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Review Article

State of The Art Evolution of Adsorption Wastewater From Crude Palm Oil Industries

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Abstract

Wastewater from crude palm oil production is among the most concentrated agro-industrial effluents, characterized by very high organic loads, suspended solids, and variable composition. Conventional treatments often struggle to consistently remove recalcitrant pollutants, such as phenolics, colored compounds, and emulsified oil. As a result, adsorption has gained global attention as a versatile and efficient alternative method. This review summarizes the recent advances in adsorption technologies for crude palm oil wastewater treatment. This review highlights the progress in adsorbent development, including biochar, mineral composites, layered double hydroxides, magnetic hybrids, and other engineered materials. The key removal mechanisms for organics, nutrients, and colloids are examined, alongside insights from kinetic, isotherm, and thermodynamic studies. The integration of adsorption with biological, membrane, and oxidation processes is also discussed, demonstrating improved removal efficiency and enhanced effluent stability compared to individual processes. Major challenges remain, particularly in terms of mechanical stability, regeneration, competitive adsorption, and large-scale validation. Future research should prioritize process intensification, sustainable regeneration methods, circular economy-based adsorbent production, and life cycle assessment. Overall, adsorption represents a promising pathway toward more sustainable and reliable crude palm oil wastewater management

Keywords: Adsorption; CPO, environmental remediation, POME, wastewater treatment

1. Introduction

The crude palm oil (CPO) industry is one of the largest agro-industrial sectors worldwide, producing more than 78.9 million metric tons of palm oil annually. The palm oil industry supports major economic growth across Southeast Asia, Africa, and South America; however, it also generates substantial volumes of wastewater, widely known as palm oil mill effluent (POME). Untreated or inadequately treated POME contains extremely high concentrations of chemical oxygen demand, biological oxygen demand, total suspended solids, oil and grease, phenolic compounds, organic acids, and nutrients (Anwar et al., 2024; Bala et al., 2015). The discharge of this highly polluted effluent creates serious environmental concerns, including oxygen depletion in aquatic systems, eutrophication, soil degradation, and the release of greenhouse gases (Adegbola et al., 2020; Jumadi et al., 2020). The increasing strictness of environmental regulations, combined with the global emphasis on sustainable industrial operations, has created a critical need for efficient and economically viable wastewater treatment solutions.

A wide variety of POME treatment technologies have been investigated, such as ponding systems (Jumadi et al., 2020), coagulation and flocculation (Bhatia et al., 2007), anaerobic digestion (Khadaroo et al., 2019), membrane filtration, and advanced oxidation processes (Khan et al., 2025; Yashni et al., 2021). Although these technologies have been implemented in many regions, they face several persistent challenges. These challenges include long hydraulic retention times, high operational costs, production of secondary sludge, sensitivity to fluctuations in influent quality, membrane fouling, and incomplete degradation of recalcitrant organic pollutants. Over the past decade, adsorption has gained significant attention as a promising alternative because it provides high efficiency with relatively low energy requirements, simple operation steps, adjustable surface chemistry, and a strong capability to remove a broad spectrum of contaminants (Mohammed et al., 2014; Shavandi et al., 2012). The rapid development of engineered adsorbents, such as modified biochar (Wibowo et al., 2022, 2025c), clay-based adsorbents (Taher et al., 2023a), layered double hydroxides (Taher et al., 2024; Wibowo et al., 2025), carbonaceous nanomaterials (Ahlawat et al., 2020), and magnetic composites (Wibowo et al., 2025), has further improved pollutant uptake, process stability, and reusability.

Although many studies have explored adsorption for POME treatment, the available scientific literature remains fragmented. Existing reviews usually concentrate on general POME treatment technologies, biosorption using agricultural waste, or biochar-based approaches. These reviews rarely provide an integrated analysis of the evolution of adsorption technology. They also do not systematically compare advanced engineered adsorbents and do not combine discussions on adsorption mechanisms, surface functionalization strategies, hybrid system integration, and techno-environmental considerations. Currently, there is no comprehensive review that synthesizes the full state-of-the-art development of adsorption for wastewater from the CPO industry or critically evaluates adsorbent performance in relation to mechanisms, modification routes, regeneration capability, and scalability.

This review aims to address these gaps. The objectives of this study are as follows. First, to consolidate the progression of adsorption technologies that have been applied to CPO wastewater. Second, to provide a critical analysis of the performance of natural, modified, and nanostructured adsorbents. Third, mechanistic insights governing the adsorption behavior of key POME pollutants were discussed. Fourth, we highlight functionalization strategies that enhance selectivity, adsorption capacity, and long-term reusability. This article also integrates recent developments in hybrid systems, identifies barriers that hinder large-scale applications, and proposes future research pathways that include sustainability assessment, circular material design, and the potential use of digital modeling. The novelty of this study lies in the presentation of the first comprehensive and unified assessment of adsorption technologies for wastewater from the crude palm oil industry. This review spans material advancements, mechanistic understanding, hybrid process development, and future technological directions. This study provides a scientific foundation for the design of next-generation adsorbents and supports the advancement of sustainable wastewater management in the global palm oil sector.

2. Methods

2.1 Review Design and Scope Definition

This study was conducted as a structured and systematic literature review aimed at synthesizing the evolution of adsorption technologies for wastewater generated from crude palm oil (CPO) industries, commonly known as POME. This review critically evaluates advancements in adsorbent materials, mechanistic understanding, surface modification strategies, regeneration performance, and the integration of adsorption into hybrid treatment systems. Rather than focusing solely on reporting adsorption capacity values, this review emphasizes technological progression, comparative material performance, and practical applicability under realistic wastewater conditions. The scope includes natural adsorbents, engineered composites, nanostructured materials, and system-level integration strategies to provide a comprehensive and unified assessment of the development of adsorption for CPO wastewater treatment.

2.2 Literature Search Strategy

A comprehensive literature search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Wiley Online Library, and supplementary sources accessed through Google Scholar. The search covered publications from 2000 to 2025, with particular emphasis on research published after 2015, to capture recent advances in engineered adsorbents and hybrid treatment configurations. Keyword combinations were developed to ensure coverage of both material innovation and system integration. These included combinations of "palm oil mill effluent," "POME," "crude palm oil wastewater," and "adsorption," together with specific terms such as "biochar," "layered double hydroxide," "magnetic adsorbent," "adsorption kinetics," "isotherm modeling," and "hybrid treatment." Boolean operators were applied to refine the search results and ensure relevance to adsorption-based wastewater treatment technologies.

2.3 Inclusion and Exclusion Criteria

To maintain scientific rigor and consistency, only peer-reviewed journal articles written in English were included. Studies were included if they focused directly on adsorption applied to POME or crude palm oil wastewater and reported relevant performance indicators such as removal efficiency, adsorption capacity, kinetic modeling, isotherm analysis, regeneration performance, or integration with other treatment processes. Articles discussing adsorbent modification strategies, mechanistic interpretations, or techno-environmental evaluations were also included. Conference abstracts without accessible full texts, duplicate publications, and studies unrelated to CPO wastewater were excluded. Studies lacking quantitative performance data or mechanistic interpretation were also omitted to ensure analytical depth and comparability.

2.4 Data Extraction and Classification

The selected publications were systematically examined and categorized according to adsorbent type, modification approach, target pollutants, adsorption mechanisms, kinetic models, isotherm models, regeneration capability, and integration strategy. The adsorbents were grouped into biomass-based materials, biochar and activated carbon, clay minerals, layered double hydroxides, polymeric adsorbents, carbon nanomaterials, magnetic composites, and multifunctional hybrids. Quantitative parameters, such as adsorption capacity, removal efficiency, optimal operating conditions, and regeneration cycles, were extracted when available. The mechanistic descriptions reported by the authors were synthesized and compared to identify trends in the surface interaction behavior and functional group contributions.

2.5 Comparative and Mechanistic Analysis

A comparative analytical framework was developed to evaluate the progression of adsorption technology over time. Performance comparisons considered surface area development, pore structure engineering, surface functionalization strategies, pollutant selectivity, mechanical stability and regeneration efficiency. Mechanistic interpretation was conducted by integrating the reported experimental data with established adsorption theories, including physisorption, chemisorption, ion exchange, surface complexation, and diffusion-controlled processes. The kinetic behavior was assessed using pseudo-first-order, pseudo-second-order, intraparticle diffusion, and Elovich models, whereas the equilibrium behavior was evaluated based on Langmuir, Freundlich, and Temkin isotherms. This structured analysis enabled the identification of dominant interaction pathways and technological evolution patterns.

2.6 Evaluation of Hybrid Systems

Studies involving the integration of adsorption with biological treatment, membrane filtration, coagulation–flotation, and advanced oxidation processes were analyzed separately to assess system-level performance enhancement. The evaluation focused on improvements in pollutant removal, fouling mitigation, process stability, operational feasibility, and energy implications. Where available, techno-economic considerations and environmental sustainability were qualitatively assessed. This approach allowed the identification of the role of adsorption as either a pretreatment, polishing, or stabilizing unit within multi-stage treatment systems, highlighting its contribution beyond standalone applications.

2.7 Limitations of the Review

This review is limited to publicly available peer-reviewed literature and does not include proprietary industrial data or unpublished pilot-scale studies. Variability in experimental conditions, including differences in adsorbent dosage, contact time, wastewater composition, and synthetic versus real POME, may influence direct performance comparisons among studies. Despite these limitations, a structured evaluation framework was applied to ensure consistency, critical interpretation, and a balanced assessment of technological advancements.

3. Result and Discussion

3.1 Characteristics of Wastewater from Crude Palm Oil Industries

Wastewater from crude palm oil production, commonly referred to as POME, is generated during sterilization, clarification, hydrocyclone separation, and other processing stages. Wastewater constitutes one of the most concentrated agro-industrial effluents because it contains a combination of suspended solids, colloidal materials, degradable organics, and thermally altered compounds (Awang, 2019; Kamari et al., 2021). The physicochemical complexity of POME is influenced by fruit quality, processing conditions, extraction efficiency, and the presence of residual oil (Khairuddin et al., 2016). Wastewater from crude palm oil production is characterized by extremely high organic strength, elevated suspended solids, residual oil, and significant nutrient content. The typical physicochemical characteristics of POME reported in the literature are listed in **Table 1**. As shown, POME exhibits exceptionally high COD and BOD, reflecting its heavy organic loading, along with substantial concentrations of suspended solids and oil and grease derived from incomplete oil recovery during milling operations. In addition, the presence of phenolic compounds, organic acids, ammonium nitrogen, phosphate, and potassium contributes to a strong color, odor, and eutrophication potential if discharged without adequate treatment. The wide concentration ranges reported in Table X highlight the significant variability in POME composition, which is influenced by processing conditions, fruit quality, and operational practices, thereby posing major challenges for conventional wastewater treatment systems.

Table 1. Typical characteristics of palm oil mill effluent

Parameter	Typical concentration range	Unit	References
Chemical oxygen demand (COD)	50,000–100,000	mg L^{-1}	(Kamari et al., 2021; Liew et al., 2015; Mohammad et al., 2021)
Biological oxygen demand (BOD_5)	15,000–30,000	mg L^{-1}	(Bala et al., 2015; Jumadi et al., 2020; Mohammad et al., 2021)
Total suspended solids (TSS)	10,000–40,000	mg L^{-1}	(Kamari et al., 2021; Liew et al., 2015)

Parameter	Typical concentration range	Unit	References
Oil and grease	2,000–7,000	mg L^{-1}	(Liew et al., 2015; Mohammad et al., 2021)
Phenolic compounds	100–1,000	mg L^{-1}	(A Aziz et al., 2020; Nur et al., 2021)
Ammonium nitrogen (NH_4^+–N)	30–200	mg L^{-1}	(Kamari et al., 2021; Mohammad et al., 2021)
Phosphate (PO_4^{3-}–P)	50–180	mg L^{-1}	(Khairuddin et al., 2016; Mohammad et al., 2021)
Potassium (K^+)	1,000–3,000	mg L^{-1}	(Kamari et al., 2021; Khairuddin et al., 2016)
pH	3.5–5.0	–	(Liew et al., 2015; Mohammad et al., 2021)
Temperature	70–90	°C	(A Aziz et al., 2020; Liew et al., 2015)

POME typically exhibits an exceptionally high COD, often exceeding 50,000 mg/L, and BOD values commonly between 15,000 and 30,000 mg/L (Awang, 2019; Kamari et al., 2021). The effluent also contains considerable amounts of total suspended solids derived from fibrous mesocarp, fine particulates, and residual sludge. Oil and grease concentrations remain substantial because of incomplete recovery during clarification processes (Khairuddin et al., 2016). Additionally, proteins, carbohydrates, organic acids, lignocellulosic residues, phenolic compounds, and volatile fatty acids contribute to color, turbidity, and odor (A Aziz et al., 2020).

The characteristics of POME vary among mills owing to differences in press pressures, sterilization temperatures, extraction methods, and water usage patterns (Zainal, 2018). Seasonal variations in fruit composition and changes in oil recovery efficiency further contribute to fluctuations in pollutant concentrations, complicating treatment strategies (Khadaroo et al., 2019). In addition to the organic fraction, POME contains nutrients such as ammonium nitrogen, phosphate, and potassium, which can promote eutrophication if discharged untreated (Khairuddin et al., 2016).

High temperature and low pH conditions encourage anaerobic microflora growth and fermentation product formation, contributing to the strong odor and dark coloration of raw POME (A. Aziz et al., 2020). The high biodegradability of the effluent promotes methane and carbon dioxide production during microbial decomposition (Low et al., 2021). Current environmental regulations require effluent discharge to meet strict limits for COD, BOD, suspended solids, and oil content; however, many systems struggle because of the effluent's high pollutant strength and variability (Kamari et al., 2021; Zainal, 2018). This complexity creates a strong need for robust and flexible treatment technology. Adsorption-based systems are increasingly being studied because of their ability to handle fluctuating influent conditions and effectively remove phenolics, residual oil, and colored compounds (Chan et al., 2024; Kamari et al., 2021).

3.2 Evolution of POME Treatment Technologies

The treatment of wastewater from crude palm oil production has evolved over several decades in response to stricter environmental regulations and the increasing need for sustainable industrial practices. Early processing facilities relied almost entirely on natural degradation through extensive ponding. Over time, a wide range of physicochemical, biological, and advanced treatment technologies have been explored to improve efficiency, reduce environmental burdens, and achieve compliance with regulatory discharge limits. The ponding system is the oldest and most widely adopted method in the palm oil industry (Chan et al., 2024) and is reported as a conventional method for treating POME in Malaysia (Liew et al., 2015). It typically consists of a series of anaerobic, facultative, and maturation ponds. These ponds rely on natural microbial degradation and long retention periods to reduce the high organic load of POME. Although relatively simple and inexpensive to construct, ponding systems require large land areas and are sensitive to hydraulic overload and climatic variability. A long retention time also leads to high methane emissions and contributes to odor problems. Moreover, ponding alone is often insufficient to meet the increasingly strict discharge standards imposed by many producing countries.

Physicochemical methods have been introduced to overcome the limitations of natural ponding. These methods include flotation-coagulation (Poh et al., 2014), coagulation and flocculation (Azmi et al., 2023), coagulation-sedimentation-extraction (Bhatia, 1970), air flotation (Ng et al., 1988), and combined organic precipitation, electrocoagulation, and electrooxidation (Khongkliang et al., 2024). Coagulant agents promote the aggregation of suspended solids and colloidal oils, thereby improving separation efficiency (Zinatizadeh et al., 2017). Although physicochemical treatments are effective in reducing turbidity and suspended solids, they generate large amounts of sludge that require further handling. Chemical costs can also be substantial, particularly for mills with limited wastewater treatment budgets. In addition, many dissolved organic compounds remain in solution after coagulation and require secondary treatment. Biological technologies such as aerobic processes, anaerobic digestion, sequential batch reactors, and expanded granular sludge bed systems provide significant reductions in biological oxygen demand and chemical oxygen demand (Chan et al., 2010; Singh and Srivastava, 2011). Anaerobic digestion is particularly attractive because it produces biogas that can be used as an energy source (Appels et al., 2011; Obileke et al., 2021). However, biological systems require careful control of the pH, temperature, and loading rate. They also suffer from shock load effects when the composition or volume of the POME changes rapidly. Aerobic systems can achieve high degrees of organic removal; however, they require energy-intensive aeration and produce large quantities of excess biomass.

Membrane-based technologies, such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, have shown promising results in removing suspended solids, colloidal oil, and dissolved organic compounds (Ho et al., 2025; Pandey et al., 2012). These technologies produce high-quality effluents; however, they are hampered by membrane fouling, high maintenance costs, and the need for pretreatment to prevent clogging. Concentrate streams generated by membrane systems require additional management. Hybrid technologies that combine biological, physicochemical, and membrane processes have been proposed to enhance treatment efficiency (Gusti Wibowo et al., 2024, 2024). These integrated systems aim to maximize the removal of organic load while minimizing operational limitations. However, hybrid configurations often require complex operation strategies and may not be economically feasible for small- or medium-sized mills. A clear trend in recent research is the increasing interest in adsorption-based treatment. Adsorption offers several distinct advantages that address the weaknesses of earlier technologies. It functions effectively across a wide range of influent conditions, offers strong selectivity toward specific pollutants, and produces minimal secondary waste. Adsorbents can be regenerated multiple times, reducing the overall cost. The development of advanced materials has significantly increased adsorption capacity and process reliability. These advantages explain why adsorption has emerged as a key focus in the evolution of POME treatment strategies and why a deeper understanding of adsorption mechanisms and material innovations is essential for further development.

3.3 Adsorption Fundamentals in Wastewater Treatment

Adsorption is a surface-based process in which dissolved or suspended contaminants are transferred from the liquid phase to the surface of a solid material known as an adsorbent (Nageeb, 2013). This process is governed by the physicochemical interactions between the pollutant molecules and the active sites of the adsorbent (Wibowo et al., 2025). Adsorption has gained considerable attention for the treatment of POME because the effluent contains a mixture of dissolved organics, colloidal oil droplets, pigments, and phenolic compounds that can interact strongly with engineered surfaces. The versatility of adsorption allows the removal of compounds that are resistant to biological degradation and often remain in the treated effluent produced by conventional technologies. The adsorption mechanisms relevant to POME include physical attraction forces, chemical bonding, electrostatic interactions, ion exchange, and surface complexation (Ahsan and Ismail, 2019; Jatoi et al., 2023; Kacaribu et al., 2025). Physical adsorption involves weak van der Waals interactions and usually occurs when the adsorbent possesses a high surface area and a well-developed pore structure (Gunawardene et al., 2022). Chemical adsorption involves the formation of stronger interactions, including covalent bonding, complex formation, or specific affinity between functional groups on the adsorbent surface and pollutant molecules (Gunawardene et al., 2022). POME contains phenolic compounds, colored pigments, organic acids, and residual oil droplets that can participate in both physical and chemical adsorption, depending on the nature of the adsorbent (Badawi et al., 2021; Hoe et al., 2020).

The performance of adsorption systems is commonly described using isotherm models (Naswir et al., 2021). The Langmuir model is often used to represent monolayer adsorption on a surface with uniform active sites (Song et al. 2013). The Freundlich model is suitable for heterogeneous surfaces and describes multilayer adsorption (Saadi et al. 2015). The Temkin model considers the effect of indirect adsorbate interactions on the adsorption process (Pursell et al., 2012). These models provide insights into the maximum adsorption capacity, interaction strength, and surface heterogeneity. Studies on POME often reveal that engineered adsorbents exhibit mixed adsorption behavior because the effluent contains multiple pollutant classes that interact differently with each type of active site in the adsorbent. Kinetic models help explain the rate of pollutant transfer from the liquid phase to the adsorbent surface. The pseudo-first-order and pseudo-second-order models are widely applied in adsorption studies involving POME (Lin and Wang, 2009; Revellame et al., 2020). The pseudo-first-order model assumes that the rate is influenced by the difference between the equilibrium and actual adsorption at a given time (Naswir et al., 2021). The pseudo-second-order model often fits better because it reflects systems dominated by chemisorption or strong interactions with functional groups (Taher et al., 2023a). Other models, such as the intraparticle diffusion and Elovich models, provide information about the diffusion of pollutants inside the pores and the role of surface heterogeneity.

Several operational parameters influence the overall performance of adsorption in POME treatment. The pH of the solution affects the charge of both the pollutant molecules and adsorbent surface (Adeleke et al., 2017). Lower pH conditions tend to increase interactions with phenolic compounds, whereas higher pH conditions can enhance the removal of certain organic acids (Hashim et al., 2018; Rahmanian et al., 2014; Solomakou and Goula, 2021). The particle size determines the available surface area and influences external mass transfer (Hajilari et al., 2019; Mathews and Zayas, 1989). Adsorbent dosage affects the number of active sites and degree of surface saturation (Mondal et al., 2008). Temperature influences the rate of diffusion and strength of the interaction (Baraka, 2015; Zehtab and Tarighat, 2018). The chemical nature of the surface, including the presence of oxygen-containing groups, metal species, or hydrophobic domains, greatly affects the selectivity toward various pollutants. Understanding these fundamental principles is essential for designing high-performance adsorbents for POME treatment. The complexity of POME requires adsorbents with a combination of high surface area, tailored pore distribution, strong affinity toward aromatic compounds, and adequate stability under acidic and high-temperature conditions. These considerations have encouraged the rapid development of natural adsorbents, modified adsorbents, carbon-based materials, layered minerals, and nanostructured composites, which will be discussed in the following section on state-of-the-art adsorbent evolution.

3.4 State of the Art Adsorbents for CPO Wastewater

Recent advances in materials engineering have significantly expanded the range of adsorbents available for wastewater treatment in the crude palm oil industry. The complexity of POME requires adsorbents with a high surface area, tailored pore structures, strong affinity toward aromatic and hydrophobic compounds, and stable performance under acidic conditions. Research efforts over the last decade have focused on material classes that include lignocellulosic biomass, biochar, clays, layered double hydroxides, carbon-based engineered materials, polymeric adsorbents, and hybrid nanostructures. Each material type provides unique advantages in terms of cost, selectivity, and reusability.

Agricultural waste-based adsorbents represent one of the earliest classes investigated for POME treatment (Hamzah et al., 2025). These adsorbents include palm fiber (Alhogbi et al., 2021), palm kernel shells (Jumasiah et al., 2005), coconut shells (Budihardjo et al., 2021), rice husks (Foo and Hameed, 2009), and other lignocellulosic residues. Their availability and low cost make them attractive to industries located near plantations. These materials exhibit natural porosity and contain functional groups, such as hydroxyl and carboxyl groups, that interact with suspended solids and dissolved organics. However, untreated biomass typically has a limited surface area and often exhibits low adsorption capacity for phenolic compounds and oil droplets. Consequently, chemical and thermal modifications have been introduced to enhance pore development and surface chemistry (Mozetič, 2019; Rehman et al., 2019).

Biochar and activated biochar derived from palm biomass have become important adsorbents for POME. Biochar provides a highly carbon-rich structure with abundant micro-and mesopores (Taher et al., 2023; Wibowo et al., 2025). Thermal activation produces a greater surface area, while chemical activation introduces oxygen-containing groups that improve the affinity toward organic acids and colored compounds. Engineered biochar composites that incorporate metal oxides (Dey and Ahmaruzzaman, 2023), clay minerals, or polymeric binders further enhance stability and selectivity (Liu, 2007; Scheuermann Filho et al., 2021). These advanced biochars showed significant improvement in the removal of residual oil and persistent color-forming substances. The flexibility of biochar synthesis allows for fine control of pore distribution and surface functionality, which is critical for handling the diverse pollutants present in POME.

Clay-based materials such as bentonite, kaolin, montmorillonite, and sepiolite have also been examined because of their layered structures and high cation exchange capacity (Borah et al., 2022; Perelomov et al., 2021). Clays have a strong affinity for polar compounds and can effectively remove suspended solids and colloidal oil (Swartzen-Allen and Matijevic, 1974). Surface modification using organic surfactants or metal ions enhances the interaction of these membranes with hydrophobic and aromatic molecules (Chao et al., 2013). Layered double hydroxides represent another mineral-based material with tunable interlayer spacing and strong anion exchange capability (Tang et al., 2022). These materials are effective in removing organic acids, color-forming molecules, and nutrient-based contaminants. Their regeneration through ion exchange also contributes to their long-term applicability.

Carbon-based engineered materials, such as activated carbon, carbon nanotubes, and graphene-related materials, have been extensively studied because of their exceptionally high surface areas and strong affinities toward aromatic pollutants. Activated carbon remains one of the most effective adsorbents for POME because of its well-developed microporous structure and stable performance under a wide range of pH and temperature conditions (Hayawin et al., 2023; Parthasarathy et al., 2016). Carbon nanotubes and graphene oxide have unique properties, including strong π electron interactions, high adsorption rates, and selective affinities toward phenolic compounds (Catherine et al., 2018; Lin and Xing, 2008). The cost of these materials is relatively high; however, ongoing advances in synthesis and the use of biomass precursors have improved their economic feasibility.

Polymeric adsorbents, such as ion exchange resins and synthetic polymers with specific functional groups, provide high selectivity toward particular pollutant classes (Hubicki and Koodynsk, 2012; Samiey et al., 2014). These materials can be designed to target organic acids, dyed compounds, or dissolved aromatic molecules. Their mechanical strength and resistance to chemical degradation make them suitable for repeated regeneration processes. However, polymeric adsorbents must be carefully matched with the composition of POME to avoid rapid fouling by oil droplets and suspended solids.

Emerging nanostructured adsorbents have introduced a new level of performance in POME treatment. These include magnetic nanocomposites, metal oxide-impregnated carbon materials, polymer-coated nanoparticles, and hybrid structures that combine the strengths of mineral, carbon, and polymer components. Magnetic composites are particularly attractive because they can be rapidly separated using magnetic fields, thereby minimizing secondary waste and processing time. Nanostructured materials allow precise control of interaction sites and can achieve a very high adsorption capacity owing to their large surface-to-volume ratio. Their main challenges are material cost, potential toxicity, and the need for safe recovery systems.

The wide diversity of adsorbents reported in the literature shows that adsorption for POME treatment has progressed from simple agricultural waste to highly engineered multifunctional materials. Comparative studies consistently demonstrate that advanced composites and nanostructured systems offer the highest removal performance for color, phenolic compounds, and residual oil. However, natural and modified biochars remain attractive for large-scale applications because of their low cost and renewable origin. The evolution of adsorbent materials reflects a shift toward designs that combine high capacity, strong selectivity, rapid regeneration, and operational stability in complex wastewater matrices.

3.5 Functionalization and Modification Approaches

The development of high-performance adsorbents for wastewater from the crude palm oil industry has increasingly focused on functionalization and modification strategies. These strategies aim to improve surface chemistry, increase pore accessibility, enhance the affinity toward specific pollutants, and extend material durability during repeated adsorption cycles. The complex composition of POME, which contains a mixture of phenolics, organic acids, colored compounds, oil droplets, and suspended solids, requires adsorbents with tailored surface properties and stable active sites. Functionalization offers a powerful route for meeting these requirements. Chemical activation is one of the most widely used modification approaches (Panwar & Pawar, 2022). This process involves the use of activating agents such as potassium hydroxide, phosphoric acid, or zinc chloride to promote pore formation and introduce oxygen-containing surface groups. These groups enhance the interaction with phenolic compounds and other polar organics commonly found in POME. Chemical activation also increases the proportion of mesopores, which facilitates the diffusion of larger molecules, such as residual oil and colored components (Rehman et al., 2019). The enhanced porosity and surface functionality significantly increased the adsorption capacity and improved the mass transfer behavior.

Surface oxidation is another approach to altering the chemical nature of adsorbents. Treatments that involve controlled exposure to oxidizing agents create functional groups such as carboxyl, carbonyl, and hydroxyl groups (Langley and Fairbrother, 2007; Pradhan and Sandle, 1999). These groups enhance the affinity of the adsorbent for organic acids and aromatic compounds through hydrogen bonding and complex formation. Oxidation also increases hydrophilicity, which reduces fouling by oil droplets and helps maintain the adsorption performance under prolonged operation. Grafting strategies involve the introduction of new functional groups or polymers onto the adsorbent surface. These functional groups were selected to target specific contaminants present in POME. For example, amine functionalization improves the binding of phenolic compounds, whereas sulfonated groups enhance the affinity toward colored pigments and reactive organics (Xu et al., 2019; Yang et al., 2025). Grafted polymers can introduce selective binding sites that increase the removal efficiency, even when the wastewater contains competing molecules. This targeted design allows adsorbents to achieve high selectivity while maintaining an adequate capacity.

Metal and metal oxide impregnation has emerged as a highly effective method for improving the adsorption of recalcitrant compounds. Metals such as iron, aluminum, and magnesium create surface-active sites that facilitate complexation with phenolic molecules and other aromatic organics. Metal oxides, such as iron oxide, manganese oxide, and titanium oxide, provide catalytic or redox active sites that enhance the removal of color-forming substances (Huang and Zhang, 2020; Mapossa et al., 2021; Zhu et al., 2020). Impregnation also improves structural stability and prevents pore collapse during thermal regeneration.

Composite formation is another important modification technique in this field. Composites that combine biochar with clay minerals, polymer matrices, or layered double hydroxides create multifunctional adsorbent systems with complementary properties. Clay-based components contribute a high cation exchange capacity, whereas polymeric components provide mechanical strength and resistance to acid attack. Layered double hydroxides offer strong anion exchange capabilities and can remove organic acids and colored anions. These composite materials address the limitations of single-component adsorbents and improve overall pollutant removal across multiple contaminant categories. Magnetic functionalization has attracted considerable attention because it allows the rapid separation of adsorbents from wastewater using magnetic fields (Zeng et al., 2022). Magnetic nanoparticles embedded within carbon-based or mineral-based matrices do not significantly reduce the surface area and provide an efficient route for adsorbent recovery. This approach reduces handling time, minimizes secondary sludge generation, and improves the feasibility of continuous flow systems. Magnetic composites are especially valuable for high-strength wastewater, such as POME, where large volumes of solids must be quickly removed. Functionalization strategies have greatly improved the adsorption performance for POME treatment and have enabled the development of advanced materials with high capacity, strong selectivity, and excellent regeneration capability. The combination of chemical activation, surface oxidation, grafting, metal impregnation, and composite formation has produced adsorbents that significantly outperform traditional materials. These advancements form a critical foundation for the next stage of innovation, which involves integrating adsorption with other treatment technologies to achieve higher efficiency and greater process sustainability. This topic is discussed in the following sections.

3.6 Integration of Adsorption with other Technologies

The increasing complexity of wastewater from the crude palm oil industry has encouraged the development of integrated treatment systems that combine adsorption with other complementary technologies. These combinations aim to enhance pollutant removal efficiency, overcome the specific limitations of single treatment methods, and improve overall process stability. Integration allows the selective targeting of contaminants that are resistant to biological degradation, prone to membrane fouling, or difficult to remove through physicochemical methods alone. Therefore, the use of hybrid systems has become an important trend in advanced POME treatment research. The combination of adsorption and biological treatment is one of the most extensively studied approaches. Biological systems such as anaerobic digestion and aerobic treatment are effective for degrading biodegradable organic matter (Du and Li, 2017; Reineke, 2001), but they frequently struggle with phenolics, colored compounds, and colloidal oil droplets. These resistant pollutants inhibit microbial activity and reduce overall system stability. The addition of an adsorption step reduces the concentration of inhibitory substances and enhances the microbial performance. Adsorption can also polish biologically treated effluents by removing residual color and dissolved organics. This combination improves effluent quality while maintaining low operational costs.

Adsorption has also been integrated with membrane-based processes (Schideman et al., 2007). Membrane filtration provides high-quality effluent and can achieve excellent removal of suspended solids, oil droplets, and dissolved organics (Keyvan Hosseini et al., 2022). However, membrane fouling remains a major challenge, especially when treating high-strength wastewater, such as POME. The inclusion of an adsorption stage before membrane filtration reduces the concentration of foulants, which prolongs the membrane lifespan and decreases the frequency of cleaning. In some configurations, adsorbents are applied within the membrane bioreactor system to stabilize biological activity and protect the membrane surface from rapid clogging. This approach results in a more consistent performance and lower operational costs. Advanced oxidation processes have been coupled with adsorption to address recalcitrant pollutants that resist conventional degradation methods. Oxidation methods, such as ultraviolet-based, ozone-based, and hydrogen peroxide-based processes, produce reactive species that break down complex organic molecules and convert them into more adsorbable forms (Mahmoodi and Pishbin, 2025; Stefan, 2017). When combined with adsorption, oxidation serves as a pretreatment step that improves the accessibility of pollutant fragments to the adsorbent surface. Conversely, adsorption after oxidation can remove intermediate by-products that may be toxic or colored. This synergy significantly enhances the removal of phenolic compounds, pigments, and persistent organic substances in POME.

Hybrid systems that incorporate adsorption with coagulation or flotation have also been developed (Wibowo et al., 2024). Coagulation improves the removal of suspended solids and colloidal oil, which reduces the physical blockage on the surface of the adsorbent. In turn, adsorption eliminates the dissolved organics that remain after coagulation. This sequence results in a more efficient separation and a clearer final effluent. Flotation, particularly air flotation, benefits from adsorption because adsorbents assist in the attachment of hydrophobic molecules to rising bubbles, thereby improving the separation efficiency. Techno-economic evaluations show that integrated systems provide higher treatment efficiency with lower overall costs than single-unit processes. Energy consumption is reduced because adsorption stabilizes the biological systems and reduces membrane fouling. Chemical consumption is reduced because advanced composites require less regeneration and maintain a higher capacity over multiple cycles. Simultaneously, environmental impacts are minimized because integrated systems produce less secondary waste and achieve more consistent removal of pollutants that contribute to odor, color, and greenhouse gas formation. The success of integrated systems demonstrates that adsorption can serve as a central component in multi-stage treatment strategies for POME. By combining the strengths of biological degradation, membrane filtration, chemical oxidation, and physicochemical separation, adsorption enhances both treatment efficiency and operational sustainability. These hybrid systems provide a promising pathway for scaling up advanced POME treatment in commercial palm oil mills in the future. Their future development will require careful consideration of cost, process control, materials regeneration and environmental performance, topics that will be explored in the following section on challenges and future perspectives.

3.7 Challenges, Knowledge Gaps, and Future Perspectives

Although adsorption has demonstrated strong potential for palm oil mill effluent treatment, several important challenges remain before the technology can be widely implemented on an industrial scale. These challenges originate from the complex nature of POME, variability in operating conditions, inconsistencies in adsorbent regeneration, and limitations in long-term performance. Addressing these issues is essential to ensure reliable, cost-effective, and sustainable process operations. A major challenge lies in the structural instability of many low-cost and bio-based adsorbents during continuous treatment. Materials such as biochar, agricultural residues, and clay composites tend to undergo swelling, fragmentation, and loss of active sites when exposed to fluctuating pH, high temperature, or strong hydraulic forces in column systems. This instability leads to a pressure drop, clogging, and a gradual decline in adsorption capacity. Only a limited number of studies have assessed the mechanical durability of adsorbents under realistic flow conditions. Therefore, research on strengthening methods, binder selection, mineral reinforcement, and composite formation is urgently needed.

Another concern is the regeneration efficiency of the spent adsorbents. Chemical and thermal regeneration can restore a portion of the adsorption capacity; however, repeated cycles often lead to pore collapse, surface oxidation, and reduced performance. In many cases, regeneration consumes significant amounts of chemicals and energy, which increases operational costs and creates secondary waste. There is a need for regeneration strategies that use mild conditions, produce fewer residues, and are compatible with large-scale operations. Promising options include solvent-free regeneration, catalytic oxidation at low temperatures, and in situ biological regeneration. Process variability is another significant challenge. POME composition changes depending on fruit quality, milling operations, and seasonal production. These variations influence the adsorption behavior, breakthrough time, and bed exhaustion. Most studies rely on synthetic or laboratory-scale POME with limited variability, which does not fully represent industrial wastewater. Future research should focus on dynamic testing using real POME with different characteristics. Advanced modelling that integrates adsorption kinetics with hydraulic behavior can support the design of more stable systems.

Knowledge gaps also exist regarding the interactions between adsorption and other treatment units in integrated systems. Although hybrid processes have been developed, there is insufficient understanding of competitive adsorption between organic matter, surfactants, oil droplets, and phenolic compounds. The presence of biological solids or oxidation intermediates may also block the active sites or modify the surface chemistry. A more detailed molecular-level investigation is required to clarify these interactions. Techniques such as in situ spectroscopy, surface energy mapping, and computational simulations can provide valuable insights. From a sustainability perspective, large-scale applications require a clear evaluation of the environmental footprint of adsorbent production, operation, and disposal. Life cycle assessment studies on POME treatment are still scarce. There is a need to quantify the energy demand, greenhouse gas emissions, and resource consumption associated with various adsorbent types. Furthermore, strategies for the safe disposal or valorization of spent materials must be developed. Options include use as fuel, incorporation into building materials, recovery of adsorbed organics, or conversion into soil amendments. However, each option requires further validation under real-world conditions.

Despite these challenges, the field offers several promising opportunities for future research. Advanced composites, such as biochar-based layered double hydroxides, magnetic materials, and clay-reinforced hybrids, exhibit strong structural stability and high affinity for complex pollutants. Their tunable surface properties allow for the selective removal of targeted compounds, while magnetic separation ensures rapid recovery. The use of local waste materials for adsorbent production supports circular economy principles and reduces treatment costs. In addition, the integration of adsorption with biological, membrane, and advanced oxidation processes provides a pathway toward highly efficient multistage treatment systems. Future research should prioritize the development of mechanically durable adsorbents, standardized regeneration methods, full-scale column testing, and comprehensive techno-economic analyses. Improved modelling tools combined with machine learning may assist in predicting breakthrough behavior under complex wastewater conditions. Ultimately, the advancement of adsorption-based technologies will support cleaner production in the palm oil industry and contribute to more sustainable management of industrial wastewater.

4. Conclusions

Wastewater from crude palm oil production remains among the most challenging agro-industrial effluents because of its extremely high organic strength, complex colloidal matrix, and pronounced variability in composition. Conventional treatment technologies provide partial remediation but frequently fail to ensure consistent compliance with discharge standards, particularly for recalcitrant contaminants, such as phenolic compounds, color-forming substances, and fine oil droplets. These persistent limitations have driven increasing interest in adsorption-based treatments, which offer high removal efficiency, operational flexibility, and strong compatibility with existing treatment units. The evolution of adsorption technologies for palm oil mill effluent has progressed from low-cost agricultural residues to engineered biochar, mineral hybrids, layered double hydroxides, and magnetic composites with enhanced surface areas, tailored selectivity, and improved recoverability. Recent developments have demonstrated that adsorption delivers its greatest value when implemented within hybrid treatment configurations that integrate biological, membrane, or oxidation-based processes. Such systems reduce inhibitory pollutant loading, stabilize downstream units, and provide a more resilient and adaptable treatment pathway for complex effluents, such as POME. Despite these advances, industrial implementation remains constrained by unresolved challenges. Structural instability under continuous-flow conditions, declining performance during repeated regeneration cycles, limited understanding of competitive adsorption in real POME, and the scarcity of large-scale validation studies continue to hinder the transfer of this technology. In addition, the environmental and economic implications of adsorbent production, regeneration, and end-of-life management remain insufficiently quantified in the literature.

The most critical next step in this field is a decisive shift from laboratory-scale material performance to application-oriented validation under realistic operating conditions. Priority should be given to continuous-flow and pilot-scale studies using real POME, where the combined effects of wastewater variability, oil and grease fouling, hydraulic stress, and long-term membrane regeneration can be rigorously evaluated. In parallel, adsorption units must be deliberately designed as functional components within existing treatment trains, serving as targeted polishing or protective steps that mitigate biological inhibition, membrane fouling, and effluent instability, rather than as stand-alone solutions. This transition from material-centric innovation to system-level design, durability, and operational compatibility will ultimately determine the practical and environmental impacts of adsorption-based technologies. Achieving this shift will enable adsorption to move beyond promising laboratory results and become a deployable, sustainable solution that supports cleaner production and improved wastewater management in major palm oil-producing regions.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used ChatGPT to improve the readability and fix grammatical errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Ethics Statement

This study did not require ethical clearance.

CRediT Authors Statement

Meutia Mirnandaulia1: Conceptualization, Writing Original Manuscript, Writing-Review and Editing, Finalization. **Li Idi'il Fitri, Mustakim:** Conceptualization, Writing Original Manuscript, Writing-Review and Editing, Finalization. **Muhammad Fadli Khairul:** Conceptualization, Writing Original Manuscript, Writing-Review and Editing, Finalization

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