

APPLICATION OF ACTIVATED CARBON IN THE TREATMENT OF PALM OIL MILL EFFLUENT: A COMPREHENSIVE REVIEW

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ABSTRACT

Palm oil mill effluent (POME) continues to pose a significant environmental threat across palm oil-producing regions due to its high organic load, persistent colour, and the presence of heavy metals and nutrients that often exceed regulatory discharge limits. This review synthesises findings from peer-reviewed studies published and indexed in the Scopus database between 2010 and 2025, focusing on the application of activated carbon (AC) for POME treatment. The reported removal efficiencies for key pollutants ranged from 55.00%–95.00% for chemical oxygen demand (COD), 60.00%–96.00% for biochemical oxygen demand (BOD), and up to 99.43% for colour, depending on the source material, surface area, and operating conditions. AC derived from agro-industrial wastes such as palm kernel shell (PKS), empty fruit bunches (EFB), rice husks, and sludge achieved surface areas up to 935 m²/g. Adsorption was primarily governed by surface complexation, ion exchange, and Van der Waals interactions. Process optimisation via response surface methodology (RSM) identified pH (3–10), adsorbent dosage (5–125 g/L), and contact time (30–240 min) as key variables. Thermal regeneration restored up to 94.00% of AC performance. The novelty of this review lies in its integrated approach combining pollutant-specific adsorption analysis, adsorption mechanisms, biomass-based AC synthesis, statistical process optimisation, and regeneration strategies-consolidating fragmented literature into a comprehensive resource. This review further outlines knowledge gaps and offers strategic recommendations for implementing low-cost, sustainable AC-based treatment technologies tailored for POME remediation.

Keywords: activated carbon, adsorption, palm oil mill effluent (POME), treatment, wastewater.

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INTRODUCTION

The palm oil industry plays a pivotal role in the economic development of many tropical countries, particularly in Southeast Asia, with Malaysia and Indonesia accounting for the majority of global palm oil production (Ahmad et al., 2022). However, alongside its economic benefits, palm oil processing generates vast volumes of highly polluted wastewater known as palm oil mill effluent (POME) (Anindita et al., 2024). POME is characterised by high chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), colour, nutrients

(e.g., nitrogen and phosphorus), and trace heavy metals (Yunanto et al., 2022). Without proper treatment, the discharge of untreated or partially treated POME into aquatic ecosystems poses serious environmental threats, including eutrophication, oxygen depletion, and long-term ecological imbalance (Aryanti et al., 2024).

Conventional treatment methods, such as anaerobic digestion and chemical coagulation, have been widely used for POME management (Aryanti et al., 2024; Lim et al., 2021). While these methods offer some advantages, they are often associated with long retention times, large land requirements, inconsistent treatment performance, and limited pollutant removal efficiency, particularly for colour and recalcitrant organics. As environmental regulations tighten and sustainable industrial practices gain importance, there is an urgent need for more efficient, affordable, and environmentally friendly treatment technologies.

Adsorption has emerged as a highly effective technique for POME treatment, especially for the removal of persistent pollutants (Hayawin et al., 2023). Among various adsorbents studied, activated carbon (AC) stands out due to its high surface area, porous structure, and superior adsorption capacity. Recent advances have enabled the production of AC from a wide array of agricultural and industrial waste materials, such as palm kernel shell (PKS), empty fruit bunches (EFB), rice husks, coconut shells, and cow bones (Embong et al., 2023; Saad et al., 2022). These low-cost biomass-derived carbons not only offer a sustainable waste management solution but also contribute to circular economy strategies in the palm oil sector.

In recent years, numerous studies have investigated the use of both raw and modified AC in POME treatment, targeting the removal of organic load, nutrients, and heavy metals (Abdulsalam et al., 2018). In addition, optimisation techniques, such as response surface methodology (RSM), have been employed to fine-tune operational conditions, while regeneration studies have explored the reuse potential of spent AC (Mahdi et al., 2024). Despite the growing body of literature, a comprehensive review focusing specifically on the application of AC for POME treatment remains lacking.

Therefore, this review aims to consolidate current knowledge on the synthesis, application, optimisation, and regeneration of AC used in POME treatment. It also highlights the adsorption mechanisms involved, summarises recent advances in composite and modified AC materials, and identifies challenges and research gaps to guide future studies and industrial-scale implementation.

NOVELTY OF REVIEW

POME remains one of the most critical environmental challenges in palm oil-producing countries due to its high organic load, persistent colour, heavy metals, and nutrient content that often exceed discharge limits, even after biological treatment. While AC has long been recognised as an effective adsorbent in wastewater treatment, its targeted application for POME has not been comprehensively reviewed with a focus on pollutant-specific removal performance, biomass-based AC development, and regeneration strategies. This review addresses this gap by critically analysing studies on the use of AC, particularly those derived from agro-waste materials like PKS, EFB, rice husks, and sludge in POME remediation. The novelty of this review lies in its integrated approach combining pollutant-specific adsorption performance, mechanistic insights, process optimisation using statistical models, and regeneration potential of spent carbon, which have rarely been consolidated in past works. By doing so, it offers both scientific clarity and industrial relevance, aligning with the pressing need for sustainable, low-cost, and high-efficiency post-treatment technologies in the palm oil sector, and resonates with the scope of the Journal of Oil Palm Research (JOPR) in advancing innovations within palm oil processing and waste management.

METHOD OF REVIEW

This review was conducted through a systematic analysis of relevant literature using the Scopus database, one of the most comprehensive and reliable sources for peer-reviewed scientific publications. A targeted search strategy was applied to identify research articles related to the application of AC in the treatment of POME. The search was limited to journal articles published between 2010 and 2025, written in English, and indexed in Scopus. The search terms were constructed using Boolean operators, specifically: TITLE-ABS-KEY ("POME" OR "palm oil mill effluent") AND TITLE-ABS-KEY ("activated carbon" OR "biochar" OR "adsorbent"), to ensure precision and relevance in the results.

After retrieving the initial set of articles, duplicates and unrelated studies were removed based on title and abstract screening. Articles were included if they focused on the use of AC (or its derivatives) in POME treatment, provided data on pollutant removal efficiencies (such as COD, BOD, TSS, heavy metals, nitrogen, and colour), and applied adsorption-based techniques. Exclusion criteria were applied to

remove studies that did not address POME, lacked experimental results, or did not utilise AC as a key adsorbent.

For each selected article, relevant data were extracted, including the type of AC used (e.g., PKS, EFB, rice husk), the activation method, surface area, operating conditions (pH, dosage, contact time), removal efficiencies, and any optimisation or regeneration approaches. This information was then thematically categorised to identify research trends, technological advancements, and knowledge gaps. The findings were synthesised into key discussion sections covering adsorption mechanisms, optimisation techniques, regeneration potential, and limitations, which form the structure of this review.

PALM OIL MILL EFFLUENT (POME): CHARACTERISTICS AND CHALLENGES

The POME is a high-strength industrial wastewater generated in large volumes during the processing of palm oil. It is characterised by a complex composition of organic and inorganic constituents, including suspended solids (SS), residual oil, nutrients, and dissolved organic matter. As reported by Quayson et al. (2020), POME, along with PKS, accounts for more than 60% of the total waste output from palm oil mills, highlighting the substantial environmental burden associated with palm oil production. The physicochemical properties of raw POME typically include high levels of BOD and COD, an acidic to neutral pH, and a dark brown colour due to tannins and oil residues. These properties contribute to significant water pollution potential if the effluent is discharged without adequate treatment.

From a biological standpoint, POME is highly biodegradable, supporting diverse microbial activity due to its elevated organic content. However, conventional biological treatment systems may not sufficiently reduce the concentrations of residual pollutants, necessitating additional post-treatment processes. Hossain et al. (2022) demonstrated that coagulation-flocculation using ferrous sulphate monohydrate ($\text{FeSO}_4 \cdot \text{H}_2\text{O}$) could effectively lower BOD, COD, and SS by up to 96%, 98%, and 97%, respectively. These findings reflect the persistent nature of pollutants in biologically treated POME and the need for multi-stage remediation.

Furthermore, the gas composition of POME-derived biogas presents another dimension of concern. According to Nor et al. (2021), simulated POME biogas consists of approximately 3,000 ppm hydrogen sulphide (H_2S), 40.0% carbon dioxide (CO_2), and 59.7% methane (CH_4), indicating a potential for air pollution and equipment corrosion if not properly treated. This reinforces the notion that POME is not only a water pollutant but also

contributes to gaseous emissions that require attention. In summary, the physicochemical and biological complexity of POME underscores the challenges in its treatment and disposal. Its rich organic and nutrient content necessitates integrated treatment approaches that combine physical, chemical and biological methods to achieve compliance with environmental discharge standards while enabling possible valorisation pathways.

ACTIVATED CARBON (AC): PROPERTIES AND ADSORPTION MECHANISMS

Sources and Types of Activated Carbon (AC)

Various types of AC have been applied in the treatment of POME, with significant emphasis on agricultural waste-based adsorbents, particularly those derived from oil palm residues (Table 1). Among the most widely utilised precursors is PKS, which has been repeatedly validated as an effective and sustainable raw material for AC production.

Zainal et al. (2025) demonstrated the use of AC in a continuous adsorption system for the final discharge treatment of POME. Their study showed > 90% removal efficiency for BOD, SS, and colour. This system was scaled up to a 50 m³/hr field-scale application, proving its operational feasibility and cost-effectiveness in a real industrial setting. Similarly, Hayawin et al. (2023) and Mubarak et al. (2023) used AC synthesised through a double-insulated carbonisation-activation process. The material exhibited high surface area (up to 935 m²/g) and efficient pollutant removal capacities for BOD, COD, TSS, and colour-reaching up to 97% removal. These findings confirm that AC is not only highly porous but also durable and regenerable.

Beyond palm-based materials, other biomass sources such as coconut shells, rice husks, and crab shells have also been converted into AC or biochar for POME treatment. Mahdi et al. (2024) reported the use of coconut shell-based AC (CAC) xerogels optimised for H_2S removal, while Saad et al. (2022) employed rice husk AC (RHAC) for decolourisation and COD reduction. In another study, Yang et al. (2024) developed KOH-activated biochar from crab shell waste (CSW) via microwave pyrolysis, which showed considerable adsorption capacity for BOD and COD from POME. In addition, some studies have advanced composite or modified adsorbents that incorporate AC. For instance, James et al. (2024) incorporated AC into a nanocomposite with titanium dioxide (TiO_2) and montmorillonite clay (MMT), achieving high removal rates of heavy metals and turbidity. Aqilah et al. (2024)

TABLE 1. OVERVIEW OF ACTIVATED CARBON (AC) SOURCES FOR POME TREATMENT

Source material	AC type	Key pollutants removed	Removal efficiency (%)	Reference
Oil palm kernel shell (OPKS)	Pilot and industrial scale	BOD, COD, SS, colour, turbidity, pathogens	>90% BOD, COD, colour; up to 97% SS	Hayawin et al. (2023)
Coconut shell	AC xerogel	H ₂ S from biogas	High efficiency at 25–50 ppm H ₂ S	Mahdi et al. (2024)
Rice husk	RHAC (KOH and NaOH activated)	Colour, TOC, COD	Up to 67% regeneration efficiency	Saad et al. (2022)
Crab shell waste (CSW)	Microwave pyrolysed KOH-activated biochar	BOD, COD	8.3 mg/g BOD, 42 mg/g COD	Yang et al. (2024)
Palm shell + TiO ₂ + MMT	Composite Nanomaterial with AC	Pb, Zn, COD, TSS, turbidity	Pb (86.7%), Zn (97.3%), turbidity (91.6%)	James et al. (2024)
Sand + AC	Filter media (sand + AC)	Turbidity, colour, COD, TSS	COD: 82.08–78.05%, TSS: 83.23–68.51%	Aqilah et al. (2024)
Electrocoagulation (EC) sludge	H ₃ PO ₄ -activated EC sludge AC	Colour, TSS in dye wastewater	TSS: 67%, colour: varies with dosage	Amalina et al. (2022)
Empty fruit bunch (EFB)	Microwave-activated biochar	BOD, COD	BOD 75%, COD 55%	Kong et al. (2022)
Palm shell vs. coconut shell	PKS and CAC (H ₂ SO ₄ -activated)	COD	854.7 mg/g AC, 826.4 mg/g CAC	Mustafa et al. (2022)
Palm kernel shell (PKS)	PKS (orthophosphoric acid-activated)	Lignin (colour)	Fractional lignin removal: 0.4 (40%)	Boontham et al. (2022)

Note: MMT - montmorillonite clay; PKS - palm kernel shell; PAC - palm shell-based activated carbon; KOH - potassium hydroxide; NaOH - sodium hydroxide; H₃PO₄ - phosphoric acid; CAC - coconut shell-based activated carbon; H₂SO₄ - sulphuric acid; PKS-AC - palm kernel shell activated carbon; BOD - biochemical oxygen demand; COD - chemical oxygen demand; SS - suspended solids; TSS - total suspended solids; H₂S - hydrogen sulphide; TOC - total organic carbon; Pb - lead; Zn - Zinc.

utilised a filter media combining sand and AC for semi-continuous filtration, significantly reducing turbidity, COD, and TSS.

Mustafa et al. (2022) compared palm shell-based activated carbon (PAC) and CAC, finding that both exhibited strong COD removal in batch adsorption studies and fitted well with the Langmuir isotherm model. The AC showed slightly higher maximum adsorption capacity, attributed to its superior surface characteristics. Finally, Amalina et al. (2022) proposed a novel source of AC derived from electrocoagulation (EC) sludge. Using chemical activation, the sludge was transformed into AC with promising surface properties for pollutant adsorption.

Physical and Chemical Characteristics

The performance of AC in treating POME is strongly influenced by its physical and chemical characteristics, including surface area, porosity, and surface functional groups. Various studies, as shown in Table 2, have demonstrated that the nature of the raw material, activation method, and modification process significantly affect the adsorptive properties of the final product. For instance, Nor et al. (2021) modified commercial palm shell AC through urea impregnation

and microwave irradiation, creating nitrogen-functionalised AC with enhanced basic surface functionalities. Characterisation by Fourier transform-infrared spectroscopy and nitrogen adsorption-desorption analysis confirmed improved sorption capacity (264.3 mg/g) for H₂S, indicating that nitrogen incorporation alters surface chemistry and enhances interaction with acidic gases like H₂S.

Similarly, Boontham et al. (2020) investigated AC produced via chemical activation using orthophosphoric acid. The treated AC exhibited high microporosity and increased surface area, which were essential for the successful adsorption of phenolic compounds in model POME. The phenol adsorption data followed the Langmuir isotherm model, where adsorption capacity increased proportionally with surface area. Wafti et al. (2017) developed AC from EFB using physical activation with CO₂ at different temperatures. The sample activated at 800°C showed the highest Brunauer–Emmett–Teller (BET) surface area analysis of 937 m²/g and excellent dye adsorption capacity (333.3 mg/g), demonstrating a correlation between activation temperature and surface development. The surface morphology also indicated a microporous structure ideal for adsorbing organic pollutants.

TABLE 2. OVERVIEW OF PHYSICAL AND CHEMICAL CHARACTERISTICS OF ACTIVATED CARBON (AC) FOR PALM OIL MILL EFFLUENT (POME) TREATMENT

Study	Raw material	Activation method	BET surface area (m ² /g)	Key features
Nor et al. (2021)	Palm shell	Urea impregnation + microwave irradiation (950°C)	Not reported (adsorption: 264.3 mg/g H ₂ S)	Nitrogen functionalities increased basicity and enhanced H ₂ S adsorption
Boontham et al. (2020)	Palm kernel shell	Chemical activation with orthophosphoric acid	Not specified (microporous confirmed)	High microporosity is effective for phenol adsorption, followed by the Langmuir isotherm
Wafti et al. (2017)	Empty fruit bunch (EFB)	Physical activation with CO ₂ at 800°C	937	High dye removal capacity; microporous structure
Liew et al. (2019)	Palm kernel shell	Microwave vacuum pyrolysis + NaOH-KOH chemical activation	1,320	Micro/mesoporous network; metal doping (Ni, Al) improved BOD/COD removal
Ngarmkam et al. (2011)	Palm shell	Chemical/physical activation + Fe oxide deposition	Not specified	Enabled magnetic recovery; effective oil removal; contained magnetite/maghemite

Note: BET - Brunauer-Emmett-Teller (surface area analysis); CO₂ - carbon dioxide; NaOH - sodium hydroxide; KOH - potassium hydroxide; Fe - iron; H₂S - hydrogen sulphide; Ni - nickel; Al - aluminium; COD - chemical oxygen demand; BOD - biological oxygen demand.

Liew et al. (2019) applied microwave vacuum pyrolysis combined with chemical activation using a NaOH-KOH mixture to produce AC from PKS. The resulting product had a high surface area (1,320 m²/g) with a micro- and mesoporous network. The ACs impregnated with Ni and Al showed improved BOD and COD removal from POME compared to unmodified AC, demonstrating the role of surface chemistry in enhancing adsorption efficiency. In another study, Ngarmkam et al. (2011) introduced magnetic properties to AC by depositing iron oxides. The material maintained a high adsorption capacity for oil removal and could be efficiently recovered using magnetic separation. The dual characteristics—porosity for adsorption and magnetism for recovery—highlight the potential of multi-functional ACs in POME treatment.

Adsorption Mechanisms Relevant to Palm Oil Mill Effluent (POME) Pollutants

The removal of contaminants from POME using AC primarily occurs through physical and chemical adsorption mechanisms. These mechanisms are governed by the physicochemical interactions between the AC surface and the diverse pollutants present in POME, including organic matter (BOD, COD), SS, colour pigments, phenolic compounds, heavy metals, and oil residues. *Figure 1* shows the overview of the adsorption mechanisms relevant to POME pollutants. Physical adsorption is predominantly driven by Van der Waals forces and is facilitated by the large surface area and

well-developed porosity of AC. Micropores (< 2 nm) and mesopores (2–50 nm) provide a high surface-to-volume ratio, enhancing the ability of AC to trap organic molecules and suspended particles. Studies such as Boontham et al. (2020) showed that microporous AC effectively removed phenol from POME, with adsorption following the Langmuir isotherm model, indicating monolayer adsorption on a homogeneous surface.

Chemical adsorption (chemisorption) involves stronger interactions, including hydrogen bonding, π - π interactions, and electrostatic forces between surface functional groups of AC and the targeted pollutants. For example, Nor et al. (2021) demonstrated that nitrogen-functionalised activated carbon (N-PSAC) had enhanced basicity due to the presence of amine and imine groups, which significantly improved the adsorption of acidic gases like H₂S in POME biogas. Similarly, functional groups such as hydroxyl, carboxyl, and carbonyl—commonly introduced via chemical activation (e.g., H₃PO₄ or KOH)—interact with polar organic compounds and metal ions through ion exchange or complexation.

In the case of colour and dye removal, which is relevant for tertiary POME treatment, Wafti et al. (2017) found that AC derived from EFB was effective in adsorbing synthetic dyes due to its high surface area and the presence of polar surface groups that interact with chromophoric compounds via π - π electron donor-acceptor interactions. The adsorption of heavy metals, as observed in Oyekanmi et al. (2019) using CAC, can be explained by coordination

Mechanisms of activated carbon in POME treatment

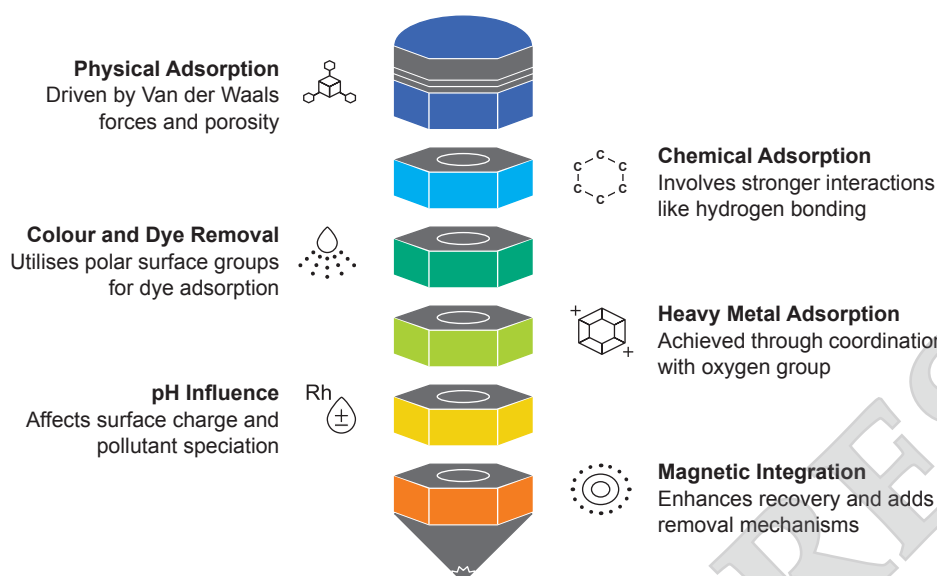


Figure 1. Overview of physical and chemical adsorption mechanisms for palm oil mill effluent (POME).

between metal ions and oxygen-containing surface groups (e.g., carboxylates). Additionally, pH plays a crucial role in adsorption mechanisms by influencing both the surface charge of AC and the speciation of pollutants in solutions. At low pH, the surface becomes more protonated, enhancing the adsorption of anionic species, while at higher pH levels, the deprotonation of surface groups facilitates cation exchange.

Moreover, the integration of magnetic components, such as iron oxides, into the carbon matrix, as shown by Ngarmkam et al. (2011), not only provides easy recovery of spent adsorbent but also contributes to additional removal mechanisms, including ligand exchange and redox reactions, particularly for metal-laden POME. In summary, the effectiveness of AC in POME treatment arises from the synergistic contribution of physical entrapment in porous structures and chemical interactions with functional groups on the carbon surface. Tailoring surface chemistry through activation and modification enhances the specificity and efficiency of adsorption mechanisms, making AC a versatile and robust adsorbent for a wide range of POME contaminants.

APPLICATION OF ACTIVATED CARBON (AC) FOR PALM OIL MILL EFFLUENT (POME) TREATMENT ORGANIC POLLUTANT REMOVAL

The POME contains a high concentration of biodegradable organic pollutants, including COD, BOD, and total organic carbon (TOC). These parameters (Table 3) are critical indicators of water

quality and environmental impact. Numerous studies have focused on enhancing the removal of these pollutants through various biological, physical, and hybrid treatment systems, with AC playing a pivotal role in adsorption and polishing steps. Co-digestion approaches have shown promise in enhancing organic pollutant removal. Lim et al. (2021) reported that co-digesting POME with decanter cake at a 0.8:1 volatile solid ratio significantly improved methane yield by 186.00% and achieved up to 99.42% COD and volatile solids (VS) removal efficiency. The integration of substrates increased the biodegradability of the feedstock and stabilised biogas production, demonstrating effective organic load reduction.

Bioadsorption and filtration systems have also been explored using agro-waste-derived materials. Lee et al. (2021) used oil palm frond fibre as a natural filtration medium and achieved 55.21% COD and 26.44% BOD removal, in addition to 98.00% TSS removal. While OPF filters showed moderate performance for organic pollutant removal, their sustainability and availability offer environmental and economic advantages, especially when combined with other treatment methods.

The AC, especially from PKS, has been widely applied as a polishing adsorbent for biologically treated POME. Tan et al. (2021) synthesised magnetic AC and achieved 85.00% COD and 99.70% colour removal under optimised conditions. The adsorbent showed high surface area and magnetic properties, allowing easy recovery and reuse with minimal efficiency loss over four treatment cycles. Similarly, Nahrul Hayawin et al. (2020) demonstrated the effectiveness of a continuous adsorption column packed, which enhanced COD

TABLE 3. ORGANIC POLLUTANT REMOVAL

Study	Treatment approach	Pollutants removed	Efficiency (%)	Keynotes
Lim et al. (2021)	Co-digestion (POME + Decanter cake)	COD, VS	COD: 99.42	Enhanced methane yield (186% increase)
Lee et al. (2021)	OPF filter	COD, BOD, TSS	COD: 55.21, BOD: 26.44, TSS: 98	Sustainable and biodegradable filter material
Tan et al. (2021)	Magnetic AC adsorption	COD, colour	COD: 85, colour: 99.7	Magnetic AC for easy recovery; reusable over 4 cycles
Nahrul Hayawin et al. (2020)	Continuous AC-OPKS adsorption column	COD, BOD, TSS, colour	COD: 92.79, BOD: 93.52, TSS: 94.84	Outperformed batch system; met DOE discharge limits
Tai et al. (2020)	PAC in AnMBRs	COD	COD: 89.45	Small PAC improved COD removal and membrane fouling control
Ng et al. (2018)	PAC-Integrated membrane	COD, colour	COD: 81, colour: 67	Enhanced permeation; reduced membrane fouling
Lee et al. (2020)	Ultrasound + Coagulation + AC	COD, BOD, TSS, colour	COD: 88.1, BOD: 89.7, TSS: 99.5	Hybrid system yielded high removal across all pollutants
Liew et al. (2019)	PKS-AC via pyrolysis + Metal impregnation	BOD, COD, TSS, O&G	High removal (exact % not stated)	High surface area AC (1,320 m ² /g); cost-effective synthesis
Zainal et al. (2018)	Double-insulated reactor AC	COD, BOD, TSS, colour	COD: 68, BOD: 90, TSS: 97, colour: 83	Efficient AC production and effluent polishing
Lee et al. (2019)	MFC + Adsorption	COD, BOD, energy recovery	COD: 93.57; power output: 74 mW/m ³	Dual benefit: treatment + energy from MFC

Note: AC - activated carbon; POME - palm oil mill effluent; OPF - oil palm frond; PKS-AC - palm kernel shell activated carbon; AC-OPKS - oil palm kernel shell activated carbon; PAC - palm shell-based activated carbon; MFC - microbial fuel cells; COD - chemical oxygen demand; VS - volatile solids; BOD - biological oxygen demand; TSS - total suspended solids; O&G - oil and grease; DOE - Department of Environment (Malaysia); AnMBRs - anaerobic membrane bioreactors.

and BOD removal up to 92.79% and 93.52%, respectively, meeting environmental discharge standards.

PAC has been applied to improve membrane bioreactor performance. Tai et al. (2020) showed that PAC with smaller particle sizes ($\approx 75 \mu\text{m}$) increased COD removal to 89.45%, improved biomass flocculation, and reduced membrane fouling. In another study by Ng et al. (2018), integrating PAC into a polyethersulphone membrane system enhanced permeation and achieved 81.00% COD and 67.00% colour removal, indicating AC's role not only in adsorption but also in membrane fouling mitigation.

Hybrid treatment technologies, combining coagulation, cavitation, and adsorption, have been particularly effective. King et al. (2019) demonstrated that combining ultrasound cavitation, ferric chloride, chitosan, and AC yielded COD and BOD removal efficiencies above 88%, with excellent TSS and colour reduction. These multi-step systems offer robustness and high efficiency, especially for raw POME.

Advanced thermal activation techniques further enhanced AC quality. Liew et al. (2019) produced highly porous AC (1,320 m²/g surface area) from PKS via microwave vacuum pyrolysis and chemical activation, achieving significant BOD and COD reductions with nickel (Ni)/aluminium (Al)-impregnated AC. Similarly, Zainal et al. (2018)

developed a double-insulated reactor for steam activation, achieving up to 90.00% BOD and 68.00% COD removal, confirming the importance of carbon structure and surface chemistry. Microbial fuel cells (MFCs) integrated with adsorption have also emerged as promising systems. Tee et al. (2018) reported COD removal up to 93.57% at optimal temperatures in an MFC-adsorption hybrid system, while Lee et al. (2019) achieved 64.40% COD removal and simultaneous biogas generation, emphasising the dual benefit of waste treatment and energy recovery.

INORGANIC CONTAMINANT REMOVAL

The POME contains not only high levels of organic matter but also significant amounts of inorganic contaminants, particularly heavy metals such as zinc (Zn), lead (Pb), manganese (Mn), and cadmium (Cd). These elements pose long-term risks to aquatic ecosystems and human health. The development of effective, low-cost, and environmentally sustainable treatment technologies is critical for reducing the concentrations of these contaminants to meet environmental discharge standards.

Advanced composite adsorbents incorporating AC and metal oxides have demonstrated significant potential in removing heavy metals from POME. James et al. (2024) developed a novel nanocomposite

powder containing TiO₂, MMT, and potassium hydroxide-activated carbon (KOH-AC). This hybrid material exhibited high removal efficiencies for Pb (86.7%) and Zn (97.3%), supported by the photocatalytic activity of TiO₂ and the high adsorption surface of MMT and AC. Additionally, the treatment significantly reduced turbidity (91.6%) and lowered COD and TSS levels, yielding effluent that met Malaysia's Environmental Quality Act 1974 standards.

In a similar effort, Rahman et al. (2023) engineered polylactic acid (PLA)-reinforced biochar composites modified with TiO₂ producing a porous structure through H₂SO₄ activation and ball milling. This eco-friendly composite demonstrated excellent compatibility among PLA, ground biochar (GB), and TiO₂, with adsorption efficiencies of 94.4% for Mn, 88.4% for Cd, and 94.4% for Zn. The scanning electron microscopy (SEM) and BET analyses confirmed enhanced porosity and surface area, which contributed to improved binding and uptake of heavy metals. The post-treatment POME exhibited acceptable levels of turbidity, COD and TSS, indicating the suitability of this method for practical applications.

Natural adsorbents such as coconut shell and cow bone AC have also proven effective for heavy metal remediation. Adeleke et al. (2017) demonstrated that both materials could achieve over 90% removal of zinc ions from raw POME under optimal conditions (pH 7, 105 min contact time, 150 rpm shaking). Among the two, coconut shell carbon showed slightly better performance. The adsorption data fit well with the BET model for coconut shell carbon and the Langmuir model for cow bone powder (CBP), indicating different surface interaction mechanisms. The SEM analysis confirmed the pore structure's adequacy in supporting ion exchange and surface adsorption.

The CBP, as a novel bio-adsorbent, was further investigated by Latiff et al. (2016) for Mn removal. The study reported exceptionally high removal efficiencies of 98.3% and 98.4% for two different POME samples at 15 g dosage levels. Even at the lower dosage of 5 g, the media showed an average removal rate of 95.34%. The high surface roughness observed under atomic force microscopy, combined with effective adsorption kinetics, supports CBP's viability as an alternative to conventional AC.

COLOUR AND ODOUR REMOVAL

Colour and odour in POME are primarily caused by complex and recalcitrant organic compounds such as lignin, tannins, and phenolics that are not fully removed by conventional biological treatments. Their persistence contributes to visual pollution,

offensive smell, and potential toxicity, making further treatment essential before discharge or reuse. To address these challenges, adsorption technologies, especially those employing AC, have emerged as highly effective polishing steps to enhance effluent quality.

Among the various approaches, PKS-AC has received considerable attention due to its availability and adsorption performance. In a study by Tan et al. (2021), the AC impregnated with iron oxide was developed to enhance magnetic separation and regeneration capability. The adsorbent achieved a remarkable 99.7% colour removal and 85.0% COD reduction under optimised conditions (pH 3.5, 9.9 g/L dosage, 3.4 hr contact time), maintaining its effectiveness over four treatment cycles. This study not only demonstrates the suitability of PKS-AC for POME polishing but also exemplifies how waste valorisation can align with sustainable palm oil production.

Building upon this concept, hybrid treatment systems that integrate coagulation, ultrasound, and adsorption have shown further potential. Lee et al. (2020) reported a synergistic system combining ultrasound cavitation, ferric chloride, and AC. This setup achieved near-complete colour removal (99.90%), along with significant reductions in COD (88.05%) and BOD (89.74%). The study highlights the benefits of coupling physical and chemical processes, particularly for POME treatment systems constrained by limited space or long retention times required in ponding systems.

While these studies focus on conventional and hybrid AC applications, emerging materials such as graphene-like carbon (GSC) have also been synthesised from POME itself, further promoting circular economy practices. Teow et al. (2019) demonstrated that GSC derived from POME could effectively decolorise methylene blue solution, with visible transformation from blue to clear. Although tested on synthetic dye, the performance indicates strong potential for removing chromophoric compounds naturally present in POME, reinforcing the role of green adsorbents in advanced treatment schemes.

Complementary to these innovations, CAC has also proven effective. Kaman et al. (2016) found the AC capable of achieving around 70% removal of COD, TSS, and colour. The adsorption equilibrium was reached within 30 hr, and isotherm modelling showed Langmuir behaviour, suggesting monolayer adsorption. These findings underscore the practical potential of agricultural by-products in decentralised or small-scale POME treatment operations.

In addition to plant-derived adsorbents, biosorbents from fruit waste, such as banana peels, have shown competitive performance. Mohammed & Chong (2014) evaluated natural and modified

banana peels, with banana peel AC showing up to 95.96% colour removal and 97.00% reduction in other key pollutants such as COD, BOD, and TSS. The data best fitted the Redlich-Peterson isotherm and pseudo-second-order kinetics, indicating that chemisorption played a dominant role. This supports the feasibility of utilising low-cost organic waste in community-level or rural effluent treatment setups.

Further advancement has been achieved through integration with membrane bioreactor systems, enhancing overall performance and reducing biofouling. Yuniarto et al. (2013) incorporated powdered AC and zeolite into aerobic submerged membrane bioreactors. These systems achieved significantly improved effluent colour quality (residual colour 16–26 Pt-Co) compared to controls (80 Pt-Co) and maintained stable operation due to improved flux and reduced membrane fouling. Such configurations represent promising options for high-strength POME in industrial applications.

To support optimisation of these processes, statistical modelling techniques like RSM have been utilised to fine-tune operating conditions. Alkhatib et al. (2015) applied central composite design (CCD) to evaluate the impact of pH, time, and AC dosage on colour removal. Their model predicted a maximum removal of 89.95% at optimal conditions, with the adsorption following Langmuir isotherm behaviour. This exemplifies the role of data-driven approaches in maximising treatment efficiency and minimising operational costs.

ADSORPTION OPTIMISATION TECHNIQUES

The optimisation of adsorption parameters is vital for enhancing the performance and cost-effectiveness of POME treatment. Various statistical

and experimental design approaches, particularly RSM and CCD, have been employed to optimise key variables influencing adsorption efficiency, such as pH, contact time, adsorbent dosage, particle size, and agitation speed, as shown in *Table 4*.

A notable study by Adeleke et al. (2017) demonstrated the use of RSM for optimising the removal of COD and ammonia-nitrogen ($\text{NH}_3\text{-N}$) using a composite based on activated CBP. Six independent parameters, pH, agitation speed, contact time, particle size, dilution factor, and adsorbent dosage, were optimised. The best performance was achieved at pH 10, a dosage of 125 g/L, and a particle size of 3 mm, yielding 89.6% and 75.6% removal for COD and $\text{NH}_3\text{-N}$, respectively. The study highlighted the value of multivariable optimisation over traditional one-factor-at-a-time (OFAT) approaches and confirmed the role of surface functionalities and thermal stability of the adsorbent in adsorption efficiency.

In another work, Amosa et al. (2016) applied CCD and factorial design to study the sorption of hardness and alkalinity using a bifunctional powdered AC derived from EFB. The statistical analysis showed that adsorbent dosage, agitation speed, and contact time significantly influenced the removal performance. High R^2 values confirmed the validity of the model, and desirability functions were used to reconcile optimal conditions for both contaminants. The adsorption equilibrium was well described by the Langmuir isotherm, and the kinetic data aligned with the pseudo-second-order model, indicating chemisorption as the dominant mechanism.

Amosa et al. (2015) further reinforced the utility of Design-Expert® software in two-step optimisation of COD removal using EFB-derived PAC. Initial factorial screening identified the influential parameters, while subsequent RSM modelling led to a maximum COD removal of 84%. The PAC was

TABLE 4. OVERVIEW OF ADSORPTION OPTIMISATION TECHNIQUES FOR POME TREATMENT

Study	Adsorbent material	Optimisation method	Key parameters optimised	Best performance
Adeleke et al. (2017)	Activated cow bone powder (CBP)	Response surface methodology (RSM)	pH, speed, contact time, particle size, dilution, dosage	89.6% COD & 75.6% $\text{NH}_3\text{-N}$ removal
Amosa (2016)	EFB-based PAC	Central composite design (CCD), RSM	Dosage, agitation speed, contact time	Langmuir fit; pseudo-second-order kinetics
Jamali & Jahim (2016)	Granular activated carbon (support media)	RSM (Quadratic Model)	pH, temperature, sludge % (for biohydrogen production)	1.22 mol H_2 /mol sugar; ~32 mL H_2 /L/ha yield
Amosa et al. (2015)	EFB-based PAC	Factorial design and RSM	PAC dosage, contact time, agitation	84% COD removal (227 ppm residual)
Amosa (2015)	EFB-based PAC	One-factor-at-a-time (OFAT)	Steam flow rate, pyrolysis activation parameters	95% Mn & 90% H_2S removal at 886.2 m^2/g BET surface area
Asih et al. (2014)	AC (immobilisation support)	Experimental screening	Lipase immobilisation conditions (material type)	94% lipase immobilisation efficiency

Note: AC - activated carbon; $\text{NH}_3\text{-N}$ - ammonia-nitrogen; Mn - manganese; BET - Brunauer-Emmett-Teller.

extensively characterised using SEM and FTIR, confirming its microporous nature and presence of functional groups favourable for adsorption. The study provided critical optimisation data supporting future scale-up applications.

Another optimisation strategy, the OFAT method, was explored in a follow-up study by Amosa (2015), where pyrolysis parameters, particularly steam flow rate, were optimised to produce high-performance PAC. An 8.0 mL/min steam flow rate yielded PAC with a BET surface area of 886.2 m²/g and high uptake efficiencies for Mn (95%) and H₂S (90%). Despite the limitations of OFAT in assessing interaction effects, the study demonstrated its usefulness for initial process parameter screening.

Beyond adsorption of conventional pollutants, optimisation also played a role in bioprocess integration. Asih et al. (2014) conducted a pilot-scale lipase production using POME as the fermentation medium and optimised immobilisation parameters for the produced enzyme. Among the various materials tested, AC showed the highest immobilisation efficiency (94%), demonstrating its multifunctionality as both an adsorbent and biocatalyst carrier. Overall, optimisation techniques such as RSM, CCD, and OFAT have played a pivotal role in refining the adsorption processes for POME treatment. These approaches not only improve pollutant removal efficiency but also support the design of scalable, resource-efficient treatment systems, making them indispensable tools in the advancement of sustainable wastewater management.

REGENERATION AND REUSABILITY OF ACTIVATED CARBON (AC)

The regeneration and reusability of AC are crucial aspects in the sustainable treatment of POME, particularly to reduce operational costs and minimise secondary waste. Various studies have explored the ability of AC to maintain its adsorption performance over multiple cycles, employing different regeneration strategies such as thermal treatment, chemical activation, and composite design modifications. These studies demonstrate that reusing AC can maintain or even enhance pollutant removal performance if properly optimised.

To begin with, Hayawin et al. (2023) demonstrated the successful regeneration of PKS-AC via thermal treatment in a continuous up-flow adsorption system. The regenerated PKS-AC, treated at 900°C for 1 hr, exhibited even higher removal efficiencies than the virgin material, 94.00% for BOD, 99.43% for colour, and 97.36% for SS. This work highlights the effectiveness of thermal regeneration not only in restoring

adsorption capacity but also in enhancing the overall performance of the adsorbent for repeated use in POME treatment.

Building upon the concept of converting biomass waste into functional adsorbents, Kong et al. (2022) introduced a microwave-assisted activation method using EFB. Although their study on granular activated carbon (GAC) did not include regeneration cycles, the high surface area (365.6 m²/g) and favourable pore structure of the activated biochar suggest potential for multiple reuse cycles. This highlights the importance of precursor material and activation technique in determining reusability outcomes.

In line with sustainable alternatives, Dashti et al. (2022) combined chickpea-based coagulation with GAC for POME treatment. While the study did not perform explicit regeneration tests, the system achieved high COD and colour removal efficiencies (88% and 91%, respectively), indicating that GAC retained its capacity after pretreatment steps. These findings suggest the potential for integrating biobased coagulants and adsorbents into a circular treatment framework.

Similarly, Hossain et al. (2022) investigated FeSO₄·H₂O-based coagulation as a pre-treatment to biological POME effluent. Though regeneration of AC was not a primary focus, their high removal rates for BOD, SS, and COD, up to 98%, reinforce the necessity for pairing such coagulation systems with reusable adsorbents to reduce cost and waste. It further emphasises the importance of coupling pre-treatment with recyclable adsorption materials for enhanced process efficiency.

Another relevant contribution comes from Mustafa et al. (2022), who compared PKS-AC and CAC. Their batch experiments demonstrated exceptional COD adsorption capacities and strong conformance to the Langmuir isotherm, yet regeneration was not assessed. Nevertheless, the high adsorption capacity and structural integrity of these carbons indicate potential for successful regeneration, especially under controlled chemical or thermal conditions.

Transitioning to novel material sources, Amalina et al. (2024) explored the reuse of electrocoagulated sludge from POME to produce AC. This innovative approach not only valorises industrial waste but also offers a cost-effective and environmentally sound adsorbent with strong adsorption potential. The H₃PO₄-activated sample had significantly higher surface area and performance than KOH-AC, underscoring how the activation method directly influences regeneration potential.

In terms of practical regeneration, Saad et al. (2022) conducted one of the few multi-cycle studies using RHAC. Their results showed a notable decline in adsorption efficiency from 67.26% in the first cycle to only 2.72% by the fifth cycle. This

sharp performance drop indicates the limitations of RHAC under repeated use and highlights the need for improved regeneration methods to preserve adsorbent efficiency over time. Finally, Jun et al. (2021) introduced two composite materials-iron oxide-doped and zeolite-supported PKS-AC. Their reusability test over five cycles revealed a minimal decline of just 5.60% in removal efficiency, especially for colour pollutants. These findings showcase how surface modification and composite engineering can significantly enhance both the durability and regenerative performance of AC-based materials.

INTEGRATING ELECTROCOAGULATION (EC) PRE-TREATMENT WITH ACTIVATED CARBON (AC) ADSORPTION FOR PALM OIL MILL EFFLUENT (POME)

In recent years, EC has emerged as a viable green pre-treatment technology for complex wastewaters rich in organic matter and heavy metals, including river water impacted by palm oil plantation run-off. Studies by Dashti et al. (2022) and Hossain et al. (2022) highlight the effectiveness of integrating coagulation–flocculation with adsorption for improving pollutant removal from POME. Similarly, study focused on Borneo's urban and midstream river systems has demonstrated that EC using aluminium electrodes can significantly reduce COD, turbidity, and trace metals such as iron, Mn, and lead-even in highly coloured and acidic waters affected by peat and palm run-off.

The application of EC for POME pre-treatment aligns well with these regional studies. For example, batch EC systems designed for Borneo's tropical water bodies achieved > 90% COD and colour removal under optimised current densities and pH conditions, with minimal sludge generation and no need for chemical coagulants. The integration of EC with AC adsorption can offer a synergistic approach: EC destabilises colloidal particles and reduces organic load, thereby enhancing the adsorption performance and extending the lifespan of AC media in subsequent stages.

This combined process is especially relevant for rural palm oil mills and plantation zones in Southeast Asia, where decentralised, cost-effective, and low-energy systems are critical. The integration of EC-AC systems can also reduce fouling in downstream membrane units or biological stages, making it an attractive solution for full-scale applications. However, challenges remain regarding energy optimisation, electrode corrosion, and the regeneration of spent carbon in hybrid systems. These gaps warrant further pilot-scale studies in real mill environments to validate the economic and environmental sustainability of EC-AC systems for POME treatment.

CHALLENGES, LIMITATIONS AND KNOWLEDGE GAPS

Despite significant progress in utilising AC and bio-based adsorbents for POME treatment, several challenges and limitations still hinder their practical deployment and upscaling. These obstacles span from material sourcing and process efficiency to regeneration capability and long-term environmental impact, indicating the need for further investigation and innovation in this domain.

One of the foremost challenges is the inconsistency in adsorbent regeneration performance across different precursor materials and regeneration methods. For example, Saad et al. (2022) reported a drastic decline in adsorption capacity across five cycles of RHAC regeneration, dropping from 67.26% to 2.72%. This sharp decline illustrates a significant limitation in adsorbent stability and reusability, especially when regeneration methods are not optimised for specific material properties. Moreover, while Hayawin et al. (2023) successfully regenerated PKS-AC with enhanced performance, such high-temperature thermal regeneration (900°C) may be economically and energetically impractical for large-scale operations.

Another critical issue is the lack of standardisation in optimisation techniques and operational parameters. Different studies apply diverse optimisation strategies making cross-comparison difficult. Additionally, optimal conditions vary significantly among studies, even when similar adsorbents or precursors are used. This variability introduces uncertainty in predicting adsorbent performance under real industrial conditions. Moreover, few studies include long-term assessments of adsorption stability, leaching of heavy metals, or performance in dynamic (continuous-flow) systems.

A major technological gap exists in scaling laboratory successes to full-scale industrial applications. Most current studies, such as those by Kong et al. (2022) and Mustafa et al. (2022), is limited to batch or bench-scale studies. Although promising in terms of pollutant removal efficiency, these approaches do not fully address process integration, adsorbent recovery, cost-effectiveness, or the environmental implications of large-scale deployment. For instance, ACs derived from palm and coconut shells showed excellent COD removal, yet their commercial viability remains uncertain without lifecycle assessments and economic feasibility analyses.

In addition, studies rarely evaluate the selectivity of AC toward specific POME pollutants, such as heavy metals vs. organics or colorants. For example, while Jun et al. (2021) focused on colour

and degradation efficiency, a comprehensive insight into how different adsorbent structures influence multi-pollutant removal is still lacking. The synergistic role of composite materials (e.g., iron oxide, zeolite, TiO_2) has shown promise, but further exploration is needed to optimise formulation, functional group interactions, and regeneration compatibility.

The EC is a versatile and compact wastewater treatment method that effectively removes organic matter, SS, and heavy metals by generating coagulants *in situ* using metal electrodes. While it offers minimal chemical usage and high removal efficiency for POME, the challenges remain related to electrode passivation, energy consumption, and sludge disposal, especially in long-term or continuous applications.

Lastly, environmental and economic assessments of adsorbent production and disposal are underreported. Although several studies (e.g., Amalina et al. [2022] and Dashti et al. [2022]) have explored waste-derived adsorbents like EC sludge or chickpea coagulants, few have analysed their environmental footprint or end-of-life management. The sustainability of converting solid waste into AC must be evaluated in terms of energy consumption, chemical use, and emissions to determine whether these adsorbents offer a truly green alternative.

CONCLUSION

The application of AC in treating POME has gained significant attention due to its effectiveness in removing a wide range of pollutants. This review highlights that AC derived from various biomass sources—such as PKS, coconut shells, cow bones, rice husks, and even EC sludge—demonstrates high efficiency in adsorbing organic and inorganic contaminants, including COD, BOD, TSS, colour, and heavy metals like Pb, Zn, Cd, and Mn. Modified or composite adsorbents, such as those incorporating TiO_2 , polylactic acid (PLA), or zeolite, have further improved performance through synergistic adsorption-photocatalytic mechanisms, offering multifunctional pollutant removal capabilities.

Optimisation strategies, particularly RSM, have proven essential in fine-tuning operational parameters to maximise adsorption efficiency. These approaches have enabled the identification of ideal conditions such as pH, contact time, dosage, and particle size for enhanced pollutant reduction. Moreover, regeneration studies show that thermally and chemically regenerated AC, especially when optimised for temperature and contact time, can achieve pollutant removal efficiencies comparable or even superior to virgin AC. This opens avenues

for improving the sustainability and economic feasibility of AC-based systems in real-world applications.

Despite these advancements, several challenges and limitations remain. There is a lack of long-term regeneration data, limited industrial-scale implementation, and insufficient standardisation across optimisation protocols. In addition, many studies focus on laboratory-scale performance without addressing energy requirements, cost analysis, or life-cycle impacts. These gaps highlight the need for future studies that bridge the lab-to-field gap through pilot-scale trials, techno-economic assessments, and comprehensive environmental evaluations.

Therefore, future works should prioritise scalable and energy-efficient regeneration methods, such as microwave-assisted or chemical regeneration. Standardising optimisation protocols across different AC types would also facilitate reliable comparisons and industrial adoption. Moreover, composite adsorbents integrating biomass-based carbon with functional materials should be further explored for their enhanced selectivity and multifunctionality. Finally, incorporating life cycle assessment and cost-benefit analysis in POME treatment studies will provide a clearer understanding of the environmental and economic viability of these systems. In conclusion, AC remains a promising solution for sustainable POME management, but achieving large-scale impact requires coordinated efforts in material innovation, process optimisation, and system-level evaluation.

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