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Effect of Plate Materials and Operational Parameters on Hybrid Phsyco-Biological Units for Palm Oil Mill Effluent

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Abstract: Indonesia's palm oil industry generates large volumes of palm oil mill effluent (POME) characterized by high organic load and suspended solids, requiring effective treatment. This study evaluates a continuous hybrid system consisting of a kapok fiber (KF) pre-treatment unit, electrocoagulation (EC) reactor, and Moving Bed Biofilm Reactor (MBBR), operated under varying plate materials (Fe, Al, Cu) at 24 V and 10 A. The system treated raw POME (pH 3.4; sCOD 20,796 mg/L; TSS 25,610 mg/L; oil and grease 3,243 mg/L) over 10-day operational cycles per condition. Results show that copper electrodes achieved the highest performance, with sCOD removal up to 66% and oil and grease removal up to 81.38%, alongside improved TSS reduction. The KF unit contributed 46–53% oil and grease removal, while EC primarily reduced suspended solids and adjusted pH, supporting stable MBBR performance. The combined configuration highlights the interaction between physicochemical and biological processes, where electrode selection and pre-treatment significantly influence overall system efficiency. These findings provide insight into optimizing integrated treatment strategies for high-strength POME, although additional polishing steps are still required to meet discharge standards.

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Keywords: electrocoagulation, hybrid reactor, MBBR, plate material, POME.

1. Introduction

Indonesia stands as the world's largest producer of palm oil, supplying approximately 57% of global production, with output reaching 78 million metric tons in the 2022/2023 marketing year [1]. However, this rapid industrial expansion has led to severe environmental consequences, primarily due to the discharge of Palm Oil Mill Effluent (POME), a highly polluting byproduct generated at a rate of 2.5 to 3.5 tons per ton of crude palm oil processed. Compounding this issue, Indonesia exported 20.5 billion tons of palm oil in just the first nine months of 2023 [2], further amplifying the scale of wastewater generation.

POME represents a critical environmental hazard, contributing 25–33% of the palm oil industry's total greenhouse gas emissions equivalent to 28 million tons of CO_2 annually while also releasing substantial methane (CH_4), a gas with 25 times the global warming potential of CO_2 [3]. The effluent's composition includes harmful pollutants such as sulfur oxides (SO_2), ammonia (NH_3), and excessively high concentrations of biological oxygen demand (BOD), soluble chemical oxygen demand (sCOD), total suspended solids (TSS), oil and grease, and nitrogen. These contaminants devastate aquatic ecosystems by depleting dissolved oxygen, triggering eutrophication, and impairing biodiversity, while untreated emissions exacerbate air pollution and public health risks. The economic repercussions are equally severe, including environmental fines (IDR 3–15 billion per case), a 30–45% decline in fishery yields, and a 25% increase in export rejections in 2023 [4], [5].

Current POME treatment methods such as ponding systems, physicochemical coagulation, bioreactors, and membrane filtration remain inadequate [6]. While ponding systems are widely adopted for their low operational costs, they suffer from inefficiency, land-intensive requirements, and uncontrolled greenhouse gas emissions, with performance further deteriorating during rainy seasons. Alternative approaches like chemical coagulation face prohibitive challenges, including high costs, secondary pollution from sludge, and unsustainable chemical usage. These limitations underscore the urgent need for innovative, scalable solutions that balance environmental sustainability, regulatory compliance, and economic feasibility.

Among the new technologies making advances today is electrocoagulation (EC), which has been proven effective in treating wastes by scavenging all the high concentrations of suspended solids contained in palm oil mill effluent POME and achieving a reduction of the pollutants before the effluent is released to the environment making it a promising alternative to conventional coagulation methods [7], [8]. The patented process of EC involves applying direct current to the effluent so that any dissolved or suspended matter sticks together or coalesces and is subsequently easier to eliminate. Similar performance has also been observed in other industrial effluents such as textile and slaughterhouse wastewater, where EC achieved efficient removal of suspended solids and organic matter due to the formation of metal hydroxide flocs and enhanced particle destabilization [9], [10]. Particular research studies have shown that POME can be treated via EC to achieve lower values of BOD, sCOD, and TSS, and also reduction of some undesirable gases such as methane and ammonia, making it an ideal product for palm oil producers irrespective of the scale of production. By this method, the environmental problems concerning the treatment of POME are also likely to be solved in the future, as such disposal is also inexpensive in the long run and does not call for extensive space and huge operating and maintenance burdens as experienced with other treatment technologies.

Apart from the efficient system of EC, it also possesses some disadvantages like passivation of electrodes, higher electricity consumption, and generation of secondary pollutants in case of compounded wastewater [11]. Furthermore, the combination of EC with another biological treatment is needed to remove the high contaminant in POME. Therefore, the Moving Bed Biofilm Reactor (MBBR) and Kapok Fiber (KF) were chosen as the units that can be arranged and be a perfect fit for the treatment reactor. High contaminant removal in MBBR systems needed to be in wastewater conditions with relatively low solid content. Excessive solids can hinder the performance of biofilms on the moving media due to media clogging. Therefore, EC and MBBR are a perfect match where EC acts as a coagulant precursor in this treatment and a sedimentation unit as a pre-treatment step to remove solid content before entering the MBBR unit. Unlike conventional chemical coagulation, EC uses electrical power to induce coagulation, removing the need for chemical coagulants and thereby lowering the chemical load in the treated water.

MBBR is an illustration of the moving-medium system. In this type, the biofilm media are in constant motion, driven by air forces. The use of biofilm-based systems, especially in WWTPs, is a common strategy to increase process stability. MBBRs also need less treatment time and space compared to conventional methods, which reduces the cost of treatment. There exist two biofilm processes: attached growth and suspended growth processes. Attached growth biofilm systems have several advantages compared to suspended growth wastewater treatment systems. These include simpler operation, eliminated equipment maintenance concerns, compactness, reduced energy consumption, no sludge bulking problems, better sludge thickening characteristics, higher active biomass concentrations, the presence of both aerobic and anoxic microorganisms in the same system, and greater resistance to shock loadings. The high specific surface area of biofilm media results in a compact design for these systems. Additionally, due to the reduced presence of filamentous non-flocculating bacteria, sludge-thickening characteristics have also been enhanced, minimizing sludge-bulking issues within the system. Moreover, the immobilization of microorganisms in the system results in a higher concentration of active biomass and, therefore, enhances the overall performance of the system concerned [12].

Another case is that high oil and grease affect the performance of the MBBR since there is no special design in MBBR for handling oil and grease, and it has no greater effect on the EC. Thus, in the present study, the pre-treatment oil and grease in an EC-MBBR reactor also comprised one made up of KF. KF can be characterized as a hydrophobic-oleophilic adsorbent because of the enormous amount of lignin on its surface. Besides that, the fiber has a big lumen, which provides its high porosity of up to 77 % and, therefore, is capable of offering more effective oil absorption compared to other adsorbents. The ligninencased, smooth exterior of the kapok fibers contributes much to the low surface energy of kapok, about 31-40 mN/m, similar to that of oil, about 20-30 mN/m, hence accounting for a higher adhesion of oil to the fiber surface [13].

Optimization needs to be assessed based on a lot of circumstances. Variables that can be controlled are the plate material, distance between plates, the thickness of the plates, current, and voltages. The variables are interconnected with each other, and each variable can change the quality of effluent that is being produced [7]. EC's effectiveness heavily depends on plate material selection (Fe, Al, or Cu). Iron plates are cost-effective and produce iron hydroxides that effectively coagulate contaminants, but their corrosion introduces unwanted iron ions into treated water. Aluminium plates generate aluminium hydroxides that excel at aggregating suspended particles into flocs and support higher currents, though they're pH-sensitive and can release potentially harmful aluminium ions. Copper plates offer antimicrobial properties and form copper hydroxide coagulants, but their higher cost and potential leaching require careful monitoring. Each material presents distinct trade-offs in pollutant removal efficiency, energy consumption, electrode lifespan, stability, ion release, and cost. No single material excels in all applications, making material selection a balanced compromise based on specific needs. The choice of plate material significantly impacts effluent quality, process longevity, and operational sustainability.

2. Methods

2.1. Research Site and Timeline

The research “Optimizing Electro-Coagulation Plate Materials and Operational Parameters Coupled with Moving Bed Biofilm Reactor for Palm Oil Mill Effluent” was conducted from October 2024 until June 2025. The preparation of KF filters and characteristics analysis of kapok as an oil and grease adsorbent were conducted from November to December 2024. Afterward, batch EC experiments were conducted to obtain the best conditions for EC operation in January 2024. The biomass seeding and acclimatization period was conducted in December 2024 with the biomass mixed cultures microorganism for the MBBR unit was obtained from Wastewater Treament Plant (WWTP) II Jababeka in the Oxidation Ditch unit. The reactor is located at the Laboratory of Water Quality at the Department of Civil and Environmental Engineering, IPB University, Dramaga, Bogor, West Java, Indonesia.

The raw POME samples used in this study were sourced from PT Perkebunan Nusantara (PN) VIII Cigudeg, located in Bogor Regency, West Java from the settling pond. This facility was chosen due to its geographical proximity to IPB University, as well as its capacity to consistently produce representative and sufficient volumes of POME with high-quality characteristics. Raw POME attributes were considered essential in ensuring that the experimental outcomes would carry both scientific validity and practical relevance to real-world conditions within the palm oil processing industry, as stated in **Table 1**. The collection of measurement data from the reactor was carried out over the period of January to March 2025. All empirical investigations and laboratory analyses were performed at the Environmental Engineering Laboratory, housed within the Department of Civil and Environmental Engineering at IPB University, Dramaga, Bogor, West Java, Indonesia.

Table 1. POME characteristics and compliance with Indonesian effluent standards

Parameter	Concentration	Effluent Standard[a]	Unit
pH	3.4	6-9	-
BOD_5	12,081	≤ 100	mg/L
sCOD	20,796	≤ 350	mg/L
TSS	25,610	≤ 250	mg/L
OG	3,243	≤ 25	mg/L
TN	95	≤ 50	mg/L

2.2. Tools and Materials

The tools used in the study are divided into reactor body partitions, measurement tools, and tools used for processing and modeling. The integrated EC-MBBR reactor consists of a pre-treatment unit (capacity 6 L), EC unit (capacity 4.5 L), primary clarifier (capacity 6.67 L), the MBBR itself (capacity 6.67 L) and secondary clarifier (capacity 3.33L). The EC unit is rectangular with a length of 15 cm, width of 28 cm, and height of 23 cm with 3 cm spacing between electrode and 140 cm^2 of effective surface area for each plate. In addition, the reactor is also equipped with electrical components for power distribution, a pump to facilitate wastewater flow, a Kaldness Helix-5 placed at one-third of the reactor volume, and four air pumps for oxygen supply aeration system uses a blower at its base that has a 6 L/min discharge. The primary substance targeted for treatment in this reactor system is POME. Measurement tools include a thermometer, pH meter, analytical balance, block heater, spectrophotometer, oven, furnace, porcelain cup, measuring cup, beaker, measuring pipette, dropper pipette, Erlenmeyer flask, measuring flask, funnel, test tube, and desiccator. This research's processing tools are Microsoft Excel and OriginLab 2024a as graphical designs. Furthermore, the primary material used for this research is POME. Biomass from Jababeka WWTP, glucose, and distilled water were also used in this study.

2.3. POME Sample Collection and Characteristics Analysis

The POME sample came from PT Perkebunan Nusantara (PN) VIII Cigudeg, Bogor Regency, West Java Province. POME sampling was conducted in accordance with SNI 6989.59:2008 concerning Wastewater Sampling Methods. POME sampling was conducted once during the research. POME characterisation analysis is conducted to identify the physical, chemical, and biological quality of POME. POME characteristic data is used to design and optimize an effective treatment system. The POME quality parameter testing includes BOD, sCOD, TSS, Oil and Grease, Total Nitrogen (TN), pH, and temperature. These characteristics were then compared against the effluent standard for POME in Indonesia, as outlined in the Indonesia Ministry of Environment Regulation No. 5/2014 on Wastewater Standard Values.

2.4. Reactor Operations

The integrated EC-MBBR reactor was operated continuously to treat POME from January through March 2025, running continuously for 2 hours and 30 minutes of resting time at ambient room temperature with KF as an adsorbent to remove oil and grease from the influent which is known for its natural oleophilic properties within the water-based systems [13], the treatment applies throughout the entire experimental period. Each experimental variation was subjected to ten days of operational runtime under unsteady state conditions, a duration deliberately chosen to ensure that the data collected remained accurate, reliable, and sufficiently representative of actual treatment performance.

The selection of a ten-day operational timeframe was grounded in several scientific and analytical justifications. A 10-day operational period was selected to ensure that reactor performance reflects stable and representative conditions rather than short-term fluctuations. EC processes require time for electrode stabilization, consistent coagulant generation, and floc formation, while integrated biological systems also need several days to adapt to operating conditions. Previous studies indicate that monitoring periods of at least 7–10 days are necessary to capture steady-state behavior and reliable treatment performance [11], [14]. By the end of the ten-day observation window, discernible trends or patterns indicative of potential issues within the treatment process become clearly identifiable, allowing for more informed evaluation of system performance. Furthermore, from a statistical standpoint, ten days constitutes the minimum dataset required to conduct a meaningful historical data analysis [15]. With regard to influent flow management, a peristaltic pump was employed to regulate and deliver the POME into the reactor in accordance with the designated influent discharge rate. To maintain adequate dissolved oxygen levels within the MBBR unit, an aeration system consisting of a blower installed at the base of the unit was utilized, operating at a discharge rate of 6 L/min.

2.5. Determination of Plate Material Variation

The EC process was evaluated using three electrode materials: iron (Fe), aluminium (Al), and copper (Cu), selected based on their electrochemical properties, cost, and environmental impacts that govern pollutant removal efficiency. This comparison provides quantitative data on pollutant removal efficiency, cost, and energy consumption for optimizing EC systems for industrial applications. Electro-coagulation decreases sCOD values through direct oxidation at the anode, causing coagulation followed by electroflotation, where hydroxide coagulants trap destabilized particles and flocs are separated by H_2 flotation produced at the anode. The selected operating conditions of 24 V and 10 A fall within commonly reported EC ranges that ensure effective coagulant generation and pollutant removal while maintaining reasonable energy consumption. Applied voltage provides sufficient driving force for anodic dissolution, while current controls metal ion release and hydrogen evolution, both essential for coagulation and flotation processes [8], [14].

2.6. Reactor Performance Evaluation

The performance evaluation was designed based on strategically selected sampling points along the reactor sequence (**Fig. 1**), enabling assessment of each unit's contribution in relation to the study objectives. Sampling was conducted at the influent, after the KF unit, after the EC unit, and at the final effluent following the MBBR and secondary clarifier. This configuration allows: (i) evaluation of oil and grease removal efficiency in the KF unit, (ii) determination of the effect of electrode material on TSS destabilization, pH adjustment, and partial sCOD reduction within the EC unit, and (iii) assessment of overall organic degradation performance in the MBBR under varying pre-treatment conditions. By comparing parameter changes between consecutive sampling points, the individual and combined contributions of KF, EC, and MBBR can be quantified, directly addressing the objectives related to hybrid system performance and plate material optimization. Accordingly, key parameters monitored at each point include pH, sCOD, TSS, and discharge, while oil and grease and temperature were measured daily to capture operational stability.

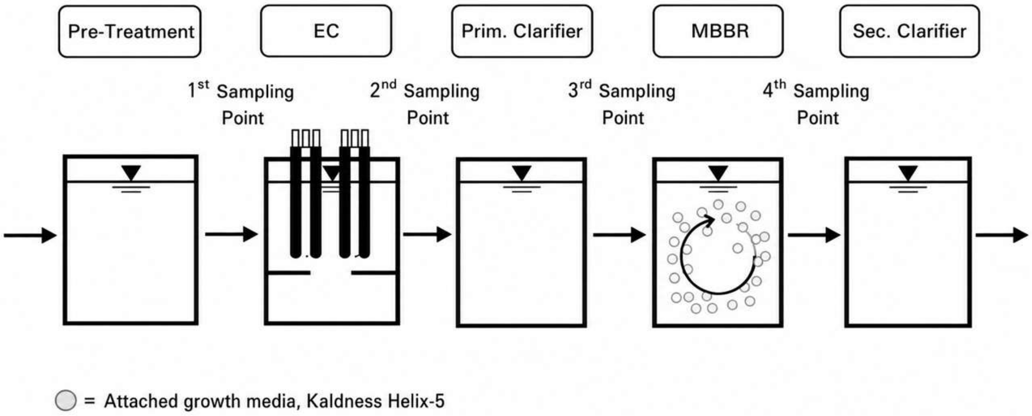

Fig. 1. Configuration of the EC-MBBR reactor

3. Result and Discussion

3.1. Characterization of Palm Oil Mill Effluent

The wastewater characteristics of POME samples from PTPN VII were examined for six key parameters: pH, BOD_5, sCOD, TSS, TN, and oil and grease content, with every measured parameter surpassing the acceptable limits established by Indonesia's Ministry of Environment Regulation No. 5/2014 for Wastewater Standard Values as shown on (**Table 1**). The POME demonstrated severe acidity with a pH of 3.4, requiring significant pH adjustment before biological treatment, with minimal dissolved oxygen availability evidenced by exceptionally high BOD5 (12,081 mg/L) and sCOD (20,796 mg/L) concentrations. BOD_5 represents biodegradable organic content by measuring oxygen required by microorganisms for organic matter breakdown, while sCOD determines the complete amount of chemically oxidizable organic substances accessible for microbial breakdown [16], demonstrating considerable oxygen demand and highlighting the critical need for effective pre-treatment processes or aeration systems to facilitate successful biodegradation.

The POME sample from PTPN VII represents a highly colloidal and oil-laden effluent with TSS levels of 25,610 mg/L (consistent with published ranges of 18,000-54,000 mg/L for fresh POME), indicating significant concentrations of fibers and fine cellulose particles from palm fruit processing operations, and oil and grease content of 3,243 mg/L attributed to inefficient oil recovery processes [17]. The total nitrogen level of 95 mg/L, originating from protein breakdown and microbial processes during primary processing, falls below standard literature ranges (180-750 mg/L) but still exceeds Indonesia's Ministry of Environment Regulation No. 5/2015 limits, indicating the necessity for nitrogen-specific treatment approaches.

3.2. Overall Performance of The Hybrid EC-MBBR Reactor System

The reactor performance evaluation examined critical parameters including pH, temperature, oil and grease, TSS, and sCOD (**Table 2; Fig.2**). Most significantly, all reactor components successfully fulfilled their fundamental operational goal of adjusting pH levels to meet regulatory requirements. During the initial two sampling periods, the incoming wastewater maintained acidic conditions at approximately pH 5.0 where studies have shown that biofilm-based processes such as MBBR can tolerate mildly acidic conditions and maintain stable microbial activity due to the protective nature of the biofilm matrix. This allows effective degradation of high-strength wastewater like POME under acidic conditions, particularly during the initial breakdown stages [11], [18]. The KF unit did not produce any direct modification to this acidic state. Nevertheless, beginning with the third sampling event, the POME pH values achieved compliance with the effluent standards (pH 6-9) specified in Indonesia's Ministry of Environment Regulation No. 5/2014.

Table 2. Temperature and pH in the hybrid EC-MBBR reactor system

Parameter	Sampling Point	Plate Material		
		Iron (Fe)	Aluminium (Al)	Copper (Cu)
pH	1st	5.32 ± 0.46	5.74 ± 0.30	6.02 ± 0.24
	2nd	5.37 ± 0.44	5.91 ± 0.43	6.48 ± 0.43
	3rd	6.14 ± 0.49	6.24 ± 0.54	6.86 ± 0.79
	4th	6.09 ± 0.63	6.68 ± 0.51	7.39 ± 0.72
	5th	8.20 ± 0.44	8.49 ± 0.84	8.96 ± 0.43
	6th	8.66 ± 0.93	9.83 ± 0.70	10.56 ± 0.47
Temperature (°C)	1st	28.70 ± 1.25	28.96 ± 1.25	28.70 ± 0.95
	2nd	29.95 ± 3.15	29.33 ± 1.34	28.40 ± 0.70
	3rd	38.80 ± 1.98	43.42 ± 6.8	45.5 ± 5.44
	4th	30.30 ± 1.18	29.42 ± 0.95	29.80 ± 0.92
	5th	29.25 ± 1.23	29.06 ± 1.17	28.70 ± 0.83
	6th	29.30 ± 1.41	29.05 ±1.01	28.50 ± 0.53

The seeding and acclimatization process began on 1 d with the seeding of the reactor, introducing an initial active biomass (MLVSS) of 7510 mg/L. The acclimatization then proceeded in a gradual manner, increasing POME concentration to 50% (around 13 d), 75% (around 23 d), and finally 100% (around 42 d). By 51 d, it reached full-strength (100%) POME and experienced a peak influent sCOD of 26,896 mg/L. Despite initial shock responses, the system adapted, and by 59 d, it successfully reduced sCOD to 4,183 mg/L, achieving a COD removal efficiency of 84.4% in 6 d. Active biomass (MLVSS) increased substantially from the initial 7,510 mg/L to a final value of 47,100 mg/L, confirming robust biomass development and effective acclimatization (**Fig. 2**). This increase in biomass concentration is directly associated with enhanced substrate removal kinetics, as higher active biomass levels improve substrate utilization rates and organic degradation efficiency within the MBBR system.

The EC unit, represented by the third sampling point, played a crucial role in conditioning the POME. It was at this stage that the pH of the acidic wastewater was successfully adjusted to meet the regulatory effluent standard of pH 6-9. This pH increase is a characteristic outcome of the EC process, primarily due to the generation of hydroxyl ions (OH^-) at the cathode, which neutralizes the initial acidity of the effluent [19]. Specifically, the pH values in this reactor rose to 6.14 with iron electrodes, 6.24 with aluminium electrodes, and 6.86 with copper electrodes. A significant increase in temperature was also observed within the EC unit across all plate materials. This is attributed to the Joule heating effect, where the electrical energy applied to the system is converted into thermal energy, thereby raising the temperature of the wastewater [10]. As detailed in the experiment's data, the temperature rose substantially to 38.80°C for Fe, 43.42°C for Al, and 45.5°C for Cu. This heating effect was followed by a cooling period in the subsequent sedimentation tank before the effluent entered the biological treatment stage. Although these temperatures were high, they did not pose a threat to the microbial community in the later stage.

The average removal rates of oil and grease in the reactor (**Fig.2**) for each Fe, Al, and Cu were 71.72%, 81.38%, and 80.18%. Notably, the independent KF unit accounted for approximately 46-53% of oil and grease removal, highlighting its effectiveness in pretreatment. TSS removal at Fe, Al, and Cu were 41.74%, 59.12%, and 73.38%, respectively. Despite these removal, residual suspended solids, oil and grease concentration remained above the discharge thresholds, indicating that the current reactor configuration is insufficient to meet regulatory standards without optimisation in each compartment unit of the reactor. Including sCOD removal, the reactor achieved average removal efficiency of 52%, 54%, and 66% at Fe, Al, and Cu. The EC unit did not meet the initial expectation.

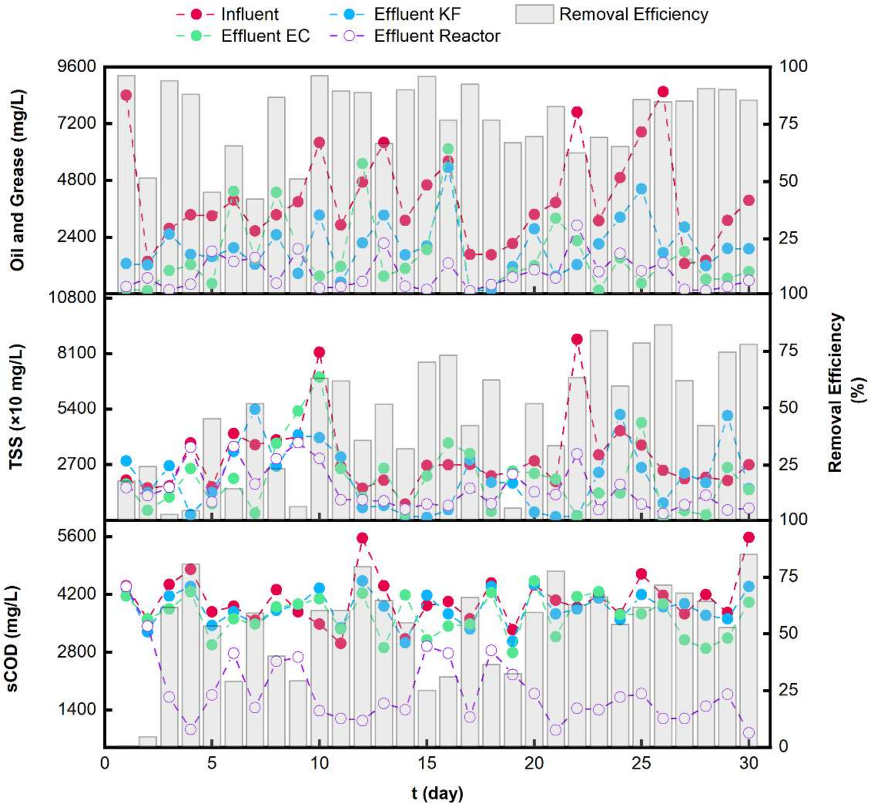

Fig. 2. Changes in oil and grease, TSS, and sCOD concentrations in the reactor

3.3 EC Performance Between Plate Materials Variations

The influent sCOD concentrations are ranging between approximately 2600 and 5700 mg/L (**Fig.3**). However, effluent values varied depending on the electrode material. During the Fe electrode phase (Day 1–10), moderate sCOD removal efficiency was observed (5–25%), consistent with prior findings that iron electrodes are effective but may suffer from limited solubility or passivation over time [9]. Aluminium electrodes (Day 11–20) exhibited fluctuating performance, with some instances of up to 30% removal but also episodes of negligible or even negative removal, possibly due to amphoteric hydroxide formation at certain pH levels and re-dissolution of organics [20]. In contrast, Cu electrodes (Day 21–30) provided more stable and generally higher sCOD removal (exceeding 20%), aligning with studies highlighting copper's enhanced redox activity and conductivity in EC systems [3].

Based on the data (**Fig.4**), TSS concentrations and removal efficiencies under the same operational sequence. Influent TSS concentrations ranged widely from 15000 to 87000 mg/L, reflecting the heterogeneous nature of raw POME. Fe electrodes yielded moderate TSS removal (20–60%), attributed to the flocculating ability of iron hydroxides [21]. Al electrodes showed poor and inconsistent TSS performance, potentially due to unstable floc structure and sensitivity to current density [22]. Conversely, Cu electrodes resulted in the highest and most consistent TSS removal, frequently exceeding 80% and reaching 100%, affirming copper's superior particle destabilization and coagulation properties [23]. These findings confirm that electrode material significantly affects EC efficiency. Copper demonstrated the best performance in removing both sCOD and TSS, likely due to its higher conductivity, redox potential, and formation of compact, settleable flocs [24], [25]. Hence, electrode selection is a critical parameter in optimizing EC systems for high-strength industrial wastewaters like POME.

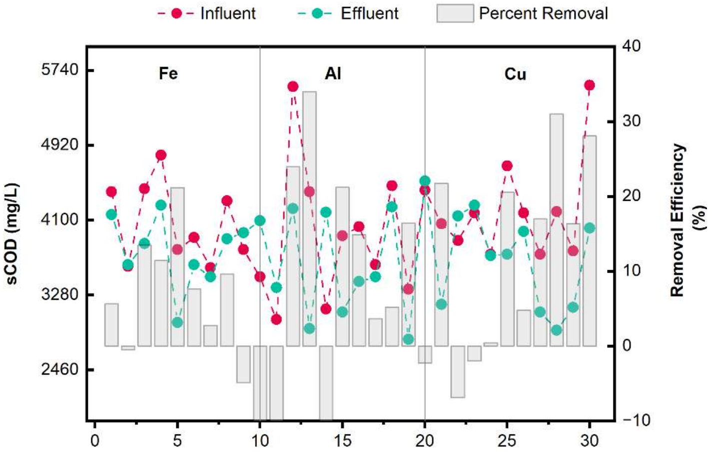

Fig. 3. Influent and effluent sCOD concentrations and corresponding removal efficiencies during three operational variations of the EC system

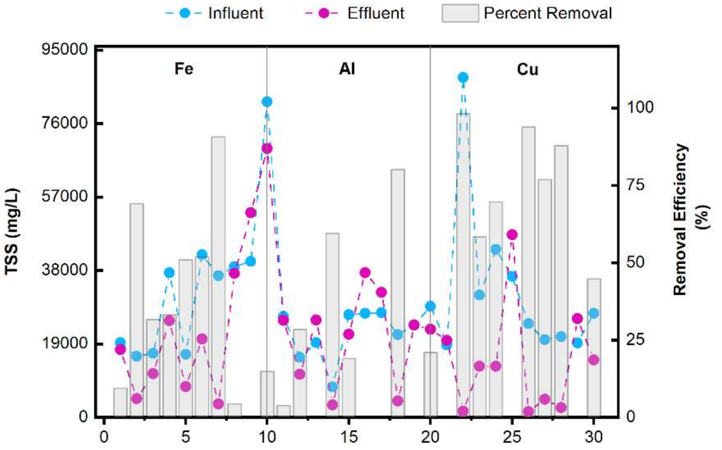

Fig. 4. Influent and effluent TSS concentrations and corresponding removal efficiencies during three operational variations of the EC system

3.4. EC's Impact on the possibilities of other units

In this study, the contribution of the EC unit to downstream unit performance can be quantitatively assessed from the observed removal efficiencies. The EC stage achieved TSS removal ranging from 41.74% (Fe), 59.12% (Al), to 73.38% (Cu), and partial sCOD reduction of approximately 9–18%, indicating that its primary role was solids destabilization rather than dissolved organic removal. This reduction in suspended solids significantly improved the influent quality entering the MBBR unit, which is reflected in the overall system sCOD removal efficiency reaching up to 66% in the integrated reactor.

Furthermore, the EC unit increased pH from highly acidic conditions (pH 3.4) to near-neutral levels (pH 6.14–6.86 at the EC outlet), creating a more favorable environment for microbial activity in the MBBR. This is critical, as stable biofilm performance depends on controlled pH and reduced particulate loading. The data indicate that without EC pre-treatment, high TSS concentrations (up to 25,610 mg/L) would likely inhibit biofilm activity through clogging and mass transfer limitations.

The integration with the KF unit also demonstrated complementary performance, contributing 46–53% oil and grease removal prior to biological treatment. This sequential reduction shows that EC not only acts as a coagulation step but also as a conditioning unit that enhances downstream biological efficiency. However, despite these improvements, residual pollutant concentrations remained above discharge standards, suggesting that EC performance, particularly for soluble organics, was not sufficient as a standalone pre-treatment and requires further optimization or coupling with additional processes.

The synergistic potential of EC also extends beyond MBBR systems by coupling with other technologies to address limitations and tackle wider pollutant ranges. While EC excels at removing suspended matter, it can be less effective against stable dissolved organic pollutants, but when combined with advanced oxidation processes like electrooxidation, treatment efficiency improves dramatically. Studies show combined EC-EO processes eliminated 60% of COD compared to EC alone removing half, while hybrid EC-Chemical coagulation systems achieved 92.21% COD removal efficiency versus 62.51% for EC alone [26]. To further enhance treatment performance, the integration of Advanced Oxidation Processes (AOPs) is recommended as a tertiary polishing step. AOPs are well-documented for generating highly reactive hydroxyl radicals (OH^-) capable of degrading recalcitrant organic compounds that are not effectively removed by EC or biological processes [8], [26]. Previous studies have demonstrated that hybrid EC-AOP systems significantly improve COD removal efficiency compared to EC alone, particularly for stable dissolved organics. Therefore, incorporating AOPs after the MBBR unit would target residual sCOD and improve compliance with discharge standards.

4. Conclusion

The research demonstrates the potential of a hybrid Electrocoagulation–Moving Bed Biofilm Reactor (EC-MBBR) system for treating high-strength Palm Oil Mill Effluent (POME). The system effectively adjusted the acidic pH of the raw effluent to meet regulatory standards, with overall pollutant removal being significant. The highest efficiencies were achieved for sCOD at 66% and oil and grease at 81.38%, both using Copper (Cu) electrodes. In addition, TSS removal showed substantial improvement across the system, reaching up to 73.38% with Cu electrodes, indicating that the hybrid configuration is particularly effective in reducing particulate matter through the combined action of coagulation, adsorption, and biological processes. Among the tested electrode materials (Fe, Al, and Cu) in the EC unit, Copper electrodes demonstrated superior and more consistent performance in removing both TSS and sCOD. Given the EC unit’s role, future work should also address its byproducts particularly sludge by characterizing its composition and exploring sustainable management options, alongside a comprehensive economic analysis to evaluate electricity consumption and ensure a balance between removal efficiency and cost-effectiveness.

While the MBBR component performed well, particularly at longer hydraulic retention times, the EC unit's contribution to sCOD removal (9–18%) was lower than initially hypothesized. This indicates the need for further optimization of both components, including the KF pre-treatment unit, which showed a significant contribution to oil and grease removal due to its highly porous adsorbent properties. Optimization could focus on fiber density, contact time, and regeneration potential to maximize performance. Additionally, as the influent total nitrogen (TN) concentration of 95 mg/L greatly exceeds the discharge standard, adjustments to MBBR operating conditions such as controlled aeration to promote anoxic zones, are recommended to enhance nitrogen removal. Despite the overall success, final effluent concentrations for TSS and oil and grease did not consistently meet discharge standards, underscoring the need for integrated improvements. To achieve higher effluent quality suitable for water reuse, the system could benefit from a tertiary treatment step, such as Advanced Oxidation Processes (AOPs) or membrane filtration, to target recalcitrant pollutants.

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