2022)	Photovoltaic-EC System	Solar radiation, current intensity, and operating time.	Reduced COD (23,837 mg/L) and BOD (15,153 mg/L) with a current intensity of 153 mA to 181 mA.
Susanto et al. (2022)	EC with continuous column plate electric reactor	Flow rates, voltages, and electrode plate distances.	Removal efficiencies of 49.30 % for TSS, 49.40 % for TDS, and 60.30 % for COD.

Table 2 presents the recent advancements in electrocoagulation for POME treatment. Studies have shown that adjusting operational parameters such as current intensity, electrode spacing, pH, and treatment time leads to improved removal of pollutants. The application of the BBD enabled the effective removal of COD, BOD, and SS by identifying optimal operating conditions. Additional improvements were demonstrated in photovoltaic-powered EC systems, where reductions in COD and BOD levels reflected the importance of coagulant dosage and electrical input in treatment efficiency. The development of a continuous flow EC system also resulted in significant reductions in TSS and COD by optimizing flow rate and voltage settings. These findings present the effect of key parameters in enhancing pollutant removal. Kinetic modeling has also further supported the role of metal ion concentration in the treatment process. These studies highlight the potential of EC as a reliable option for POME treatment, particularly with optimizing process conditions and incorporating renewable energy sources to support sustainable wastewater management in the palm oil industry.

5. Conclusions

POME is a major source of industrial wastewater that requires effective treatment that meets the regulated standards to mitigate its influence on the environment. This review compared several technologies including ponding systems, MAS, MFC, SWCG, and EC for POME treatment. EC showed the most potential as a treatment option due to its simple operation, cost-effectiveness, and ability to work without the need for complex biological or thermal processes. Studies have shown that adjusting key operational parameters such as current intensity, pH, electrode spacing, and treatment duration can significantly enhance pollutant removal. Integrating renewable energy sources like solar power further improves the sustainability of the process by lowering energy demand. Compared to other technologies, EC offers more stable treatment performance and greater adaptability to high-strength wastewater like POME. Its potential to reduce environmental impact, improve energy efficiency, and lower sludge generation supports its application in future palm oil processing operations. Continued optimization and scale-up studies are essential to realize its role fully. Succeeding investigations must prioritize integrating biological systems with EC to improve biodegradable pollutant removal. This approach could enable effective methane recovery from generating sludge at the end of the process. The exploration of energy recovery from EC waste-byproducts could further support the environmental and operational sustainability of the process. The integration of fuzzy optimization exhibits considerable promise in refining EC parameters to achieve an optimal trade-off between treatment efficiency and the cost of POME treatment.

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